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An iteration-based design algorithm for high frequency transformer in SSTs and its validation by finite element analysis

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Abstract

This paper proposes an iteration-based algorithm for the optimum design of a high frequency transformer for solid-state transformer (SST) applications. This algorithm minimizes the total owning cost (TOC) of a distribution type solid-state transformer. The unique features of this algorithm compared with the available algorithms in the literature are as follows: it iterates eight design variables, four constraints are defined for selecting the valid designs, and it works with different core materials and AC test voltages. The algorithm uses various user-defined data inputs to calculate loss capitalization values for TOC calculation. In every iteration, TOC is estimated, and calculated values of design constraints are compared with their threshold limits. A case study is conducted on a high-frequency transformer (HFT) incorporated in 1000-kVA, 11-kV/415-V, Dyn11 three-phase wound core SST. This is to determine the optimum design parameters. In this case study, the algorithm was iterated with 2,100,000 design data inputs, generating 258,272 designs that satisfied all design constraints. The optimum design with minimum TOC is selected from the generated 258,272 designs. The optimum design is validated using finite element analysis in ANSYS software. Comparing the results of both analyses, the deviation is less than 5%. Hence, the algorithm's reliability is proved.

Keywords: High frequency transformer, Total owning cost, Solid-state transformer, Smart-grid

Introduction

Solid-state transformer (SST) is an essential component of the smart-grid infrastructure, being capable of controlling and communicating at medium voltage levels [1, 2]. The potential merits of SST over conventional transformers are, the ability to control real and reactive power [3], the ability to isolate loads quickly under fault conditions, the ability to integrate renewable energy sources and energy storage elements, and the ease of connecting AC and DC loads [4]. The structure of an SST consists of the following components; they are power electronic modules, high frequency transformer (HFT), DC link capacitors, control and communication systems, and cooling system. Power is fed to SST through the front end AC/DC converter, and medium voltage DC-link is provided to smooth out the voltage and to provide energy storage. Dual active bridge (DAB) consists of a DC/AC inverter followed by a high frequency transformer (HFT) and an AC/DC converter. Power is transferred from SST to the load or distributor through a low voltage DC-link and DC/AC inverter as shown in Fig. 1 [4].

SSTs are more expensive than conventional transformers of the same power rating. This is because it require additional power electronics circuits and controllers. The conventional power frequency distribution are now purchased based on total owning cost (TOC) rather than conventional capital cost. Because TOC accounts for losses that benefit the country in generation, transmission, etc., TOC of SST is the sum of product-cost and cost of energy losses during the lifetime [5]. For a specific rating of SST, TOC changes only with changes in HFT parameters. There is no change in the power electronic circuits required for SST in that specific rating. Therefore, the optimum TOC of HFT can be taken as the optimum TOC of SST. It is essential to reduce the TOC of high frequency transformers in order to compete with conventional transformers for product-cost benefits. Hence, the objective of the HFT design for reliable power transfer is to get the maximum reduction in life time cost [6]. This can be achieved by selecting a core material with a suitable saturation flux density [7] and winding arrangements, and conductor dimensions that reduce load loss at high frequencies [8]. Oil-free dry-type designs are preferred for HFTs to reduce the risk of fire hazards caused by liquid dielectric leakage and to reduce the environmental pollution due to oil leakage. So the design of its insulation structure with solid insulating materials is extremely important for meeting the objective of life time cost reduction [9].

A preliminary analytical approach for the design of HFT was detailed in [10]. An analytical approach to optimize the leakage inductance and flux density with minimum power loss have been described by Du Y. et al. [11], and advancement to this approach with the incorporation of skin and proximity effects for calculation of load loss at high frequencies is presented in [12]. An iterative design approach that selects the design parameters of a single-phase HFT for optimum flux density to maximize its efficiency was proposed in [13]. A multi-physics-based optimization approach to minimize total losses, power density and manufacturing cost by optimal selection of core dimensions is detailed in [14]. However, an appropriate design

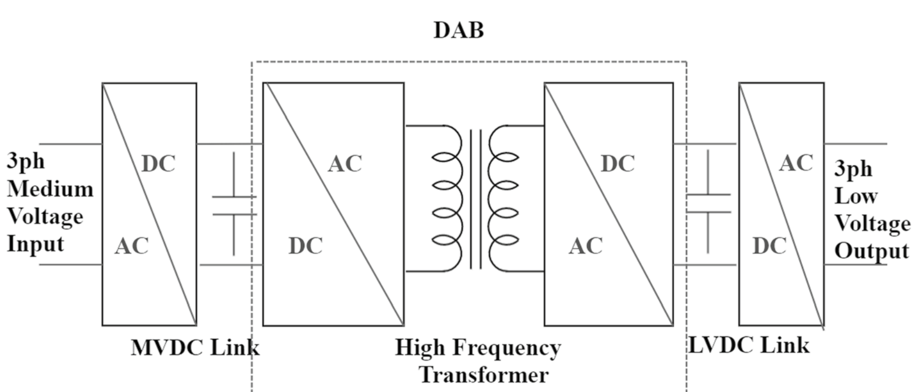

Fig. 1 Structure of SST

of HFT should consider the winding parameters along with the core dimensions for optimizing its design based on an objective function. The complexity and large computation time associated with the application of a coupled multi-physics-based optimization approach necessitate the adoption of a much simpler iteration-based scheme for HFT design.

The development of iteration methods to optimize the design of HFT reveals the formulation of an objective function accompanied by a set of electrical, magnetic, and thermal constraints. An iterative design algorithm for a shell type stacked core HFT yields the optimum design parameters based on minimizing the transformer volume as the objective function is described in [15]. The development of an iteration-based algorithm for a specific frequency, which optimizes the selection of design variables to meet a set of design constraints, has been detailed in [16]. This method offers flexibility for the user to choose the design based on their selection criteria; however, this process requires expert personnel to make the final decision. A preliminary study to develop an iterative algorithm with TOC as an objective function and inclusion of necessary constraints was done by Joseph S. et al. [17]. The authors of [17], improved their work in this paper by adding flux density to the iteration variables and incorporating high-frequency effects into the estimation of load loss during iteration. This paper presents the formulation of a generalized algorithm for the design of a high frequency transformer that takes TOC as the objective function and checks four design constraints, such as saturation flux density, maximum temperature rise under full load, percentage impedance, and fault current temperature rise. The design variables considered for iteration are flux density, frequency, transformer constant, high voltage and low voltage conductor dimensions, and core dimensions. Furthermore, this algorithm offers the convenience of choosing a core material from a list of three and calculates clearance magnitudes based on the AC test voltage and as per IEC standards [18–20].

With the developed algorithm, a set of 2,100,000 design data of a high frequency transformer incorporated in 1000-kVA, Dyn11, three-phase, SST of 11 kV/415 V are given as input and 258,272 designs are generated. The result of the optimum design with minimum TOC is used to develop a finite element model of the HFT, which can work as a model incorporating real operating conditions. Finite element analysis software "Ansys" is used to validate the performance of the proposed algorithm. In this software, Ansys Maxwell is coupled with Ansys Mechanical to perform and analyze different parameters of HFT such as magnetic flux, temperature, and no-load and load losses.

Methods

The methods used for finding optimum design of high frequency transformer incorporated in solid-state transformer with minimum total owning cost is explained in this section. An iterative algorithm is developed for finding the optimum design using analytical technique. The details of that is given by briefly explaining about the iterative algorithm considering the formulation of objective function, selection of design variables and constraints, and developing flowchart of the same. Validation of the optimum design developed is done using finite element analysis, the details of

HFT model development in Ansys software and its excitation and various responses and interconnections with other platforms are well explained.

Development of an iterative algorithm for the design of HFT

Formulation of the objective function and selection of design variables play an important role in the development of an iterative algorithm for HFT design. The objective function in this iterative algorithm is to minimize the total owning cost. TOC includes the product cost along with losses incurred for a specific period of time. Transformer design variables must be selected to minimize the sum of product cost and cost due to core loss and load loss. The optimal design is derived from iterating over eight design variables and considering four design constraints. A set of designs which satisfy all these constraint are shortlisted and an optimum design with minimum TOC is selected from the set of shortlisted designs.

The following sections discusses the development of the iterative algorithm based upon the formulation of the objective function, the selection of the design variables, and constraints based on the analytical design of HFT and flowchart of the proposed iterative algorithm.

Formulation of the objective function

TOC method permits the user to estimate the cost of losses of the transformer for a specific life cycle. The cost of losses is estimated by taking the energy rate, borrowing rate and load factor for a period of time. The lifetime cost with no load and load losses discounted to the present value is accounted for the TOC calculation. The expression for calculating total owning cost is given in (1).

$$\begin{aligned} TOC &= Initial\ Cost\ of\ Transformer\ in\,\$ + \\ &A \times No\,Load\,Losses + B \times Load\,Losses \end{aligned} \tag{1}$$

where A and B are the cost of one unit no-load loss and load loss respectively, measured in $\$/W$. The factor A calculates the monitory value of a unit of loss for the design life of transformer discounted to the present value. However the load loss varies as the square of the load current and the load current is not constant. It changes with the time of the day, season, type of load etc. Considering this the factor B is derived which is based on the square of the load factor. Product cost or initial cost of the transformer depends on the construction details and design parameters along with materials used for the construction. The design of HFT explained here is based on the analytical equations given in [21, 22]:

The design of HFT core is based on the selection of core structure and the core material. Compared to stacked core construction, wound core construction has fewer joints to minimize the core loss. Wound core construction is therefore selected to minimize TOC. The high saturation flux density at high operating frequencies makes amorphous, nanocrystalline, and si-steel suitable for core material. The core magnetization is considered to be nearly sinusoidal, so fundamental transformer equations are used to calculate the core dimensions. Two important steps in core construction are, calculation of the core lamination width and stacking thickness. This can be achieved with the following design equations.

Net iron area of transformer core (A_i) is

$$A_i = E_1/(4.44fB_m) \tag{2}$$

where E_1 represents volt/turn of HFT which is equal to $k\sqrt{Q}$ (k transformer constant and Q kVA rating), f is the frequency of operation in Hz and B_m is the maximum flux density in Tesla. Gross core area (A_g) is calculated by dividing the net iron area by the stacking factor. Material data-sheets provide the stacking factor. Each limb has a gross core area of $A_g/2$. The dimensions of the core structure are calculated by knowing the width of core lamination and the thickness of core stacking. Based on industry practices for wound core construction with amorphous core material, the stack thickness is normally maintained between 1/3 and 1/2 of the built-up core's width.

$$Gross\ core\ area\ of\ one\ limb = A_g/2 = (thickness \times width\ of\ lamination) \tag{3}$$

By substituting thickness-width in the above equation, the maximum width of the core lamination (W_{max}) and the minimum width of the lamination (W_{min}) are obtained. For every width in between, calculate the thickness of the lamination and then $Ag/2$ from (3).

High frequency transformer winding structure design plays an important role in the entire HFT design process. LV winding is placed near the core structure to reduce insulation requirements, and HV winding is placed over LV winding. In the three-limb structure, each limb represents a particular phase. LV windings of the HFT design use foil-type windings for better heat dissipation and for handling high currents over 1000 amperes. The required cross-section area is calculated based on the current flowing through the LV winding and the current density. Based on this area, the width and thickness of the foil is calculated. For HV winding with phase current of around 30A, the rectangular conductor is preferred. This is because of the improved space factor and lower eddy current losses when compared to a round wire of equivalent cross section. So rectangular type winding is adopted for the design of HV winding. Design equations of HV winding are similar to LV. The number of turns of HV and LV winding are calculated from the terminal voltage and volt/turn equation. The working voltage between the layers of HV winding is calculated in (4).

$$Working\ Voltage\ between\ layers = Volt/turn \times Turns/layer \times 2 \tag{4}$$

In the induced over voltage test, the voltage induced is twice the working voltage, so inter-layer insulation is provided to withstand it [23].

Calculating no-load and load loss are other critical parameters in TOC calculation. Analytical calculations of these losses are detailed below: Original Steinmetz's equation is used for calculating no-load loss. The general form of this equation is given by

$$P_s = Kf^{\alpha}{B_m}^{\beta} \tag{5}$$

where B_m represents the peak flux density in Tesla, f represents frequency in kHz. K, α and β values depend on the core material. Total core loss is the product of the total weight of the core and specific core loss obtained from Steinmetz's equation.

The transformer's behavior can significantly change as frequency increases. This is due to the redistribution of the magnetic field as well as current density within the conductor. The load loss at high frequency creates an additional loss caused by the skin and proximity effect along with the I^2R losses [16]. This can be verified by the calculation of eddy current effect. The effect of eddy current is incorporated in the calculation of AC resistance of rectangular HV and foil type LV winding. The procedure adopted in this analytical design is explained below:

AC resistance factor for foil type LV winding: The total ohmic loss of a foil type winding is calculated using Dowell's expression given in (6)

$$P_w = I^2 \frac{l_w}{2\delta\sigma h_w} m\left[\zeta_1 + \frac{2}{3}(m^2 - 1)\zeta_2\right] \tag{6}$$

where I is the peak current carried by the conductor in *ampere*, l_w is the length of winding in one layer, m is the number of layers. The skin depth is given as δ and σ is the material conductivity. h_w represents the height of winding or width of the foil. ζ_1 and ζ_2 are the skin and proximity factors given by

$$\zeta_1 = \frac{\sinh(2\triangle) + \sin(2\triangle)}{\cosh(2\triangle) - \cos(2\triangle)} \tag{7}$$

$$\zeta_2 = \frac{\sinh(\triangle) - \sin(\triangle)}{\cosh(\triangle) + \cos(\triangle)} \tag{8}$$

where $\triangle = d_w/\delta$ is the penetration ratio and d_w represents the thickness of the foil type winding. $\delta = \sqrt{\frac{\rho}{\pi\mu f}}$ where ρ and μ are the resistivity and permeability of the conductor and f is the frequency of operation. The power dissipated in any resistive element R_{ac} due to rms current I_n is given by

$$P_w = {I_n}^2 R_{ac} = \frac{1}{2} I^2 R_{ac} \tag{9}$$

Equating (6) and (9), the AC resistance expression is obtained as

$$R_{ac} = \frac{l_w}{\delta\sigma h_w} m\left[\zeta_1 + \frac{2}{3}(m^2 - 1)\zeta_2\right] \tag{10}$$

The DC resistance of the foil type conductor is given by

$$R_{dc} = \frac{l_w}{d_w \sigma h_w} m \tag{11}$$

Comparing Eqs. (10) and (11), the relation between AC resistance and DC resistance, which is also known as Dowell's resistance factor F_r is obtained.

$$F_r = \triangle\left[\zeta_1 + \frac{2}{3}(m^2 - 1)\zeta_2\right] \tag{12}$$

AC Resistance Factor for Rectangular HV Winding: For windings with rectangular conductors, Dowell introduced a factor called porosity factor (η_w) in the load loss expression. This factor converts rectangular conductors with its equivalent foil type conductors in the window. So the effective conducting area increases, thus an equivalent conducting material is defined which generates an equivalent magnetic field along the conduction path.

$$\sigma' = \eta_w \sigma \tag{13}$$

where η_w is the porosity factor for approximating a rectangular conductor to a whole window foil type conductor. It consists of two terms η_{w1} and η_{w2} given below

$$\eta_{w1} = \frac{N d_{w'}}{h_{w'}} \tag{14}$$

where N is the number of turns in one layer, $d_{w'}$ represents the width of HV conductor and $h_{w'}$ is the electrical height of HV winding.

$$\eta_{w2} = \frac{h_{w'}}{h_w} \tag{15}$$

Therefore, the AC resistance factor (F_r) for the HV winding is given by Eq. (16)

$$F_r = \triangle' \left[\zeta_1' + \frac{2}{3}(m^2 - 1)\zeta_2' \right] \tag{16}$$

where $\triangle' = \sqrt{\eta_w}\,\triangle$ and ζ_1' and ζ_2' are calculated similar to the calculation of ζ_1 and ζ_2 by substituting $\triangle'$ instead of $\triangle$. The analytical design discussed above reveals that the minimization of TOC is achieved by minimizing initial cost and cost due to losses of transformer. The suitable values of design variables aid to get the optimum design from the iterative algorithm which must satisfy all design constraints.

Selection of design variables and constraints

Proper selection of design variables and constraints considerably affects the optimum design of HFT. Since TOC depends on losses and the initial cost of HFT, the dimensions of core, winding, and parameters directly related to construction are taken as design variables. The design variables considered in this work for optimizing core design are, the width of core lamination (w_c) and thickness of core stacking (t_c), for winding design optimization, the design variables considered are, conductor dimensions of HV (w_{hv}, t_{hv}) and LV (w_{lv}, t_{lv}) winding, for reducing product cost the design variables considered are, frequency (f), flux density (B_m) and transformer constant (k). The design of high frequency transformer is verified by calculating various constraints of HFT such as percentage reactance, maximum flux density, fault current temperature rise, and maximum permissible temperature rise at full load. Analytical calculations of design constraints are detailed below: Calculation of percentage reactance is significantly important in HFT design [22]. Percentage reactance is given by

$$\%X = 8\pi^2 f (I_{ph}/V_{ph}) T^2 K \triangle \times 10^{-8} \tag{17}$$

where I_{ph}, V_{ph} are the per phase current and voltage respectively. The ratio (I_{ph}/V_{ph}) and T (turns per phase) are taken with respect to LV side or HV side. f is the frequency of operation in Hz and K is the Rogowski factor, which is given by

$$K = 1 - \left(\frac{W_1 + W_2 + W_g}{\pi \left(\frac{H_{LV} + H_{HV}}{2} \right)} \right), \tag{18}$$

$$\triangle = \frac{W_1.L_1}{3.H_{LV}} + \frac{W_g.L_g}{\left(\frac{H_{LV} + H_{HV}}{2} \right)} + \frac{W_2.L_2}{3.H_{HV}} \tag{19}$$

where W_1, W_2, and W_g are the width of LV, HV, and gap between LV and HV winding (which is 11 mm for 28 kV AC test voltage) respectively. H_{LV} and H_{HV} are the electrical axial height of LV and HV winding. L_1, L_g, and L_2 and are the mean length of LV, LV-HV gap and HV winding respectively. Provision is given in the algorithm for entering the limiting values of percentage reactance based on the DAB design.

The working flux density at different areas of the core structure must be less than saturation flux density to avoid magnetic saturation. The value of saturation flux density of core material is available in the manufacturer's data sheet and it is possible to select desired core material from a list of three. The program itself takes the saturation flux density value from the storage data of that core material and each design checks the same for validation.

Whenever a short circuit occurs, the temperature θ_1 in the individual winding with copper conductor must be less than 350 °C for class F insulation for a duration of 2 s [22].

$$\theta_1 = \theta_0 + 2 \left[\frac{\theta_0 + 235}{\frac{106{,}000}{J^2.t} - 1} \right] \tag{20}$$

where initial winding temperature in °C is represented by θ_0, short circuit current density in A/mm^2 is represented by J and t is the duration of short circuit in seconds. Each design is checked with this constrain for verifying the same.

Temperature rise calculation of HFT directly depends on the cooling system design [19], which is based on the total losses to be dissipated. The total loss to be absorbed by the cooling medium is calculated by taking load loss along with core loss produced in the limbs, where the winding is placed. The exposed winding surface area is the sum of the inner and outer surface area of individual winding. For class F insulation, the maximum permissible temperature rise is 100 °C for an ambient temperature of 40 °C [19]. If the surface area is not sufficient for dissipating the heat, then the algorithm itself calculate the number of cooling fan and/or duct that can be provided to increase the total surface area of heat dissipation.

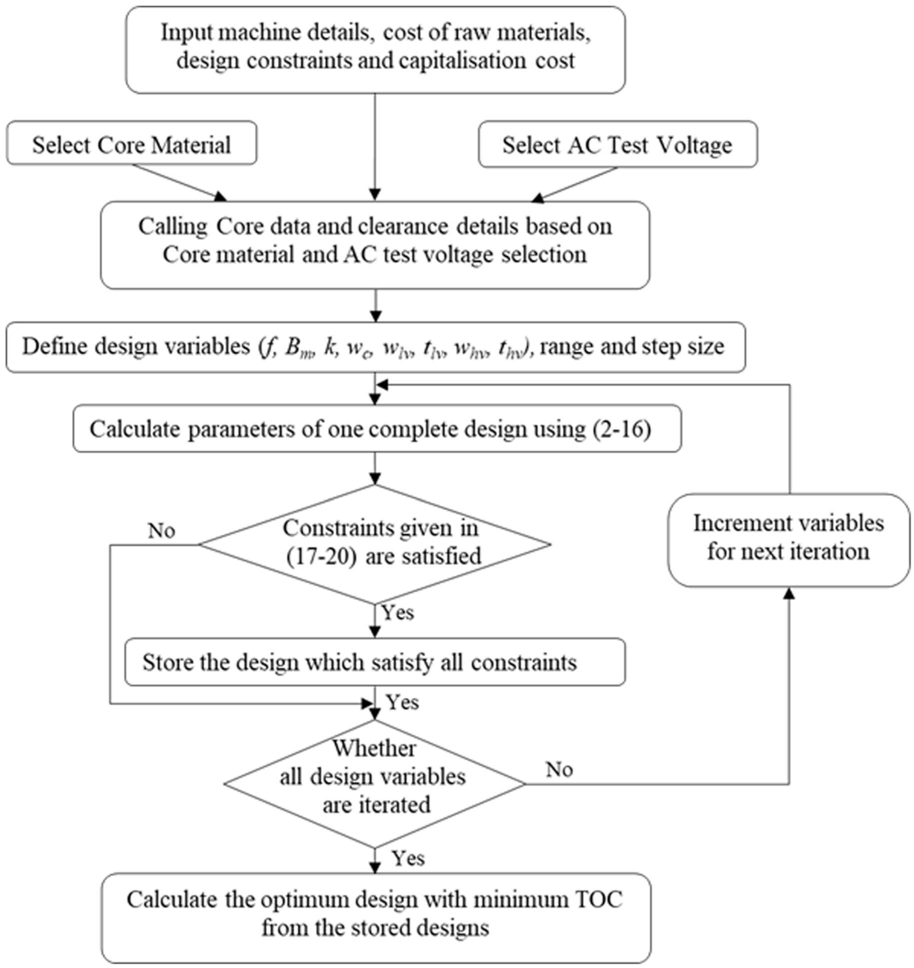

Fig. 2 Flowchart of the proposed algorithm

Flowchart of the proposed iterative design algorithm

The flow chart of the proposed algorithm for the design of high frequency transformer for distribution application SST is shown in Fig. 2. During the execution of the program, it can take database inputs and direct user inputs. The database inputs are taken from the set of predefined values stored in the program. These values are selected based on the core material and AC test voltage. Direct user inputs are of five categories ie, design variables, machine details, cut-off values or limiting parameters, material costs and capitalization details.

This algorithm requires kVA rating, voltage ratings, and transformer configuration as machine details. Users can set the minimum and maximum range of design variables as well as the number of iterations. It is possible to increase the number of design iterations by decreasing the step size of variables, which increases the accuracy of the result. The algorithm prompts for entering energy cost, discounting rate, transformer life cycle, and load factor for calculating capitalization cost. The range of limiting parameters can be entered by the designer as per standards. An option is given for selecting a core material from amorphous, nanocrystalline and si-steel and the user can select the required AC test voltage from 28 kV, 38 kV, 50 kV, and 70 kV.

Once all the inputs are properly entered and selected desired core material and AC test voltage, calculate all the parameters of one HFT design and check whether this design satisfies all the limiting parameters. If the design satisfies all limiting parameters then store that design and increment design variables to complete all the iterations of all the variables. Finally, select the design which gives lowest TOC from the stored designs.

A sample set of data entry details for a 1000-kVA 11-kV/415-V three-phase transformer considered for the case study are given in Table 1. When a specific test voltage is selected, the corresponding clearances required for the design are taken from the program database and the same method is applicable for core material also (when a specific core material has been selected the parameters of the core materials taken from the data sheet are entered in the program database and is automatically taken for further calculations). 28-kV AC test voltage and amorphous core material are selected in this case study.

The relationship between TOC and frequency at different values of flux density is detailed in graphical form in Fig. 3. It is found that the frequency corresponding to minimum TOC is 600 Hz at a flux density of 0.94T.

Table 2 shows the details of the optimum design (corresponding point is shown in Fig. 3) selected after iteration with amorphous core material and 28-kV AC test voltage. This optimum design with minimum TOC is selected from a list of valid 258,272 designs after iterating 2,100,000 design inputs.

Validation of optimum design by the numerical method using finite element analysis

The analysis of flux distribution, current flow and hence temperature rise, and losses are decisive tasks in validating the design of the transformer. The optimum design of HFT incorporated in 1000-kVA, 11-kV/415-V, Dyn11 three-phase solid-state transformer

Table 1 Values entered for optimum design

Design variables	Min. values	Step size	Max. values	Count
Frequency (H_z)	200	200	5000	24
Flux density (T)	0.2	0.05	1.45	25
k value	0.8	0.8	4	4
HV width (mm)	4.5	0.8	8.5	5
HV thickness (mm)	0.8	0.24	2.5	7
LV sheet width (mm)	300	50	550	5
LV sheet thickness (mm)	0.7	0.3	2	5
Machine Details	**Cutoff values**			
Rating of transformer - 1000 kVA	B_m - 1.5 T			
LV/ HV voltage - 415/11000 V	$\%Z$ - 15%			
Type of insulation - class F	Max. Temp. at short circuit - 350 ^0C			
Rate of material	**Capitalization**			
Amorphous - 3.5$\$/kg$	Energy cost - 0.07$\$/kWhr$			
Rate of insulation - 7.84$\$/kg$	Discount rate - 12 %			
Rate of copper - 10$\$/kg$	Life cycle - 25 years			
Price of fan - 160 $	Load factor - 0.4			

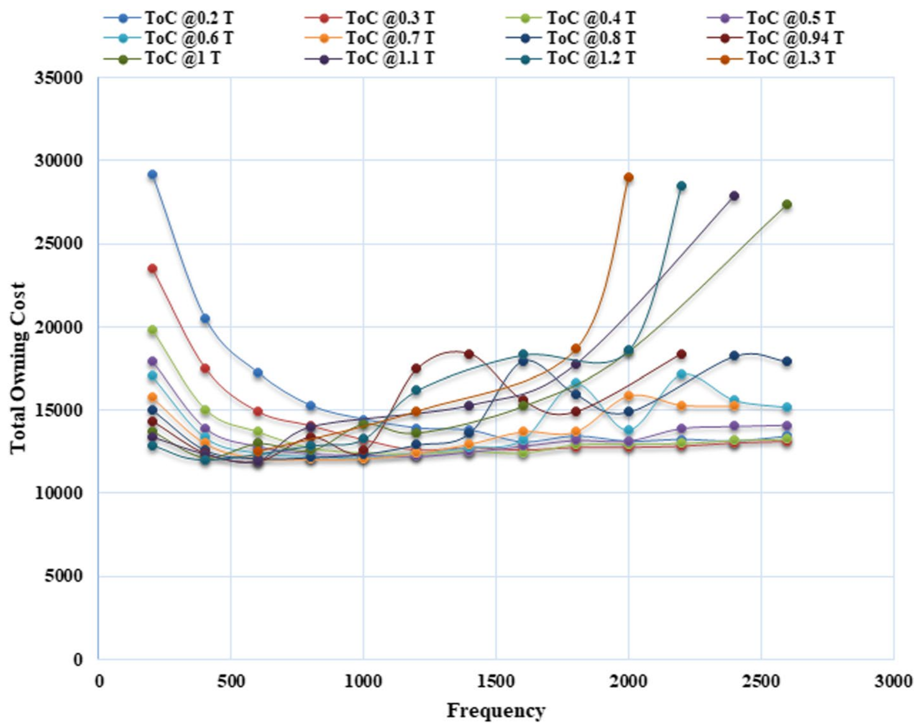

Fig. 3 Total owning cost *vs* frequency graph

developed from the iterative algorithm is validated by conducting finite element analysis in Ansys-Maxwell software. The developed model of high frequency transformer in Ansys-Maxwell software is shown in Fig. 4. It consists of wound core structure and winding arrangement. Insulation and clearances required are incorporated in the model. Amorphous metal 2605SA1 is added as a new core material in Maxwell software for developing the wound core structure of HFT. Copper material is used for the winding development of HFT and is available in Maxwell system library. The specific core loss of Amorphous core material is calculated by the below-given expression, which is taken from the manufacturer's data-sheet.

$$P_{core} = 6.5f^{1.51}B_m^{1.74} \quad (21)$$

where P_{core} represents the specific core loss in W/kg, f is the frequency of operation in kHz and B_m is the maximum flux density in *Tesla*.

Ansys-Maxwell model of HFT from the optimum design data is developed with the following properties. Length-based meshing is done inside the selected elements. The maximum element length of the core structure is 100 mm and that of winding is 60 mm. The element length of region around the core coil assembly is 538.2mm. The total number of elements in this design is 148,918 and the number of nodes is 681,533. The parameters calculated in the FEM method for validating the iterative algorithm are flux density, current density, core loss, load loss, and temperature rise. The parameter calculation in the magnetic transient solution set up of Ansys software is performed using the following Maxwell's equations [24].

Table 2 Optimum design data of HFT

Parameters	Values
Rated power in kVA	1000 kVA
No load voltage (HV)	10500 V
No load voltage (LV)	435 V
Vector group	Dyn11
Core material	Amorphous 2605SA1
Flux density	0.943 T
Current density (LV winding)	$3.4A/mm^2$
Current density (HV winding)	$4.14A/mm^2$
Rated current on HV	54.98 A
Rated current on LV	1327.96 A
Number of turns in HV	210
Number of turns in LV	5
Conductor dimension, HV	1.04 × 7.7 (mm)
Conductor dimension, LV	1.3 × 300 (mm)
Core width	170 mm
Optimum frequency of operation	600 Hz
% impedance (Z)	3.27 %
No load losses	1141 W
Load losses	2683 W
Max. winding temperature rise	100^oC
Insulation class	Class F
Type of cooling	AN-AF (one fan and one duct)
Fault current temperature rise	332^oC
Weight of the transformer	510 kg
Capital cost	2600 $
Total owning cost	12,000 $

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{22}$$

$$\nabla . B = 0 \tag{23}$$

where H represents the magnetic field intensity, J represents the current density, D is the electric flux density and B shows the magnetic flux density. Temperature rise calculation is performed based on fundamental law of thermodynamics and the corresponding governing equation is

$$k\nabla^2 T + q = \rho c \frac{\partial T}{\partial t} \tag{24}$$

where k is the thermal conductivity in W/m°C, T is the temperature in °C, q rate of heat generation inside the volume in W/m^3, ρ is the density of the material in kg/m^3 and c is the specific heat of the material in J/kg.K and $\frac{\partial T}{\partial t}$ is the rate of change of temperature with respect to time in K/s [25]. Calculation of flux density at various regions of the core

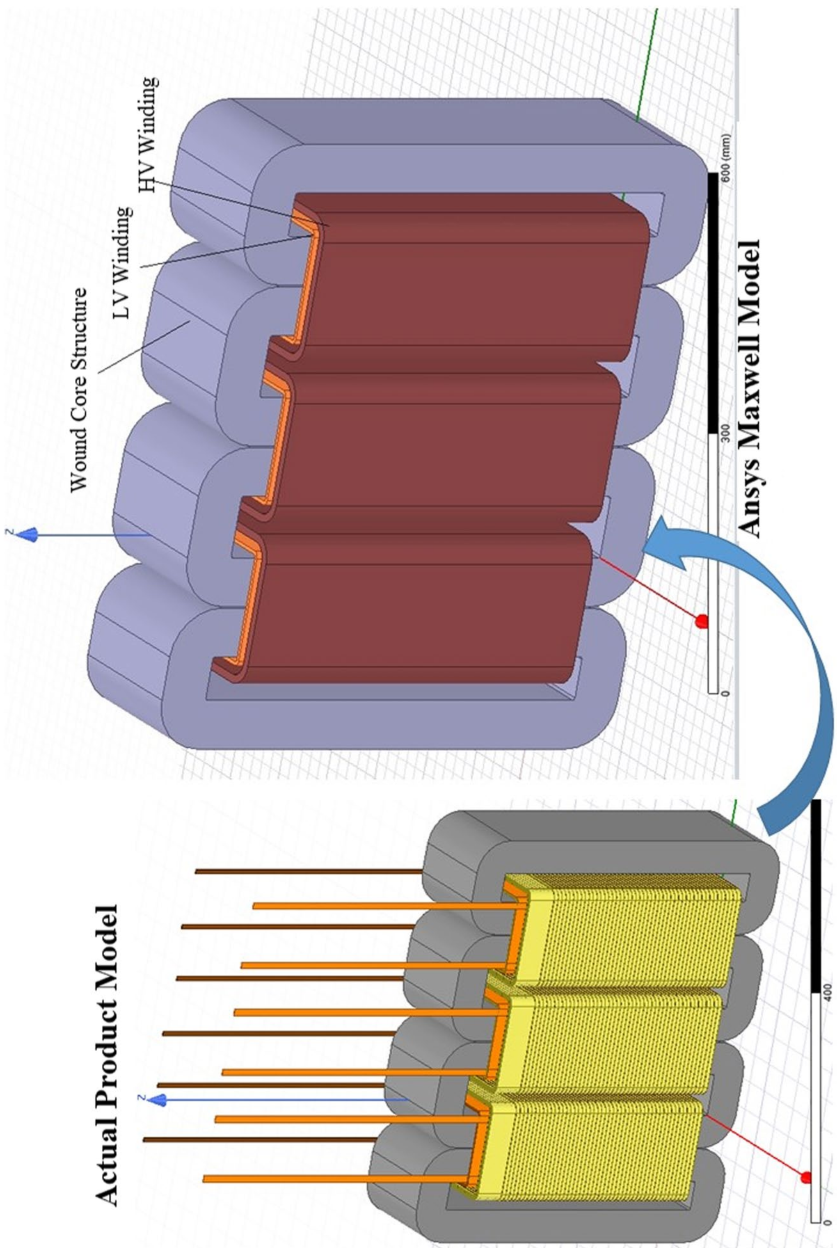

Fig. 4 Basic structure of HFT based on optimum design data

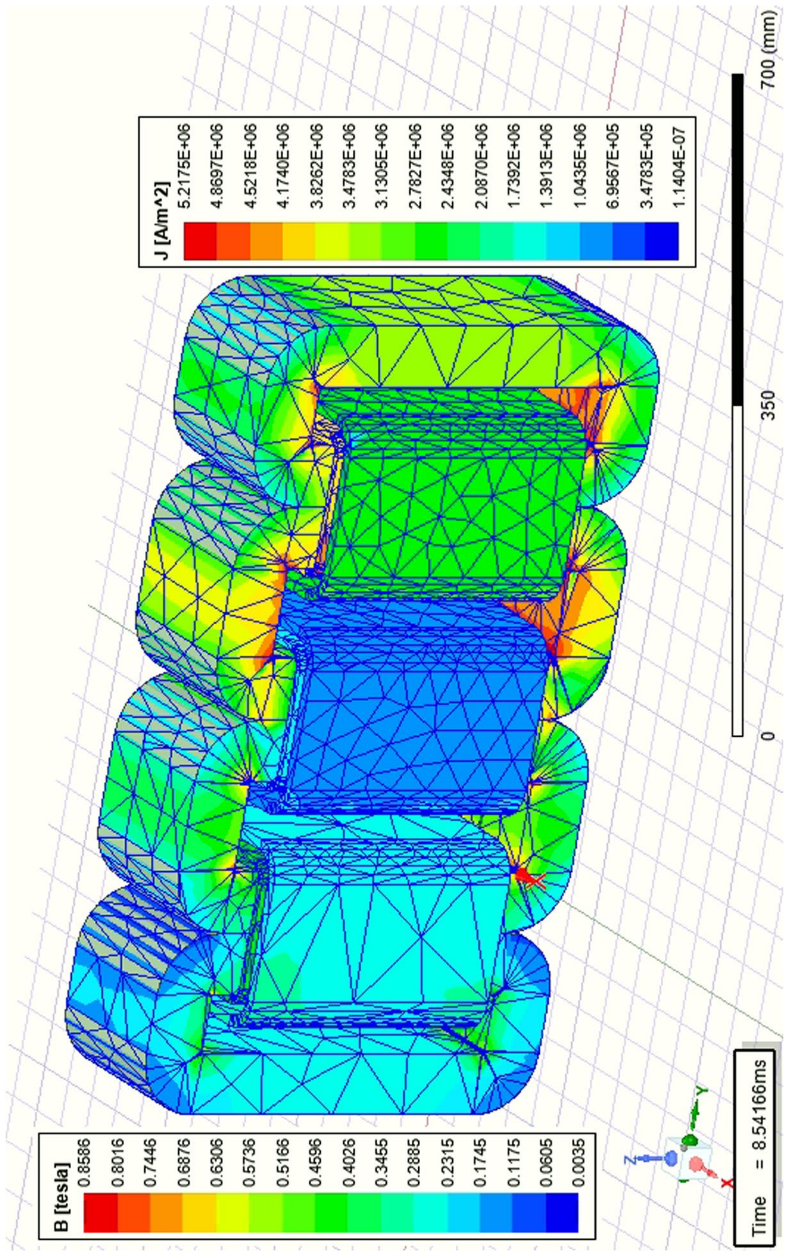

Fig. 5 Flux density and current density distribution

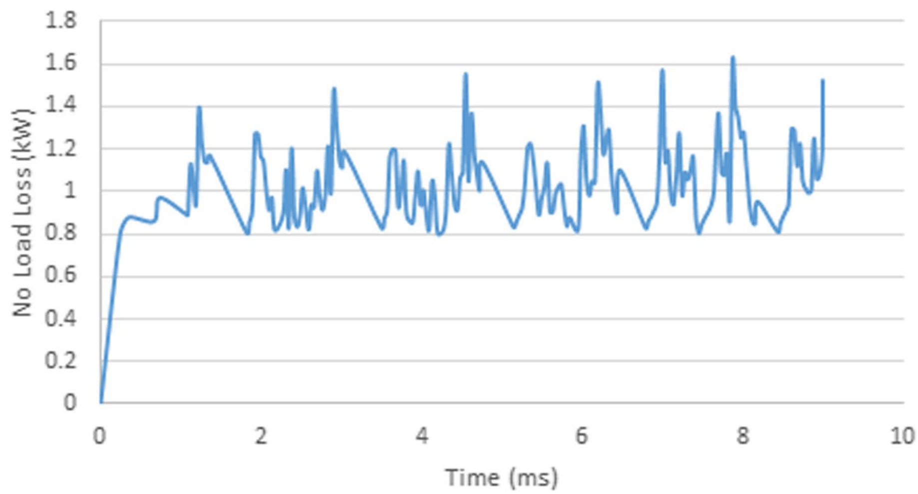

Fig. 6 Core loss plot

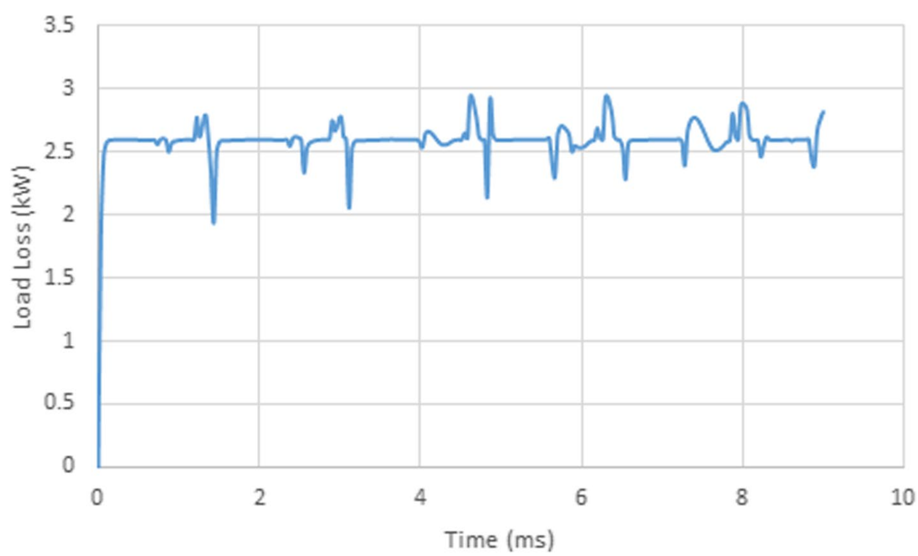

Fig. 7 Load loss plot

structure is important for analyzing the core saturation. The flux density distribution of the design is shown in Fig. 5.

Flux density distribution is different at various regions of the core structure at the specified time instant and maximum flux density position can be identified from the color distribution. The flux density distribution depends on the value of applied excitation. The maximum value of flux density obtained is 0.85 T and is in the inner corner of the wound core structure. The transformer is energized by giving rated voltage on LV winding and load is connected to the HV winding so as to flow rated current through LV and HV winding. Current density distribution of the optimum design is shown in Fig. 5. Current density distribution at different winding position can be observed from the color distribution of the winding in the plot. The maximum value of current density obtained is $5.2175 A/mm^2$.

The core loss characteristics of the high frequency transformer obtained after simulating the FEM model in Ansys-Maxwell software is shown in Fig. 6. The average value of core loss obtained is 1090 W, which is very close to the analytical result.

The load loss characteristics of the FEM model obtained by passing rated current through LV and HV winding shown in Fig. 7. The average value of load loss is 2618 W. In this design LV winding is foil type with 5 concentric turns with 0.25 mm insulation between the layers. HV winding consists of 210 turns in 5 layers and provided duct after first layer of HV winding to limit the temperature rise below 100 °C. The average value obtained in FEM analysis is in close proximity to the analytical results.

The temperature rise calculation of the assembled model is done by integrating the model developed in Ansys-Maxwell to transient thermal through Ansys Workbench. The maximum permissible temperature rise under normal full load operating conditions is 100 °C uniform due to uniform loss filed distribution in core structure. I^2R loss in winding depends on the instantaneous value of current flowing through the winding and its is found that these losses are also uniform in LV and HV winding of all phases . While performing temperature rise test, rated current is passed through the windings and measured temperature rise at different time intervals. The temperature rise reaches to a steady value and the distribution is shown in Fig. 8.

Results and discussion

The optimum design has been chosen from a set of designs generated using the iterative algorithm and validation of the algorithm is done using FEM analysis. The authors selected eight design variables as inputs, with a range of possible minimum and maximum values given in Table 1. By decreasing the step size of the variables, more combinations of the standard values of the design parameters are iterated and took larger iteration time. In other words, by increasing the step size less number of combinations are iterated in less time. So a a balance is maintained between the time and step size based on the capacity of processor used for iteration and set of healthy designs required for selecting optimum design. All designs were derived from the mutually exclusive combinations of all variables. At the time of execution, there were 24 steps in frequency, 25 steps in flux density, 4 steps in k value, 5 steps in HV width, 7 steps in HV thickness, 5 steps in LV width, and 5 steps in LV thickness. Thus 2,100,000 designs were iterated and each design is checked with a set of four design constraints. Among the accepted 258,272 designs, the optimum design is determined by selecting the design that has the least TOC. The Ansys-Maxwell software is used to model the optimum design for validating the same. Maxwell 3D transient analysis is performed to obtain accurate results by providing sinusoidal excitation. Maxwell design and Transient thermal are integrated through Ansys Workbench to determine the temperature rise. In comparing the numerical analysis results with the analytical results, the maximum deviation of losses are less than 5%. These results are summarized in Table 3.

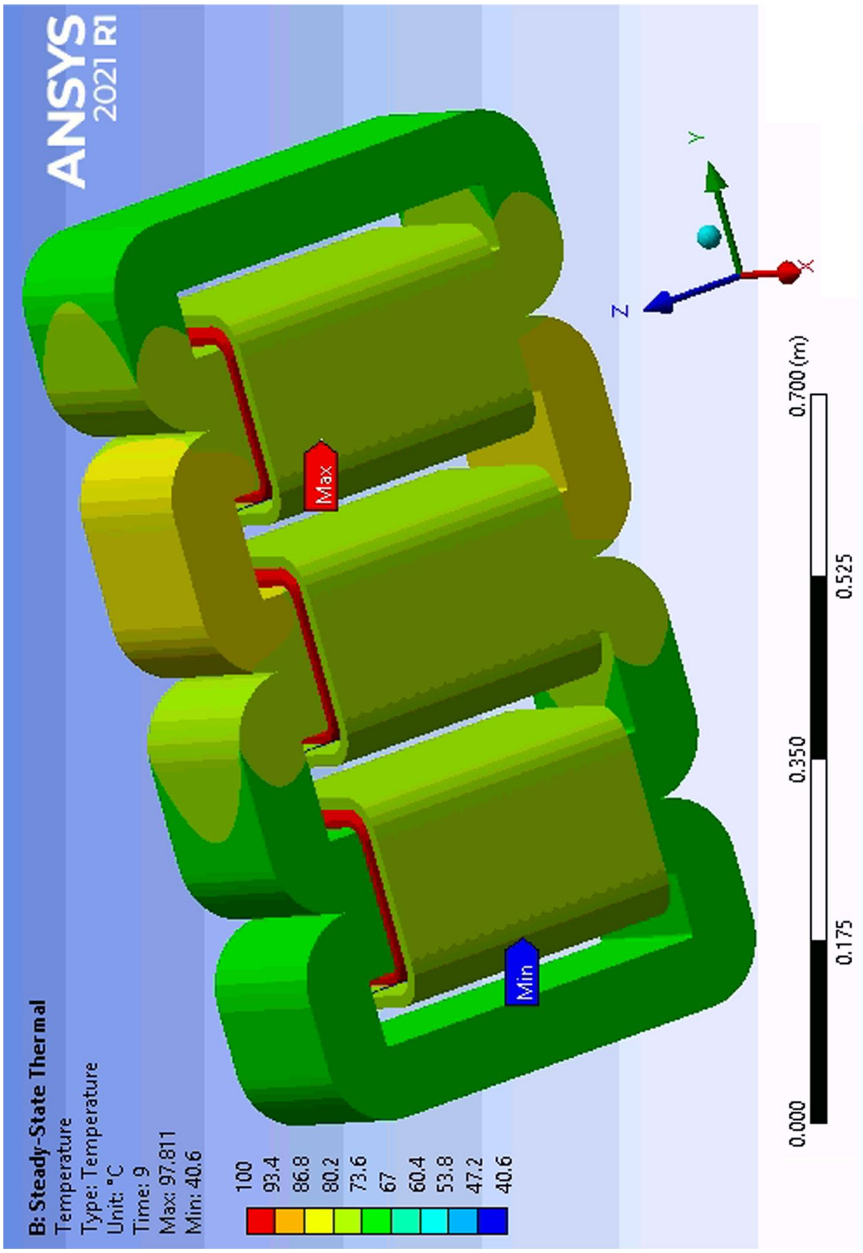

Fig. 8 Temperature distribution in assembled model

Table 3 Analytical *vs* numerical results

Parameters	Analytical results	FEA results	Max. deviation from analytical results
No load losses	1141 W	1090 W	4.46%
Load losses	2683 W	2618 W	2.4%

The results developed can be compared with the design details of power frequency transformer of the same rating and is given in [17]. The values of noload losses and load losses are 1550 W and 9000 W, respectively. The total weight of the transformer in 3305 kg. Comparing with these design data the optimum design developed in this work is very much less. The details of the optimum design is given in Table 2. The designs considered in the literature are of low power rating and not considered TOC as objective function so, the optimum design developed in this work is not directly comparable with the designs developed in the literature.

Conclusions

An iteration based algorithm, which minimizes total owning cost is formulated for the optimum design of high frequency transformer for SST application. The main feature of the algorithm is the consideration of all the parameters which directly depend on the TOC of the transformer. All critical constraints of the design of HFT are considered in this algorithm for shortlisting the valid designs. Dowell's equation is used for the calculation of load losses and Steinmetz's equation is used for the calculation of core losses. Design of the cooling system aimed at limiting the temperature rise below 100 °C which is applicable for dry-type transformer with class F insulation.

The unique features of the algorithm are as follows: It is possible to select one core material from amorphous, nanocrystalline, and si-steel. The user can select the AC test voltage and clearances are taken from the database based on that. The user can change the values of machine details, rate of materials and capitalization cost parameters based on their design requirements. The algorithms detailed in the literature are not meeting all these features. The proposed algorithm is validated numerically using Ansys Maxwell software. The FEM analysis shows that the results of the analytical calculations are in close agreement with a maximum deviation of 5%. This algorithm will equally contribute to the research community and industry in the development of high frequency transformers. Industries use this algorithm for selecting the optimum design by giving power rating, voltage rating, transformer configuration, and selecting magnetic material and AC test voltage. Hardware model development using the validated algorithm can accelerate research activities for integrating power electronics circuits with HFT to develop a solid-state transformer.

Abbreviations

SST	Solid-state transformer
TOC	Total owning cost
HFT	High frequency transformer
DAB	Dual active bridge
LV	Low voltage
HV	High voltage
AN-AF	Air natural air forced

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Authors' contributions
All authors are equally contributed to the research work and article preparation. The academic experience of S. Joseph, K.P. Pinkymol, and S.K. John contributed to the development of the iterative algorithm. The industrial exposure of J. Joseph and K.R.M Nair helped to develop the HFT in compliance with IEC standards. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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