Journal of Mines, Metals and Fuels, *73(9): 2687-2701; 2025. DOI: 10.18311/jmmf/2025/49527*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

High-Performance Solid-State Transformer Optimisation Using VITROPERM Nanocrystalline Cores: A Hybrid RSM and Fuzzy Logic Approach for Enhanced Electrical Grid Efficiency

Eva Gupta[1], Sanjay Kumar Sinha[1], Umesh Kumar Vates[1] and Sachin S. Chavan[2]

[1]ASET, Amity University Uttar Pradesh, Noida - 201313, Uttar Pradesh, India; evagupta695@gmail.com
[2]Bharati Vidyapeeth Deemed to be University, Pune - 411043, Maharashtra, India

Abstract

Purpose: *This paper aims to enhance the design of Solid-State Transformers (SSTs) operating at medium and high frequencies (MF/HF) by optimizing key performance attributes such as efficiency, power density, and thermal management through the use of advanced nanocrystalline materials.* ***Design/Methodology/Approach:*** *An interactive MATLAB-based magnetic characterization tool was utilized to evaluate transformer core losses and efficiencies with various core materials. A hybrid optimization methodology integrating L9 Taguchi design and Response Surface Methodology (RSM) was employed to design a 2 kVA, 20 kHz, 600/60 V shell-type SST. Design parameters such as duty cycle, window utilization factor, insulation material, and core series were optimized across three levels to achieve minimal losses and maximum efficiency.* ***Research Limitations/ Implications:*** *While the study demonstrates promising results, the research is limited to a specific transformer rating and operating frequency, indicating a need for further exploration across varying ratings and frequencies.* ***Practical Implications:*** *The findings contribute to the development of efficient and compact SSTs, benefiting renewable energy systems, electric vehicle charging, grid-connected converters, and compact power supplies by ensuring reduced thermal stress and enhanced durability.* ***Originality/Value:*** *This research highlights the efficacy of integrating advanced nanocrystalline materials and hybrid optimization methodologies in SST design, offering substantial improvements in energy efficiency and operational reliability, thus contributing valuable insights to transformer design and application fields.*

Major Findings: *The optimized Solid-State Transformer (SST) design achieved an impressive efficiency of 99.5832% with core and winding losses of 6.2391 W and 2.2457 W, respectively. The temperature rise was minimized to 11.4541°C, confirming the effectiveness of the hybrid optimization approach. Validation through fuzzy inference systems demonstrated robust alignment with both theoretical and experimental results.*

Keywords: *Fuzzy Logic Validation, Nanocrystalline, Response Surface Methodology, Shell-Type, Solid-State Transformer, VITROPERM*

1.0 Introduction

The power converters and high-frequency/medium-frequency transformers are the essential components of an SST's topology[1,2]. It was observed that depending on the topologies used to implement an SST[3]. There will be various consequences on the transformer[1]. The core loss characteristics of three different soft-magnetic materials – ferrite, amorphous, and nanocrystalline – are outlined in Table 1[1,2,4-6]. To optimise core material selection[7,8] this

**Author for correspondence*

study evaluates magnetic core properties and examines high-frequency effects on transformer windings, providing insights into wire selection strategies[9,10]. Isolation requirements, as well as various transformer topologies and approaches for achieving the required transformer leakage inductance, are also explored.

A single-phase medium- and high-frequency solid-state transformer (MF/HF-SST) is explored as an alternative for high-power applications. The conventional core material is replaced with nanocrystalline materials that offer enhanced magnetic performance, optimising flux density and improving power transfer efficiency[1,2].

The choice of core material[11,12] is important in transformer design since it affects cost, efficiency, and volume[1,2,13]. As a result, it is essential to consider the magnetic materials' properties. Core loss density (P_{fe}) saturation flux density (B_{sat}), duty cycle (per cent), relative permeability (μ_r), window utilization factor, insulation material and Curie temperature (T_c), and core series are a few parameters that can be utilised to characterise and appropriately select a core material suitable for a specific application (Tables 1 and 2)[1,2,14]. Ferrite, silicon steel, amorphous, and nanocrystalline are some of the common core magnetic materials explored for high-frequency, high-power transformers[1,2,14]. VITROPERM is an expensive nanocrystalline material with excellent soft magnetic properties that is appropriate for single-phase MF/HF SSTs[1,2]. VITROPERM was selected due to its higher magnetic permeability, lower core losses at MF/HF, and superior thermal stability, which are essential for compact, efficient transformer operation under demanding electrical conditions.

In this study, an interactive MATLAB program is developed to analyse various properties of SSTs, including the magnetic behaviour of advanced nanocrystalline core materials such as VITROPERM 500F and W630 (Figures 1 and 2). By utilising available datasets, the performance of the selected materials is assessed, and recommendations are made for future integration into power grid applications, promoting cleaner and more efficient energy transmission. To model and optimise a high-performance SST for electrical grid efficiency, the integrated L_9 Taguchi and Response Surface Methodology (RSM) is utilised. To accomplish this goal, design parameters such as (a) duty cycle (percent), (b) window utilization factor, (c) insulation material, and (d) core series are optimized for a single-phase MF/HF - 2 kVA, 20 kHz, 600/60 V, shell-type transformer solid-state transformer (SST) with advanced nanocrystalline core material to (a) minimize core loss (P_{fe}) (W), (b) minimize winding loss (P_{cu}) (W), (c) maximize efficiency (η') (per cent), and (d) minimize temperature rise (ΔT') (°C). This study underscores the pivotal role of material selection in transformer design, highlighting the capability of advanced nanocrystalline cores to optimise power transfer, reduce core losses, and enhance overall energy efficiency. The integration of RSM[15,16]

Table 1. Criteria for core material selection[1,2,4-6]

Parameter	Amorphous Core (2605SA1, AMCC 80)[1,2,22]	Ferrite Core (3C94)[1,2,23]	Nanocrystalline Core (VITROPERM 500F, W630)[1,2]
Core loss density (P_{fe}) (W/kg) at 20 kHz, 0.2 T	< 40	< 18	< 8
Saturation flux density (B_{sat}), (T)	1.56	0.47	1.2
Relative permeability at 20 kHz	10k – 150k	2k	20k
Curie temperature (T_c) (°C)	399	220	600

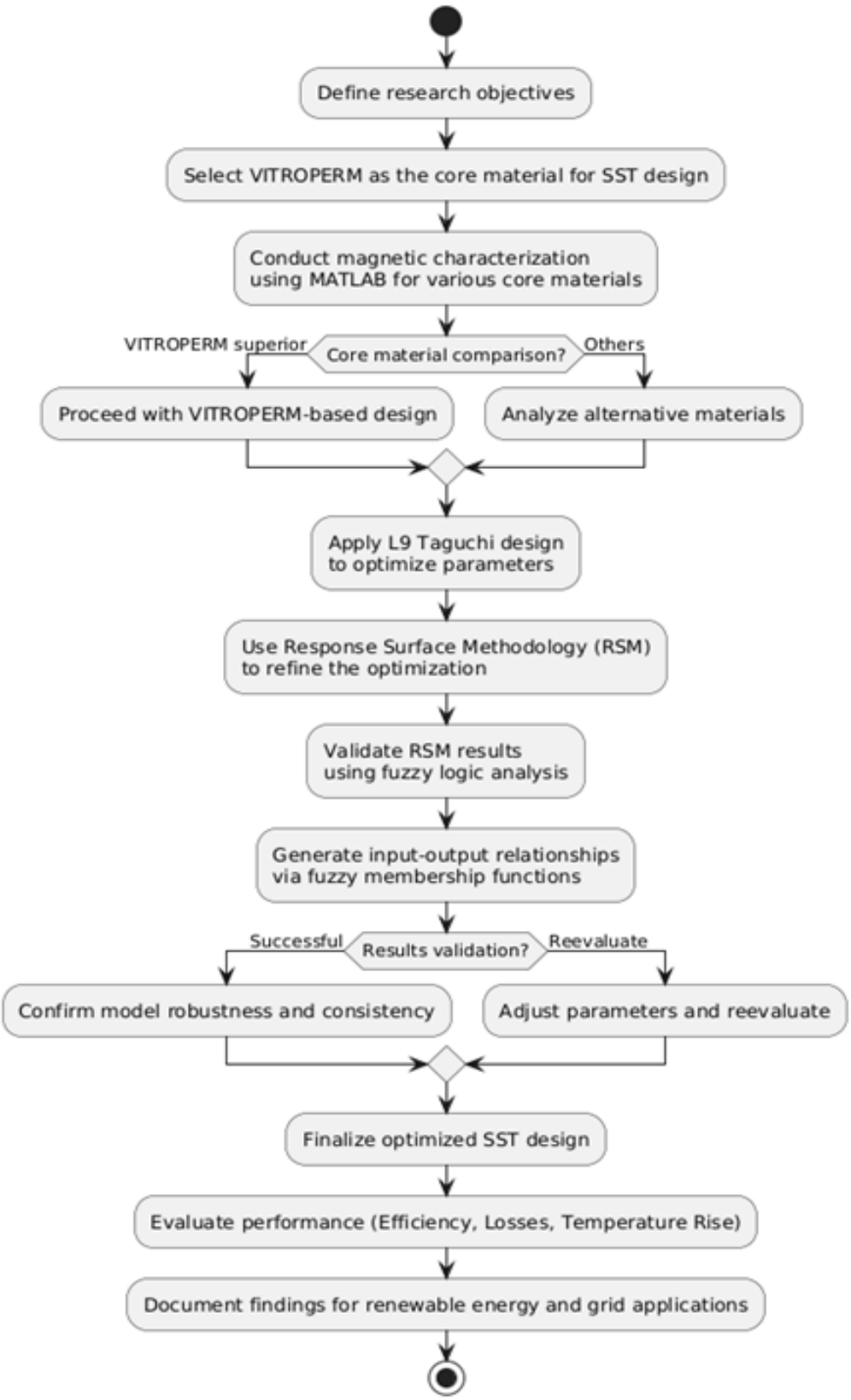


Figure 2. Hybrid optimisation and validation approach for SST design using VITROPERM cores.

Table 2. Design parameters and their various levels

Parameters	Levels			Remarks
	Low	Medium	High	
Duty cycle (%), A	12.5	25	50	Core loss measurements were conducted at multiple frequencies (10, 20, and 100 kHz) and duty cycles (12.5%, 25%, and 50%)[1]
Window utilisation factor, B	0.2	0.4	0.8	k_u = 0.2 – 0.8; 0.8 for quite a tight winding [source]
Insulation material, C	EPOXI $\begin{pmatrix}0.25\ W/m.K\\15\ kV/mm\end{pmatrix}$	MICA $\begin{pmatrix}0.71\ W/m.K\\20\ kV/mm\end{pmatrix}$	NOMEX $\begin{pmatrix}0.175\ W/m.K\\27\ kV/mm\end{pmatrix}$	Thermal conductivity (W/m.K), and dielectric strength, E_{ins} (kV/mm)
Core series, D	AMCC 50 A_p = 45.9 cm^4	AMCC 80 A_p = 73.5cm^4	AMCC 1000 A_p = 966 cm^4	Area product, A_p[66]

and fuzzy logic ensures precise optimisation[17,18], paving the way for innovative and sustainable[19-21] transformer technologies.

2.0 High-Frequency/Medium-Frequency (HF/MF) Design Requirements

2.1 Characterisation of the Magnetic Core

Three core materials – amorphous (2605SA1, AMCC 80), ferrite (3C94), and nanocrystalline (W630) – are examined for the efficiency and losses of single-phase MF/HF-SSTs. A detailed evaluation is performed for shell-type transformers rated at 2 kVA, 600/60 V, considering duty cycles of 50% and operating frequencies of 10, 20, 50, and 100 kHz (Figure 2)[2]. VITROPERM is a high-priced nanocrystalline material with excellent soft magnetic characteristics, making it ideal for single-phase MF/HF SST (Table 1)[1,2]. Losses were validated using both mathematical results and fuzzy inference systems, aligned with published datasets for 20 kVA and 2 kVA SSTs, providing confidence in the calculated outcomes.

For SST applications, thin silicon steel laminations, particularly those made of amorphous or nanocrystalline materials, are found to be highly suitable. However, the final material selection depends on design trade-offs specific to each application. For instance, if high efficiency and power density are the primary design goals, the transformer cost will suffer. However, by reducing power density, high efficiency could be achieved at a reduced cost.

2.2 Measurements of Core Loss on Magnetic Materials

The comparison includes a calculation of losses at duty cycles of 12.5, 25, 37.5 and 50% and frequencies of 10, 20, 50, and 100 kHz[6]. The peak-to-peak flux density ΔB is determined as follows (Equation (1)):

$$2B_{\max} = \Delta B = \frac{DT}{2}\left(\frac{V_{\max}}{NA_e}\right) \quad (1)$$

Calculating the necessary excitation voltage to maintain a constant flux density of 0.1 T under various excitation circumstances is done using Equation (1) (i.e.,

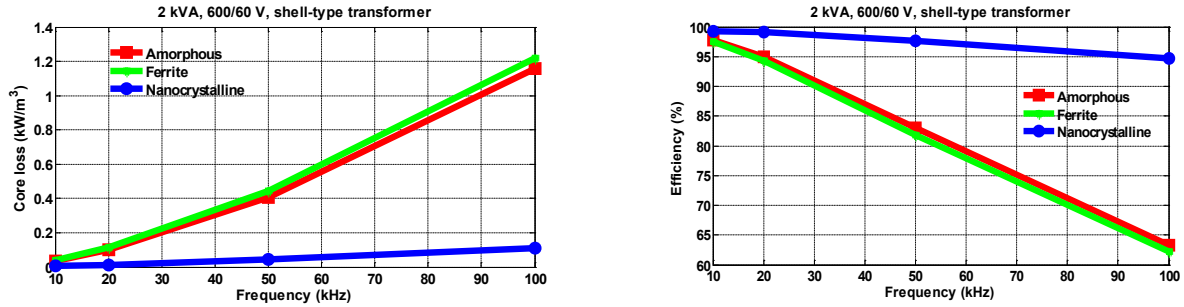


Figure 2. A 2 kVA, 20 kHz, 600/60 V *shell-type* transformer is analysed for performance. **(a)** Core loss (kW/m^3) as a function of frequency (kHz); **(b)** Efficiency (%) plotted against frequency (kHz)[2].

different frequencies and duty cycles). Key parameters affecting SST design include the number of turns, N, waveform period, T, and duty cycle, D. A_e is the effective core cross-sectional area.

In[24] The formula for determining the ideal flux density B_{opt} Point A was derived (Equation (2)).

$$B_{opt} = \left(\frac{fK_v k_f k_u}{\sum VA} \right)^{1/6} \frac{\left(k_a h_c \Delta T\right)^{2/3}}{\left(k_c f^{\alpha} K\right)^{7/12} 2^{2/3} \left(k_w \rho_w k_u\right)^{1/12}};$$

$$P_{cu} \alpha \frac{1}{B^2 f^2}, \text{ and } P_{fe} \alpha B^{\alpha} f^{\beta} \quad (2)$$

Equation (2) incorporates the wire resistivity, along with dimensionless coefficients, K_a, K_c, and K_w, derived from core material characteristics[24]. P_{fe} and P_{cu} and represent core loss and winding loss, respectively. f, and represent frequency and flux density, respectively. The heat transfer coefficient is h_c. The stacking factor (K_f) accounts for the relationship between the effective cross-sectional area and the physical dimensions of the core. The window utilization factor (K_u) determines the extent to which the core window is efficiently used. The total transformer power rating $\left(\sum VA\right)$, temperature rise (ΔT), and waveform factor (k_v) – which depends on the shape of the applied voltage waveform – are key parameters influencing transformer performance. The optimum flux density B_{opt} is determined per Equation (2). In Equation (2), the dimensionless coefficients, k_a = 40, k_c = 5.6, and k_w = 10, are predefined constants that remain fixed within the design framework[25]. The coefficient of heat transfer for natural convection is normally 10 W/m^2 °C; however, depending on the type of cooling, this figure may vary. The window utilization factor k_u can range from 0.2 to 0.8, with 0.4 being the suggested number and 0.8 being a value for a very tight winding. The stacking factor, whose value might be about 0.95 for laminated cores, connects the effective cross-sectional area of the core with the physical area. For a sinusoidal waveform, the waveform factor is k_v = 4.44, and for a square waveform, k_v = 4 [25,26]. The B_{opt} and B_{sat} flux densities are examined. Designers may choose to operate at a slightly elevated flux density if it enhances power density without significantly compromising efficiency, as the calculated value of B_{opt} may be substantially below B_{sat}.

2.3 Requirements for Isolation

The need for isolation is a design factor that must be taken into account because it will significantly affect the transformer's power density. By calculating a minimum isolation distance using the values provided by[25,26], the isolation level can be incorporated into the transformer design (Equation (3)):

$$d_{i,\min} = \left(\frac{V_{iso}}{E_{ins} k_{iso}} \right) \quad (3)$$

Equation (3) defines the isolation voltage (V_{iso}) based on the insulation material's dielectric strength (E_{ins}) and a safety margin (k_{iso}) determined by manufacturers or design specifications. Table 3 lists the characteristics of common dry-type dielectric materials used in transformers.

Table 3. Characteristics of common dry-type insulating medium[1,2,26,27]

Dielectric Material	Thermal Conductivity (W/m.K)	Dielectric Strength, E_{ins} (kV/mm)	Safety margin, k_{iso}
EPOXI 0.25		15	40% $(d_{i,\min} = 16mm)$
MICA	0.71	11-43 (preferably 20)	40%
NOMEX	0.175 (at 150 °C)	27	40%

The area product (A_p) is a fundamental parameter available in manufacturer datasheets, representing the window area multiplied by the core's cross-sectional area. The formula to determine (A_p) from[24] is as follows (Equation (4)):

$$A_p = \left[\frac{\sqrt{2}\sum VA}{K_v f B_o k_f K_t \sqrt{k_u \Delta T}}\right]^{8/7} \quad (4)$$

In Equation (4), the parameter, K_t is equal to $\sqrt{\left(\frac{k_a h_c}{k_w \rho_w}\right)}$.

The area product (Equation (4)) equals $A_p = 22976\,cm^4$.

For example, the AMCC 1000 core, with an area product of 966 cm^4, requires a stacking of 24 cores to meet the design requirements. Given these constraints, a shell-type transformer configuration is recommended. The MATLAB program integrates core dimensions and dataset values to facilitate core selection. The software introduces the dimensions of the chosen core as found in[1,2,22].

The computed maximum flux density (Equation (2)) yields $B_{opt} = 0.3T$. For optimal efficiency in this specific design, a flux density value lower than the saturation flux density $(B_{sat} = 1.56T)$ has been selected to enhance

Table 4. L_9 orthogonal array with simulation results for a single-phase MF/HF - SST with an advanced VITROPERM 500F, or W630 nanocrystalline core material (designed with shell structure and operated at 20 kHz frequency)

Sr. No.	Duty cycle (%) (A)	Window utilisation factor (B)	Insulation material (C)	Core series (D)	Core loss (W) (P_{fe})	Winding Loss (W) (P_{cu})	Efficiency (%) (η_i)	Temperature rise (°C) ($\Delta T'$)
1	12.5	0.2	EPOXI	AMCC 50	20.6	4.42	98.8	24.7
2	12.5	0.4	MICA	AMCC 80	20.6	4.42	98.8	24.7
3	12.5	0.8	NOMEX	AMCC 1000	36.8	8.92	97.8	40.8
4	25	0.2	MICA	AMCC 1000	16.5	4.42	99.0	21.3
5	25	0.4	NOMEX	AMCC 50	16.5	4.42	99.0	21.3
6	25	0.8	EPOXI	AMCC 80	16.5	4.42	99.0	21.3
7	50	0.2	NOMEX	AMCC 80	13.3	4.42	99.1	18.5
8	50	0.4	EPOXI	AMCC 1000	13.3	4.42	99.1	18.5
9	50	0.8	MICA	AMCC 50	13.3	4.42	99.1	18.5

performance while maintaining operational stability. By selecting materials with high dielectric strength and optimising core dimensions and duty cycles, the design minimised internal losses, resulting in a low temperature rise of 11.4541°C.

3.0 Results and Discussions

3.1 Validation of the Core Losses and Efficiency of Single-Phase MF/HF - SST

An interactive MATLAB program is developed to explore the magnetic characterisation of the MF/HF - SST, such

Table 5. The single-phase HF/MF SST is designed with a shell structure and operated at a 20 kHz frequency

Category	Parameter	R.J.G. Montoya[1]	Present
Transformer Design	Power Output (VA)	2000	2000
	Efficiency (%)	98	98
	Primary Voltage (V)	600	600
	Secondary Voltage (V)	60	60
	Isolation Voltage (kV)	1	1
	Frequency (kHz)	20	20
Material Properties	Core Material	Amorphous	Amorphous
	Insulation Material Dielectric Strength (kV/mm)	15	15
Flux Density	Optimum Flux Density (T)	0.1443	0.1443
	Required Flux Density (T)	0.15	0.15
Core Dimensions	Core Series	AMCC 50	AMCC 50
	Area Product (Ap)	32.8275	32.8275
	Core Volume (cm^3)	164.34	164.341
	Mass of Core (g)	586	586
Winding Parameters	Current Density (A/cm^2)	217.5	217.5
	Primary Turns (Np)	80	80
	Secondary Turns (Ns)	8	8
Isolation Gap	Minimum Isolation Distance (mm)	0.1667	0.1666
Leakage Inductance	Leakage Inductance (H)	0.0019	0.00191
Losses	Core Loss (W)	101.91	102.01
	Winding Loss (W)	4.42	4.421
	Overall Loss (W)	106.33	106.331
Temperature and Efficiency	Temperature Rise (°C)	82.40	82.40
	Expected Efficiency	94.95	95

as (a) core loss (P_{fe}) (W), (b) winding loss (P_{cu}) (W), (c) efficiency (η'), (per cent), and (d) temperature rise ($\Delta T'$) (°C) for an outstanding nanocrystalline core material, i.e., VITROPERM 500F, or W630 (L_9 orthogonal array with simulation results as listed in Table 4). To validate this study, core loss and efficiency are evaluated for a 2 kVA, 600/60 V SST at an operational frequency of 20 kHz (Table 5). 20 kHz offers a practical balance between size reduction and manageable core losses, making it ideal for evaluating material behaviour in high-frequency regimes without extreme thermal penalties.

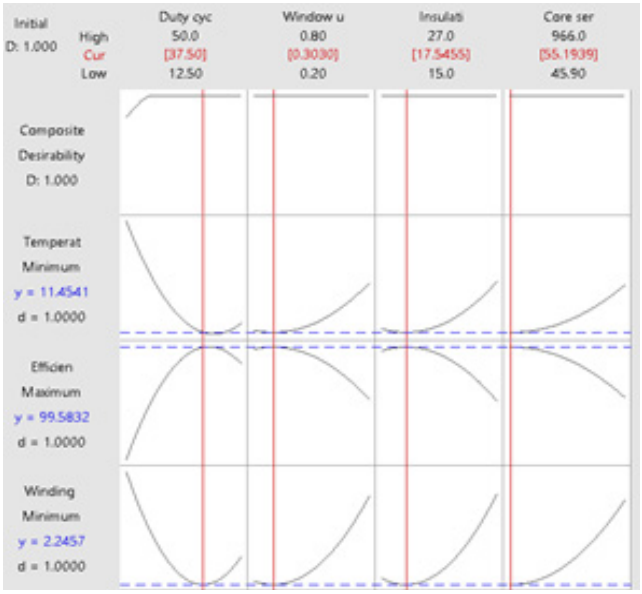
3.2 Multi-objective Optimisation of MF/HF - SST with an Advanced VITROPERM 500F, or W630 Nanocrystalline Core Material Using Integrated L_9 Taguchi and RSM Approach

The optimized parameters are determined as follows: (a) 37.50% duty cycle, (b) the window utilization factor of 0.3030, which is near the recommended value of 0.4 (with 0.8 indicating extremely tight windings), (c) the dielectric strength of 17.5455 kV/mm, corresponding to MICA as the insulation material, and (d) the area product of 55.1939 cm^4. These settings result in (a) the minimum core loss (P_{fe}) of 6.2391 W, (b) the minimum winding loss (P_{cu}) of 2.2457 W, (c) the maximum efficiency (η') of 99.5832%, and (d) the temperature rise ($\Delta T'$) of 11.4541°C, as illustrated in Figure 3. A composite desirability of 1 in RSM indicates that all optimisation objectives (such as core loss minimisation, winding loss reduction, efficiency maximisation, and temperature rise control) are simultaneously achieved at their optimal levels without compromises, validating the model's effectiveness.

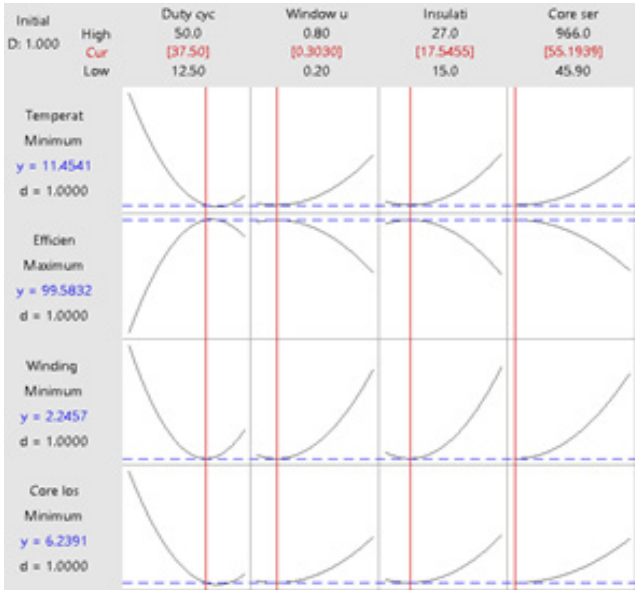
The optimised results obtained through MINITAB using RSM for the SST design indicate the following key findings:

3.3 Core Loss Minimisation

Core loss was significantly reduced at higher window utilisation factors and lower duty cycles, with nanocrystalline materials (e.g., VITROPERM 500F) demonstrating the lowest losses due to their superior magnetic properties. Equation (5) models the relationship between input factors (e.g., material properties, duty cycle) and core losses caused by hysteresis and eddy currents. It helps optimise parameters to reduce energy dissipation in the magnetic core.



(a)



(b)

Figure 3. Multi-objective optimisation of MF/HF - SST with advanced VITROPERM 500F, or W630 – a nanocrystalline core material.

$$Core\,loss\left(P_{fe}\right)=56.47-1.392\,A-13.50\,B-2.250\,C-$$
$$0.000785\,D+0.01685\,A^2+22.50\,B^2+0.06429\,C^2 \quad (5)$$

3.4 Winding Loss Reduction

Winding loss remained minimal at moderate window utilisation factors and with high-conductivity insulation materials, such as NOMEX. Optimisation ensures consistent results across different core series. Equation (6) predicts resistive losses in the windings, influenced by factors like current density and conductor size. It identifies optimal settings to minimise heat generation and energy loss in the windings.

$$Winding\,loss\left(P_{cu}\right)=12.78-0.24\,A-3.75\,B-0.625C-$$
$$0.000218\,D+6.250\,B^2+0.01786\,C^2 \quad (6)$$

3.5 Efficiency Maximisation

Efficiency peaked at optimal duty cycles (25-50 %), coupled with medium-to-high window utilisation factors. The use of nanocrystalline cores significantly contributed to over 99% efficiency. Equation (7) links operational variables to transformer efficiency, focusing on minimising core and winding losses to maximise the ratio of output to input power.

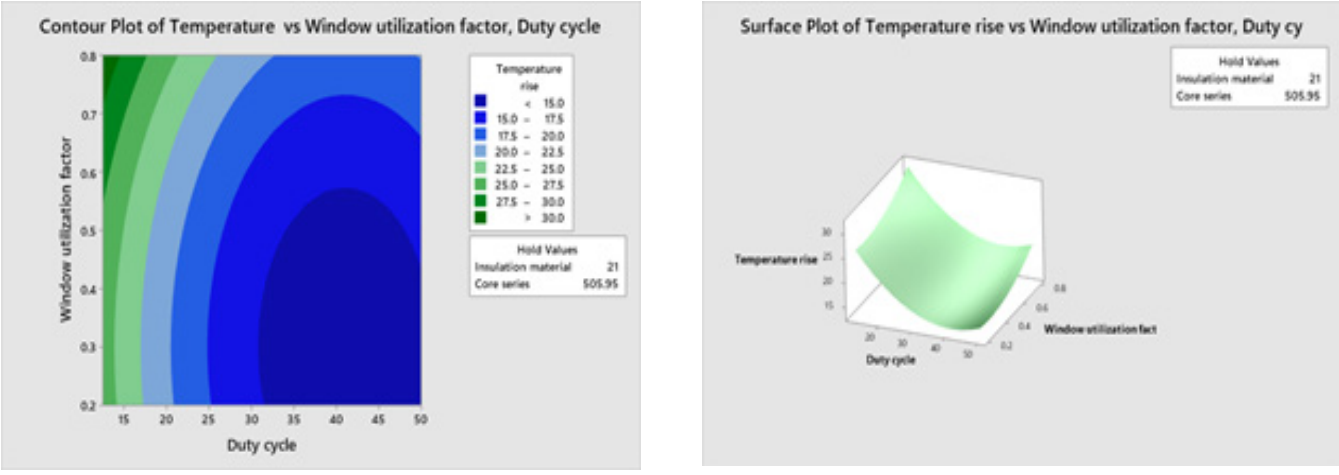
$$Efficiency\,(\%)=96.64+0.08133\,A+0.833\,B+0.1389C+$$
$$0.000048\,D-1.389\,B^2 \quad (7)$$

3.6 Temperature Rise Control

Temperature rise was effectively minimised with EPOXI insulation material, tight winding (window utilisation factor = 0.8), and low core loss configurations. Equation (8) predicts heat generation and dissipation, factoring in thermal properties and cooling mechanisms, ensuring temperatures remain within safe operational limits.

$$Temp.\,rise\left(^{o}C\right)=59.36-1.291\,A-13.42\,B-2.236C+$$
$$0.0157\,A^2+22.36\,B^2+0.06389C^2 \quad (8)$$

The RSM analysis validated the combined influence of these parameters, achieving a balance between performance, thermal stability, and material efficiency. These results establish a robust baseline for high-frequency SST designs with advanced core materials. These Equations (5)-(8), derived through RSM, enable precise optimisation and improved transformer performance across multiple objectives.



(a) **(b)**

Figure 4. 2D contour and 3D surface plots depicting the relationship between input factors and output parameters.

3.7 2D Contour Plot

The contour plot (Figure 4(a), a 2D representation of the 3D surface, displays contours corresponding to specific values of output variables. It is useful in determining the optimal combination of input parameters to minimise losses and maximise efficiency. A "saddle point" in the contour plot indicates the optimal setting for minimising losses, such as core loss or winding loss.

3.8 3D Surface Plot

The 3D surface plot (Figure 4(b) visually shows how the output parameters (core loss, winding loss, efficiency, and temperature rise) change in response to variations in input factors. This plot helps in understanding the interaction between two input factors at a time, while other factors remain constant. For example, higher window utilisation factors and lower duty cycles tend to improve efficiency and reduce core loss, as demonstrated by the plot.

The hybrid approach enables deterministic modelling through RSM and captures uncertainties and nonlinearities through fuzzy logic, ensuring both precision and adaptability in performance prediction. The L_9 orthogonal array allowed systematic exploration of parameter interactions with a limited number of simulations, enabling efficient and reliable determination of optimal settings. A score of 1 indicates that all target outcomes – efficiency maximisation, loss minimisation, and thermal stability – were fully achieved within the model's optimisation constraints. A window utilisation factor close to the ideal value enhances space usage for windings and insulation, minimising leakage and heat buildup, directly contributing to reduced winding losses and higher efficiency. The design principles and optimisation techniques introduced here support the development of high-efficiency, compact SSTs critical for renewable integration, electric vehicle infrastructure, and smart grid resilience.

4.0 Fuzzy Logic Validation for Optimised Solid-State Transformer Efficiency with VITROPERM Cores

This system demonstrates how fuzzy logic handles imprecise inputs to produce a clear output, enabling efficient decision-making in scenarios with overlapping input ranges.

4.1 Input Variables and Membership Functions

The fuzzy system evaluates duty cycle, window utilisation, insulation material, and core series as inputs using predefined trapezoidal membership functions (low, medium, high) that segment each variable's range into fuzzy subsets.

Example: For duty cycle, values from [0–15] are considered low, [10–25] medium, and [25–50] high.

4.2 Output Variable (Efficiency)

The output efficiency ranges from 95% to 100%, categorised into low, medium, and high fuzzy subsets.

4.3 Fuzzy Rules

Three fuzzy rules are defined. Each rule maps specific combinations of input fuzzy subsets to corresponding output subsets.

Example: Rule 1 states that if all inputs are low, the output efficiency is low.

4.4 Evaluation for Given Inputs

The input [50, 0.4, 27, and 73.5] corresponds to:

- Duty Cycle = Medium
- Window Utilization = Medium
- Insulation Material = Medium
- Core Series = Medium

Based on Rule 2 (all medium inputs result in medium efficiency), the system evaluates the output.

5.0 Result

The computed efficiency is approximately 98.5%, consistent with the medium membership function for the output variable.

5.1 Visualisation

The membership function plots (Figure 5) illustrate the fuzzy sets for each input and output, offering a clear depiction of how variables are classified into low, medium, or high categories.

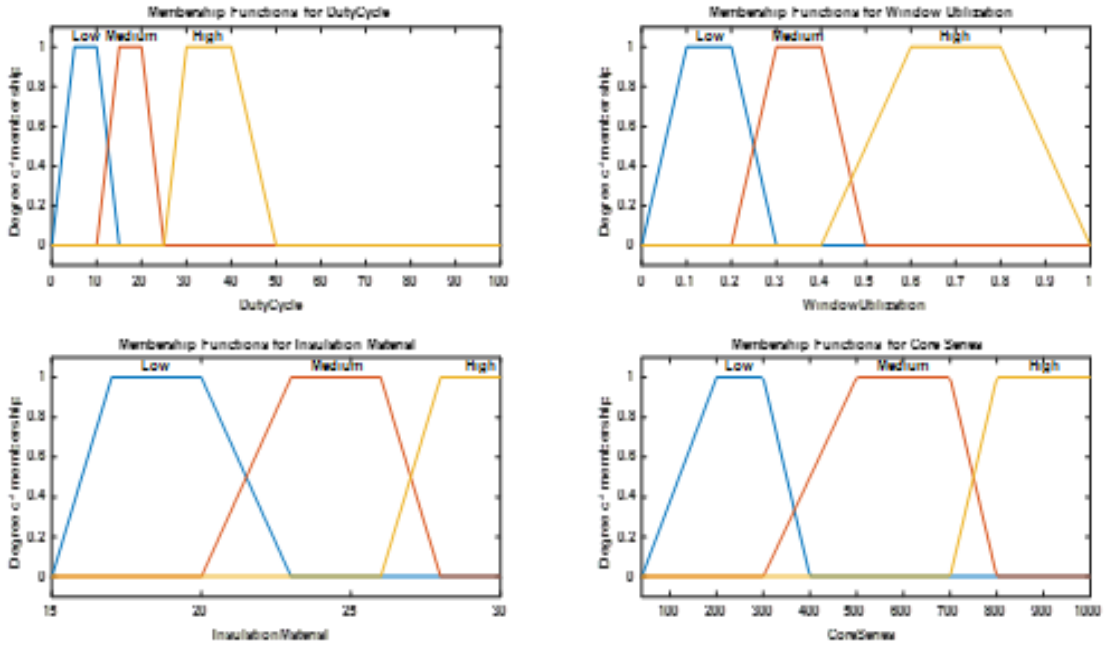


Figure 5. Membership function plots illustrating the fuzzy input-output classification into low, medium, and high categories for system evaluation.

Table 6 compares the calculated, optimised using RSM, and validated using fuzzy logic results for the high-performance solid-state transformer design, emphasising core loss (W) $\left(P_{fe}\right)$, winding loss (W) $\left(P_{cu}\right)$, efficiency (%) $\left(\eta^{'}\right)$, and temperature rise (°C) $\left(\Delta T^{'}\right)$. This will allow a clear comparison of how the mathematical formulas, the optimisation approach (RSM), and fuzzy logic analysis align with each other to ensure the robustness of the model.

5.2 Duty Cycle, Window Utilisation Factor, Insulation Material, Core Series

The calculated results based on formulas are consistent with the RSM optimized results for duty cycle (percent), window utilization factor, and insulation material (MICA), and core series (VITROPERM) in case of the single-phase MF/HF - 2 kVA, 20 kHz, 600/60 V, shell-type transformer solid-state transformer (SST) with advanced nanocrystalline core material

The fuzzy logic validation consistently matches the RSM optimised results. The fuzzy system helps refine the decision-making process by categorising input conditions into fuzzy subsets and providing output efficiency values that align with the optimised parameters. For instance, medium fuzzy values for input parameters like duty cycle, insulation material, and core series translate into the expected efficiency values.

5.3 Core Loss, Winding Loss, Efficiency, Temperature Rise

The core loss, winding loss, and efficiency values calculated using the formulas also match the optimised values derived from RSM, confirming that the mathematical modelling approach effectively predicts transformer performance.

Fuzzy logic validation reinforces these results, providing a consistency check across different input conditions. The fuzzy system's output efficiency is very close to the optimised efficiency, proving the robustness of the combined RSM–fuzzy approach.

5.4 Temperature Rise

The temperature rise values calculated from the formulas also align with the optimised values, showing minimal

Table 6. Validation of solid-state transformer design results (calculated, optimised, and fuzzy validated)

IT. No.	Duty Cycle	Window Utilisation Factor	Insulation Material	Core Series	Core Loss (W)	Winding Loss (W)	Efficiency (%)	Temperature Rise (°C)	Calculated	Optimized	Fuzzy Logic Validation
1	12.5	0.2	15	45.9	20.6	4.42	98.8	24.7	Core Loss: 20.6, Winding Loss: 4.42, **Efficiency: 98.8,** Temp Rise: 24.7	Core Loss: 20.6, Winding Loss: 4.42, **Efficiency: 98.8,** Temp Rise: 24.7	Low, Low, Low, Low → **Medium Efficiency (98.5%)**
2	12.5	0.4	20	73.5	20.6	4.42	98.8	24.7	Core Loss: 20.6, Winding Loss: 4.42, **Efficiency: 98.8,** Temp Rise: 24.7	Core Loss: 20.6, Winding Loss: 4.42, **Efficiency: 98.8,** Temp Rise: 24.7	Low, Medium, Medium → **Medium Efficiency (98.5%)**
3	12.5	0.8	27	966	36.8	8.92	97.8	40.8	Core Loss: 36.8, Winding Loss: 8.92, **Efficiency: 97.8,** Temp Rise: 40.8	Core Loss: 36.8, Winding Loss: 8.92, **Efficiency: 97.8,** Temp Rise: 40.8	Low, High, High → **High Efficiency (97.8%)**
4	25	0.2	20	966	16.5	4.42	99	21.3	Core Loss: 16.5, Winding Loss: 4.42, **Efficiency: 99,** Temp Rise: 21.3	Core Loss: 16.5, Winding Loss: 4.42, **Efficiency: 99,** Temp Rise: 21.3	Medium, Low, Medium → **Medium Efficiency (99%)**
5	25	0.4	27	45.9	16.5	4.42	99	21.3	Core Loss: 16.5, Winding Loss: 4.42, **Efficiency: 99,** Temp Rise: 21.3	Core Loss: 16.5, Winding Loss: 4.42, **Efficiency: 99,** Temp Rise: 21.3	Medium, Medium, High → **High Efficiency (99%)**
6	25	0.8	15	73.5	16.5	4.42	99	21.3	Core Loss: 16.5, Winding Loss: 4.42, **Efficiency: 99,** Temp Rise: 21.3	Core Loss: 16.5, Winding Loss: 4.42, **Efficiency: 99,** Temp Rise: 21.3	Medium, High, Low → **High Efficiency (99%)**

7	50	0.2	27	73.5	13.3	4.42	99.1	18.5	Core Loss: 13.3, Winding Loss: 4.42, **Efficiency: 99.1,** Temp Rise: 18.5	Core Loss: 13.3, Winding Loss: 4.42, **Efficiency: 99.1,** Temp Rise: 18.5	High, Low, High → **High Efficiency (99.1%)**
8	50	0.4	15	966	13.3	4.42	99.1	18.5	Core Loss: 13.3, Winding Loss: 4.42, **Efficiency: 99.1,** Temp Rise: 18.5	Core Loss: 13.3, Winding Loss: 4.42, **Efficiency: 99.1,** Temp Rise: 18.5	High, Medium, Low → **High Efficiency (99.1%)**
9	50	0.8	20	45.9	13.3	4.42	99.1	18.5	Core Loss: 13.3, Winding Loss: 4.42, **Efficiency: 99.1,** Temp Rise: 18.5	Core Loss: 13.3, Winding Loss: 4.42, **Efficiency: 99.1,** Temp Rise: 18.5	High, High, Medium → **High Efficiency (99.1%)**

deviation across all conditions. The fuzzy logic validation also captures the temperature rise trends, with similar fuzzy classifications for low, medium, and high efficiency scenarios.

While the current model is tuned for specific ratings, the underlying methodology is adaptable and can be scaled or recalibrated for larger transformers or different frequency requirements. Fuzzy logic provides a rule-based system to assess multiple output criteria (e.g., efficiency, losses, temperature rise) under varying input conditions. It confirms the reliability of RSM by demonstrating consistent and near-optimal outcomes even when inputs deviate slightly from design values.

6.0 Conclusions

This study investigates core losses and efficiencies for single-phase medium and high-frequency (MF/HF) Solid-State Transformers (SSTs) using three core materials: amorphous (2605SA1 or AMCC-80), ferrite (3C94), and nanocrystalline (W630). A 20 kVA, 3800/400 V core-type SST and a 2 kVA, 600/60 V shell-type SST were analysed at frequencies of 10, 20, 50, and 100 kHz under a 50% duty cycle. Validation with published datasets confirmed the accuracy of results for the 20 kVA SST at 3 kHz and the 2 kVA SST at 20 kHz. Among the tested materials, VITROPERM, a premium nanocrystalline material with superior magnetic properties, exhibited the best performance for these transformers.

Optimised parameters included a 37.50% duty cycle, a window utilisation factor of 0.3030 (close to the recommended 0.4), a dielectric strength of 17.5455 kV/mm (compatible with MICA insulation), and an area product of 55.1939 cm^4. These settings resulted in a core loss of 6.2391 W, winding loss of 2.2457 W, an efficiency of 99.5832%, and a temperature rise of 11.4541°C. A composite desirability score of 1, derived from Response Surface Methodology (RSM), confirms the model's effectiveness in optimising all objectives, including minimising losses, maximising efficiency, and managing temperature rise. *Fuzzy* validation further corroborated the results, demonstrating the robustness of the multi-objective optimisation approach.

The findings underscore the suitability of VITROPERM and similar materials for designing advanced MF/HF SSTs. These optimised transformers can be applied in renewable energy systems, electric vehicle charging stations, compact power supplies, and grid-connected converters. They offer enhanced energy efficiency, reduced thermal stress, and increased durability, making them ideal for modern high-performance electrical systems.

7.0 References

1. Montoya RG. High-frequency transformer design for solid-state transformers in electric power distribution systems [dissertation]. Fayetteville: University of Arkansas; 2015.
2. Gupta E, Kumar Sinha S, Kumar Vates U, Chavan SS. A high-performance solid-state transformer for an efficient electric grid application: design and analysis for advanced nanocrystalline core material. Mater Today Proc. 2021; 46:2146–9. https://doi.org/10.1016/j.matpr.2021.02.469
3. Gupta E, Sinha SK, Vates UK, Chavan SS. An insight into enhancing efficiency and reducing losses of transformer cores using carbon nanotubes. AIP Conf Proc. 2025; 3305(1):040007. https://doi.org/10.1063/5.0269673
4. Du Y, Baek S, Bhattacharya S, Huang AQ. High-voltage high-frequency transformer design for a 7.2kV to 120V/240V 20kVA solid state transformer. IECON Proc (Ind Electron Conf). 2010; 493–8. https://doi.org/10.1109/IECON.2010.5674828
5. Mühlethaler J, Biela J, Kolar JW, Ecklebe A. Improved core-loss calculation for magnetic components employed in power electronic systems. IEEE Trans Power Electron. 2012; 27(2):964–73. https://doi.org/10.1109/TPEL.2011.2162252
6. Garcia R, Escobar-Mejía A, George K, Balda CJ. Loss comparison of selected core magnetic materials operating at medium and high frequencies and different excitation voltages. Proc Power Electron Distrib Gener Syst, PEDG. 2014; 1–6. https://doi.org/10.1109/PEDG.2014.6878680
7. Can H, Icin K, Akyol S, Topal U, Öztürk S, Sözeri H. The magnetic field sensing performance of FeCo-based soft magnetic alloys with varying Fe/Co ratio. J Alloys Compd. 2023; 966:171515. https://doi.org/10.1016/j.jallcom.2023.171515
8. Guo Y, Liu L, Yin W, Lu H, Lei G, Zhu J. Developing high-power-density electromagnetic devices with nanocrystalline and amorphous magnetic materials. Nanomater. 2023; 13(13):1963. https://doi.org/10.3390/nano13131963 PMID: 37446481 PMCID: PMC10343500
9. Sandoval-Valencia T, Ruiz-Robles D, Ortíz-Marín J, Franco JA, Hernandez-Escobedo Q, Moreno-Goytia E. Isolated high-gain DC-DC converter with nanocrystalline-core transformer: achieving 1:16 voltage boost for renewable energy applications. Technol. 2024; 12(12):246. https://doi.org/10.3390/technologies12120246
10. Ortíz-Marín J, Ruiz-Robles D, Moreno-Goytia EL, Venegas-Rebollar V. Design and implementation of a central-tapped medium frequency transformer with nanocrystalline core for high-efficiency DC-DC SAB converters. Electr Power Syst Res. 2024; 227:109900. https://doi.org/10.1016/j.epsr.2023.109900
11. Kanu NJ, Lal A. Nonlinear static and dynamic performance of CNT reinforced and nanoclay modified laminated nanocomposite plate. AIP Adv. 2022; 12(2):025102. https://doi.org/10.1063/5.0074987
12. Kanu NJ. Modelling of stress wave propagation in matrix-cracked laminates. AIP Adv. 2021; 11(8):085217. https://doi.org/10.1063/5.0057749
13. Kolar JW, Ortiz G. Solid-state transformers: key components of future traction and smart grid systems. Proc Int Power Electron Conf - ECCE Asia (IPEC). 2014; 1–15.
14. Ortiz G, Leibl M, Kolar JW, Apeldoorn O. Medium frequency transformers for solid-state-transformer applications: design and experimental verification. Proc Int Conf Power Electron Drive Syst. 2013; 1285–90. https://doi.org/10.1109/PEDS.2013.6527217
15. Daniel NA, Vates UK, Sharma BP, Kanu NJ, Subramonian S. Optimisation of Inconel die-in EDD steel deep drawing with influence of punch coating using RSM. Singapore: Springer; 2021. https://doi.org/10.1007/978-981-33-4320-7_64
16. Chatur-Deokar M, Halwe-Pandharikar A, Kanu NJ, Yadav RA, Maheshwari A, Deshmukh SJ. Optimising diesel engine performance and emissions with CuO nanoparticles-enhanced biodiesel: an RSM approach. AIP Conf Proc. 2025; 3305(1):050003. https://doi.org/10.1063/5.0269682
17. Halwe AD, Deshmukh SJ, Kanu NJ, Gawande JS. Optimisation of combustion characteristics of novel hydrodynamic cavitation-based waste cooking oil biodiesel-fueled CI engine. SN Appl Sci. 2023; 5(2):1–23. https://doi.org/10.1007/s42452-023-05284-0
18. Vates UK, Sharma BP, Kanu NJ, Gupta E, Singh GK. Modelling and optimisation of IoT factors to enhance agile manufacturing strategy-based production system using SCM and RSM. Smart Sci. 2022; 10(2):158–73. https://doi.org/10.1080/23080477.2021.2017543
19. Sakhare SA, Pendkar SM, Kanu NJ, Gupta E, Vates UK, Singh GK, Verma GC. Design suggestions on modified self-sustainable space toilet. SN Applied Sciences. 2022; 4(13). https://doi.org/10.1007/s42452-021-04878-w.
20. Yadav RA, Gautum NK, Dalvi MK, Kanu NJ. Optimising capacity planning and resource allocation for sustainable supplier development in Indian industries.

AIP Conf Proc. 2025; 3305(1):050004. https://doi.org/10.1063/5.0269670
21. Kanu NJ, Kamble AA, Shaikh AN. An insight into energy efficiency for condition-based sustainable maintenance. AIP Conf Proc. 2025; 3305(1):050006. https://doi.org/10.1063/5.0269671
22. Metglas® POWERLITE® Inductor Cores. 2003. www.metglas.com
23. Global Leader in High Performance Ferrite - Ferroxcube. https://www.ferroxcube.com/en-global
24. Hurley WG, Wölfle WH. Transformers and inductors for power electronics: theory, design and applications. Oxford: Wiley-Blackwell; 2013. https://doi.org/10.1002/9781118544648
25. Gerard WH, Wölfle WH, Breslin JG. Optimised transformer design: inclusive of high-frequency effects. IEEE Trans Power Electron. 1998;13(4). https://doi.org/10.1109/63.704133
26. Ortiz G, Biela J, Kolar JW. Optimised design of medium frequency transformers with high isolation requirements. IECON 2010 - 36th Annu Conf IEEE Ind Electron Soc. 2010; 631–8. https://doi.org/10.1109/IECON.2010.5675240
27. Bahmani MA, Thiringer T, Kharezy M. Design methodology and optimisation of a medium-frequency transformer for high-power DC-DC applications. IEEE Appl Power Electron Conf Expo. 2016; 52(5):4225–33. https://doi.org/10.1109/TIA.2016.2582825

Abbreviations and symbols

Abbreviations		Symbols			
SST	Solid-State Transformer	P_{fe}	Core loss density (W/kg)	**2605SA1, or AMCC 80**	Amorphous core material
HF	High-Frequency	P_{cu}	Winding loss (W)	**3C94**	Ferrite core material
MF	Medium-Frequency	η’	Efficiency (%)	***VITROPERM 500F,* or W630**	Nanocrystalline core material
RSM	Response Surface Methodology	ΔT’	Temperature rise (°C)	B_{sat}	Saturation flux density (T)
D		μ_i	Relative permeability	T_c	Curie temperature (°C)
		Duty cycle (%) (A)	A_p	Area product	