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Design of an Experimental Approach for Characterization and Performance Analysis of High-Frequency Transformer Core Materials

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Abstract: High-frequency transformer core materials are used in power converter applications due to high efficiency performance. Their volume and weight can be reduced when higher operating frequencies are used but at the expense of an increase in core material losses. Some studies analyzed transformer core material performance by using finite element method (FEM) analysis, while others used an experimental model. This study proposes an experimental approach to compare the high-frequency transformer efficiency performance of different core material types. In this way, newly produced core material performance can be rapidly analyzed by comparing it against a known core material type, thereby resulting in the fast identification of improved core material design. This empirical approach makes use of a standard half-bridge inverter topology to enable an analysis of high-frequency transformer core material efficiency performance. Actual voltage and current measurements are used to determine the efficiency and output power performance throughout a specified constant current load range at different switching frequencies. Initially commercial standard polycrystalline or ferrite E-core materials were used to validate the characterization jig performance measured curve trends. The usefulness of the jig is then demonstrated by comparatively analyzing and then verifying the expected performance difference between polycrystalline and nanocrystalline toroidal core materials.

Keywords: high-frequency transformer core material; polycrystalline; nanocrystalline; efficiency performance; switching frequency; half-bridge converter; characterization jig

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1. Introduction

Driven by electronic consumer and renewable energy markets, demand for efficient power converters has exponentially grown. It is imperative that power converters are therefore designed to be as efficient as possible. The main factors that contribute to the inefficiencies in these power converters are device switching and conduction losses, which are generated in the windings and the transformer core material. Transformer cores that operate at high switching frequencies above 20 kHz are an integral part of power delivery including galvanic isolation between input primary and output secondary circuits. The transformer core losses, thermal behavior and efficiency are greatly influenced by the type of core material used including the excitation voltage waveform and operating frequency. Magnetization and demagnetization continuously occur as the alternating current passes through the transformer windings. Magnetic properties of the transformer core material determine its saturation level and how fast it can be magnetized. By using a transformer core material with desirable magnetic properties, the efficiency of a power converter can be improved [1]. Power converters make use of soft magnetic materials for high-frequency transformer cores such as polycrystalline, nanocrystalline and amorphous.

Previous studies on the performance analysis of high-frequency transformer core materials have primarily utilized FEM software packages or experimental techniques. However, the purpose of this study is not to conduct an extensive comparative analysis with other approaches but rather to find an empirical approach that can quickly determine the actual efficiency and output power performance between different compared transformer core material types. Newly produced core materials could then be rapidly analyzed by comparing the efficiency and output power performance against a known core material type, thereby resulting in the fast identification of improved core material performance. Therefore, the aim of this study is to develop an experimental characterization jig that can be used to obtain the actual performance of high-frequency transformer core materials in terms of efficiency and output power over a defined loading range. Initially, various standard polycrystalline or ferrite E-core materials will be analyzed in order to validate the performance profile measured curves obtained by the characterization jig. Thereafter, the efficiency and output power performance comparison of polycrystalline and nanocrystalline core transformer material with the same dimensions will be investigated.

2. Background

A transformer is a stationary electrical device that transfers electrical energy through an alternating magnetic field [2]. Transformers work on the principle of Faraday's law of mutual electromagnetic induction. When an alternating current (AC) is passed through a winding coil wound around a transformer core, an alternating magnetic field proportional to the current amplitude is then generated in the core material. Placing another winding coil wound around the transformer core with the changing magnetic field, a voltage is then induced into the coil winding with the same frequency but at a different magnitude of voltage and current that is dependent on the winding ratio [2]. The two windings of the transformer are not electrically connected but are instead magnetically coupled. The high-frequency transformers that are used in switched mode power supplies (SMPS) are small, compact, and light weight because the operating switching frequency is between 20 and 500 kHz. The transformer can either be polycrystalline, nanocrystalline or an amorphous core material that is used to confine the magnetic flux in a high permeability path in order to reduce flux leakage so that the efficiency performance improves [2]. Therefore, in order to understand why certain core material types are used for high-frequency transformers, a characteristic behavior review of different types of magnetic materials will be required.

2.1. Magnetic Material Types

Magnetic materials are used in almost all electrical and electronic devices. Magnets are found in electric machines such as motors, generators, loudspeakers and transformers including data storage hard disks and compact disk players where even superconductors are viewed as a type of magnetic material [3]. A material is said to be magnetic if it possesses at the atomic scale, magnetic moments that show long-range ordering below the Curie temperature or its atomic-scale magnetic moments show no spontaneous ordering but respond to an applied magnetic field with an increase in its magnetic moment density [4,5]. A magnetic material is said to be soft if it responds to relatively weak external fields by changing its state of magnetism [4]. Soft magnetic materials are said to be temporarily magnetic and are dependent on an external field excitation to induce a magnetic field within the material. The soft magnetic material requires a lower amount of energy to be magnetized because it has a narrow hysteresis loop [6]. The area of the hysteresis loop is directly related to core energy losses during cyclic magnetization and a lower coercive field increases efficiency, thereby making soft magnetic material suitable for use in high-frequency applications. There are five types of magnetic materials, and each material type exhibits a distinct behavior that makes it suitable for a particular application [3]. These magnetic material behaviors are summarized as follows:

- For diamagnetic material, an external applied field will induce a magnetic field in this material in the opposite direction, causing a repulsive force. When subjected to a magnetic field, magnetic dipoles are induced for the entire atom by influencing the magnetic moment caused by the orbiting electrons [7].

- For paramagnetic material, an external applied field will weakly magnetize this material in the same direction. Large magnetic fields are required to align all dipoles, and when the field is removed, it will lose its magnetism. The material has permanent dipoles due to the electron spin of unpaired electrons [7].
- For ferromagnetic material, an external applied field will strongly magnetize this material in the same direction. Permanent unpaired dipoles quickly line up with the applied field due to exchange interaction or mutual reinforcement of the dipoles [7].
- For ferrimagnetic material, an external applied field can be amplified by this material. The populations of ions or atoms in ceramic materials have opposing magnetic moments that are aligned in unequal numbers, either in parallel or antiparallel directions, which then results in net spontaneous magnetization [7].
- For super-para-magnetic material, when the grain size of ferro or ferri materials falls below a specific critical size, these materials behave as if they are paramagnetic. The magnetic dipole energy of each particle is said to be comparable to its thermal energy in this state. The moments change their direction randomly because of this thermal energy, and therefore, the material behaves as if it has no net magnetic moment [7].

2.2. Soft Magnetic Materials

Magnetic core materials should provide high magnetic performance and compact volumes in order to realize high power and efficient SMPS requirements [8]. These core materials must follow very stringent technical requirements over a range of temperature variations from below freezing to more than 100 °C, operate across frequency variations, and withstand mechanical shocks [8]. To achieve these requirements, core materials require high saturation induction (B_s), adjustable uniaxial anisotropy (K_u), high thermal stability, low hysteresis losses, and low eddy current losses. In addition, they should be inexpensive and easy to produce in mass. Polycrystalline cores are dense ceramic-based ferrimagnetic materials that are commonly known as ferrites. They are dark gray or black in appearance and extremely hard, making them brittle and thereby restricting their size [9,10]. These materials can operate over a wide frequency range from 100 Hz to 2.5 GHz [3]. From a crystallographic aspect, soft magnetic ferrites are inverse spinel and belong to the cubic crystal system, which means that ferrites are composed of iron oxide and are divalent or have a valency of two metal oxides [9]. The soft magnetic ferrite properties arise from the interactions between metallic ions occupying positions relative to oxygen ions in their spinal crystalline structure that generate microscopically magnetized regions referred to as magnetic domains within the material [9]. With no external applied magnetizing force, magnetic domains are random, so the net flux contribution is zero even though the local domains are fully magnetized. The molecular formula for ferrites is MFe_2O_4, where M is the divalent metal oxide, and when a ferrite contains two or more metal ions in the M position, the material is then referred to as a mixed ferrite [3]. These configurations are predominately used in power electronic converter applications. The two most utilized mixed ferrites are manganese zinc ferrites ($MnZnFe_2O_4$), which have incredibly high saturation levels that are ideal for frequencies less than 5 MHz, and nickel zinc ferrites ($NiZnFe_2O_4$), which are ideal for frequencies above 2 MHz but are temperature sensitive. Typical polycrystalline magnetic material or ferrite characteristics are low cost, reduced volume with lowest flux density, high thermal, high humidity, and pressure stability including high volume resistivity with low eddy current losses over a wide frequency range, loose magnetic properties at specific Curie temperatures, and high magnetic permeability over a wide temperature stability range [9–11].

The ferrites' most crucial feature is its high-volume resistivity characteristic [11]. This is because eddy current losses usually dominate at high frequencies and will increase with the square of the frequency [12]. However, these losses are inversely proportional to the materials' resistivity. Therefore, a higher resistivity results in lower eddy current losses at the higher frequencies, thereby making ferrites more desirable for power conversion-type applications. Ferrite cores can also be made in a variety of different shapes, such as the following:

- EI cores are ideal for power, differential, and telecom inductors.
- ETD cores are ideal for power transformers.
- EFD cores have cross-sections within them that are ideal for various inductor and transformer applications.
- EER cores have round center legs instead of a square shape, allowing for shorter winding length.
- Toroidal cores are ideal for low noise circuits because they can more adequately confine stray magnetic fields.

Alternatively, nanocrystalline magnetic core materials have a crystal structure which measures less than 100 nm in at least one dimension, where the smallest fundamental component of a nanocrystal is known as a grain or a crystallite [8]. Materials with nanocrystals dispersed throughout the lattice are known as nanocrystalline. The nanocrystals are ferro-magnetic at room temperature and are also closely related to amorphous soft magnetic materials. Nanocrystalline materials start as amorphous ribbons but then rely on heat treatment above the crystallization temperature to create refined crystalline grains [7]. The typical nanocrystalline chemical structure is $F_eC_uN_bS_iBF$, and they are magnetically quasi-isotropic [8,12]. Isotropic in chemistry means that the materials' properties remain constant, no matter the direction of testing. Therefore, the materials' magnetic properties are equally distributed through all directions in the structure due to their ultrafine grains with a mean diameter of about 10 to 15 nm. The ultrafine grain is achieved because of the annealing heat treatment at 500 to 600 °C, which causes the magneto crystalline anisotropy to disappear [8]. This results in a grain which is smaller than the width of the crystalline domain walls. The advantages that nanocrystals have compared to ferrites can be summarized as follows [7]:

- Extremely high impedance.
- Lower eddy current losses.
- Wideband frequency (favorable high-frequency behavior of several hundred kHz).
- Mechanically hard with a Vickers hardness from 800 to 1000 HV and a high yield strength around 3000 MPa.

The nanocrystalline core materials also have the following typical characteristics [13]:

- High permeability.
- High saturation flux density.
- Low core losses.
- Excellent temperature characteristics.
- Low magnetostriction.
- Excellent frequency performance.

The nanocrystalline cores are generally preferred over ferrite cores for high-power applications because of the limiting size factor of ferrites [10]. They also perform more effectively than ferrites in the medium frequency range from 10 to 25 kHz [14]. The unique properties of nanocrystalline materials have gained attention in electric vehicle, power distribution, railway traction, renewable energy generation, and energy storage system applications [13].

The amorphous magnetic core materials are not considered crystalline because the material characteristic lacks a crystalline structure [15]. The common polycrystalline and nanocrystalline alloys have uniformly formed metallic crystalline structures. However, in amorphous materials, the structure is non-existent because atoms are randomly arranged and therefore said to be anisotropic. Random atomic arrangement results from the molten alloys' rapid cooling, which results in thin ribbons of about 20 µm thick. The rapid cooling rate is necessary as it limits the upper bound of the ribbon thickness to 50 µm [7]. The amorphous magnetic materials are divided into two major groups, namely Fe-based and Co-based alloys. The Fe-based alloys are characterized by high saturation magnetization. Alternatively, Co-based alloys can achieve zero magnetostriction if doped with tiny amounts of ferrite (Fe) or manganese (Mn). However, their saturation is considerably lower when compared to Fe-based alloys [7]. When magnetized, their magnetostriction value will increase considerably with an increase in frequency, and this limits their usage at high frequencies because their acoustic properties lead to excessive vibrations [10]. Since these materials possess the highest saturation density, they yield the smallest core transformer volume, thus reducing the required space and cost compared to polycrystalline and nanocrystalline core materials that are used in high-power converter applications [16].

The literature concludes that nanocrystalline material has improved performance over a wide range of frequencies compared to polycrystalline and amorphous materials. Generally, amorphous materials perform better than their polycrystalline counterparts. Nanocrystalline materials have relatively constant core losses throughout a wide range of frequencies and only experience a slight increase in losses above 50 kHz. Conversely, the ferrite or polycrystalline and amorphous core materials experience far higher losses for frequencies as low as 20 kHz. Therefore, in most cases, nanocrystalline core materials can be considered a superior choice for medium-frequency applications [12].

2.3. Performance Characterization

Soft magnetic material performance characterization is often performed by using FEM analysis tools including experimental methods in an attempt to model high-frequency transformer core material efficiency performance. However, for newly produced magnetic core materials including any production process variations, accurate mathematical modeling has not yet been conducted. Therefore, this study proposes an empirical approach that can experimentally compare the efficiency performance of two high-frequency transformer core material types. Newly produced core material performance can then be rapidly analyzed by comparing it against a known core material performance type and thereby quickly identifying improved core material design.

Therefore, this study develops and validates an experimental characterization method that can be used to effectively determine the actual measured efficiency and output power performance comparison between different high-frequency transformer material cores. Initially, commercially available standard polycrystalline or ferrite E-core materials are used to verify characterization jig operation and measurements. The efficiency and output power performance measured by the characterization jig for toroidal transformer polycrystalline and nanocrystalline material cores with the same dimensions are then comparatively analyzed.

3. Experimental Method

To characterize the performance of high-frequency transformer core materials, the proposed experimental approach uses a standard half-bridge inverter topology driven by a Texas Instruments TL494 pulse width modulation (PWM) controller integrated circuit (IC) configured in push–pull operation mode. The standard half-bridge inverter topology was chosen because the driving voltage waveform is bidirectional, which results in the transformer core being magnetized and demagnetized in both directions. In this way, the entire hysteresis loop of the high-frequency transformer is activated in order to ensure effective performance characterization of the core material. In addition, the TL494 driven half-bridge inverter circuit will reset the transformer core automatically without the need to introduce a compensation winding.

The efficiency and output power performance of the selected transformer core material under test will also be characterized at different operating frequencies, which is set by an external ceramic capacitor and resistor oscillator. The set PWM frequency of the TL494 controller IC is varied by a digitally controlled MCP41010 single potentiometer IC for the external resistor in order to set operating test frequencies of either 25 kHz, 50 kHz, 75 kHz or 100 kHz. The overall design specifications of the proposed characterization jig are shown in Table 1.

Table 1. Proposed Characterization Jig Specifications.

Description	Specification
Input Voltage	40 VAC (56 VDC)
Input Current (Max)	3 A
Output Voltage	12.24 VDC (Regulated)
Output Current (Max)	5 A
Operating Frequency	25 kHz, 50 kHs, 75 kHz, 100 kHz
Rated Output Power	60 W
Rated Input Power	76 W
Rated Efficiency	85%
Output Ripple Voltage	70 mVp-p
Output Regulation	+/−14%

3.1. Characterization Jig Description

The characterization jig consists of an auxiliary power supply unit (PSU) that will supply power to the TL494 controller IC including an ATmega328P microcontroller. The TL494 controller PWM drives an isolated half-bridge inverter circuit topology that allows selected high-frequency transformer cores to be manually inserted for characterization. The inverter output circuit is filtered before it is connected to a direct current (DC) adjustable digitally controlled electronic load. The power MOSFETS used by the electronic load operate in the linear region and act as variable power resistors that can adjust the required constant current load of the half-bridge inverter output circuit. The firmware program of the ATmega329P microcontroller is used to set the PWM controller frequency, measure the core material surface temperature and adjust the electronic load while measuring both the inverter input voltage and current including the inverter output voltage and current. By multiplying the voltage and current measurements, the input and output power at a set specific load current can be calculated. The efficiency can then be calculated by dividing the output power by the input power at each constant current load setting, as expressed in the following equation:

$$\text{Efficiency} = \frac{V_{out} \times I_{out}}{V_{in} \times I_{in}} \times 100 \quad (1)$$

The simplified block diagram of proposed characterization jig is shown in Figure 1, and the actual constructed characterization jig platform is shown in Figure 2.

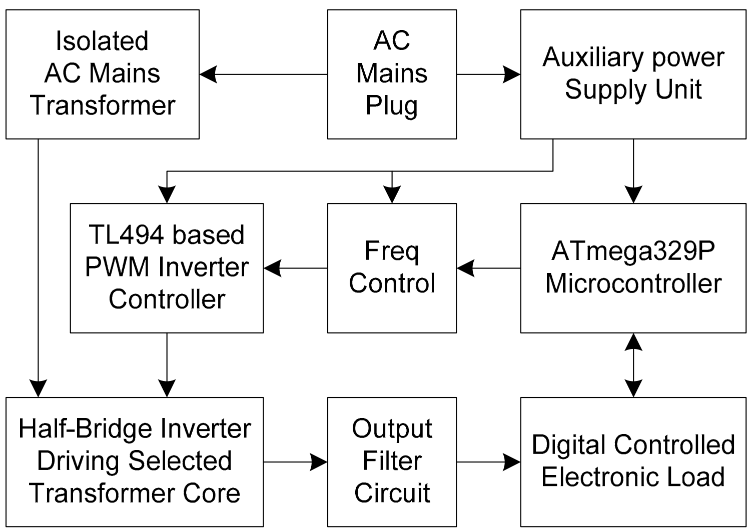

Figure 1. Block diagram of proposed characterization jig.

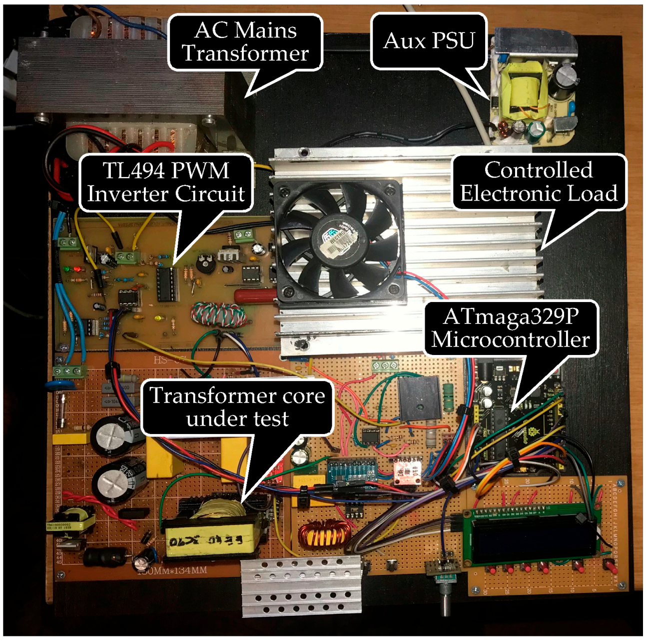

Figure 2. Actual constructed characterization jig platform.

3.2. Data Measurement Methods

The characterization jig measured data and the method used, including the determined percentage error compared to a Fluke 71 reference meter, is shown in Table 2.

Table 2. Characterization Jig Measurements.

Measured Data	Method Used	% Error
Input Current	ACS723 (5 A)	3.10
Input Voltage	Voltage Divider	0.36
Output Current	Shunt Resistor	0.57
Output Voltage	Voltage Divider	0.19

The input voltage could not be measured directly with a voltage divider because there is no common ground on the half-bridge inverter circuit. Therefore, an auxiliary transformer wound with the same winging ratio is connected in parallel with the input of the high-frequency transformer core under test. The input voltage is measured using the conversion ratio and a voltage divider connected to the secondary of the auxiliary transformer. To ensure high precision, the voltage divider output is then fed into a 16-bit analog-to-digital converter (ADC) of an ADS1115 IC, and the measurement is then serially obtained by the microcontroller.

The input current could not be measured with a shunt resistor because there is no common ground on the half-bridge inverter circuit. Therefore, the input current measurement needs to be galvanically isolated. A current transformer (CT) is not accurate because its output is not linear throughout the current measurement range. Therefore, a precision Hall Effect ACS723 IC sensor that can measure currents from 10 mA up to 5 A is selected because it is linear throughout the current measurement range. The output of the Hall Effect ACS723 IC sensor is fed into another 16-bit ADC channel of the ADS1115 IC, and the measurement is serially obtained by the microcontroller.

The output voltage is measured using a voltage divider connected to the half bridge inverter output circuit. The voltage divider output is fed into another 16-bit ADC channel of the ADS1115 IC, and the measurement is serially obtained by the microcontroller. The output current is measured using a combination of a shunt resistor and a non-inverting LM358N Op-Amp IC buffer that is also fed into another 16-bit ADC channel of the ADS1115

IC, where the measurement is then serially obtained by the microcontroller. The LM358N IC has been chosen for this application because it is a rail-to-rail Op-Amp.

The load of the half-bridge inverter circuit output is increased in steps of 500 mA up to 5 A by adjusting the digitally controlled DC electronic load. The measured voltage and current data at each load setting is used to calculate the input and output power in order to determine the efficiency performance profile of the transformer core under test. The implemented adjustable DC electronic load circuit block diagram is shown in Figure 3.

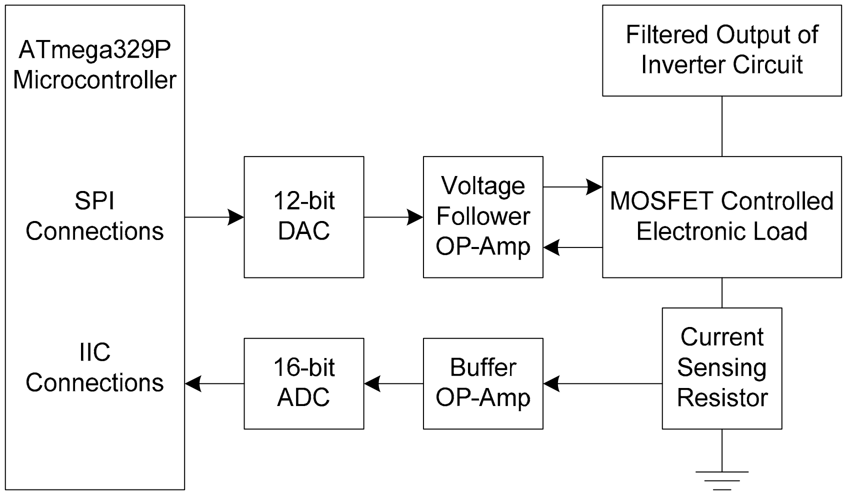

Figure 3. Block diagram of DC electronic load circuit.

Ease of control and improved accuracy were achieved by using a DC electronic load. A heat sink and a computer fan were used to cool down the thermal dissipation of the DC electronic load power MOSFETS. To ensure high precision, a 12-bit digital-to-analog (DAC) MCP4725 IC was used in combination with an LM358N Op-Amp voltage follower to adjust the current load settings. A factory-calibrated DS18B20 precision temperature sensor device with an accuracy of ±0.5 °C from –10 to +85 °C was securely placed on the transformer core surface to measure the temperature rise.

The characterization jig makes use of a programed ATmega328P microcontroller in order to automatically measure voltage, current and temperature data at each set load setting. The programed ATmega328P microcontroller then serially transmits these data to a computer where it is captured by the Data Streamer Add In feature of Excel.

3.3. Characterization Jig Operation

The characterization jig was designed to be semi-automated in order to ensure that measurement inconsistency is avoided. When the power is switched on, a default 500 mA current load setting and an inverter switching frequency of 25 kHz is set. The 12-bit MCP4725 DAC and the 16-bit ADS1115 ADC are then initialized. The characterization jig is manually operated using push buttons in order to select the inverter preferred switching frequency. The inverter output load current setting which is adjustable in 500 mA steps up to 5 A is then manually selected by using push buttons. The microcontroller then automatically measures the inverter input voltage and current, including the output voltage and current. The surface temperature of the transformer core is also measured, and then all these measured data are serially transmitted to the Data Streamer Add In feature of Excel.

Each core was tested at four different fixed frequencies by using a serial port interface (SPI) controlled MCP41010 digital potentiometer IC that sets the PWM frequency of the TL494 controller IC. One complete load cycle of 500 mA steps to 5 A is carried out for each selected half-bridge inverter frequency. The ATmega328P microcontroller algorithm flowchart of the characterization jig operation is shown in Figure 4.

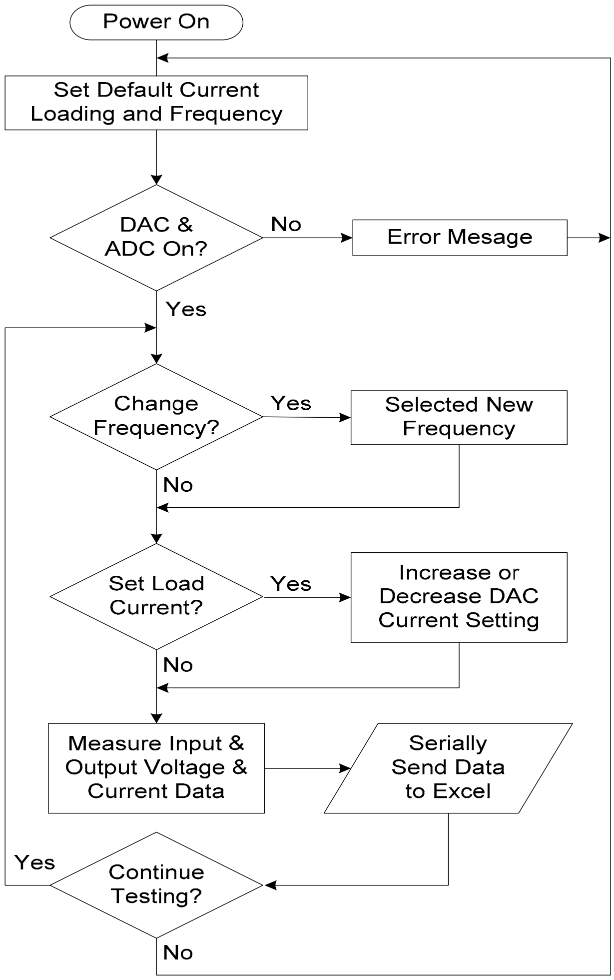

Figure 4. Flowchart of characterization jig operation.

Each voltage, current and temperature measurement was sampled twenty times by the microcontroller and then averaged before the record was serially transmitted to the Data Streamer Add In feature of Excel. This measurement process was also repeated in order to acquire another twenty saved records in Excel of each voltage, current and temperature measurement so that it can be averaged again. This results in an average of 400 samples for each measurement, thereby ensuring that measurement noise is reduced to obtain smooth characterization graph plotted curves. The standard deviation based on the 20 records of 20 samples for each voltage, current and temperature measured data point at all operating frequencies and output current loading was no greater than 0.3.

4. Results

In order to validate the proposed characterization jig operation, standard available polycrystalline or ferrite E-cores will be analyzed including an unknown core material scavenged out of a commercially available SMPS. The characterization jig can be verified if similar measured efficiency performance trends are obtained for each ferrite E-core throughout the output loading range at different operational frequencies. The output power at each output load setting for each operational frequency will also be analyzed in order to determine the power-handling capability of each polycrystalline or ferrite E-core. The characterization jig will then also be used in order to comparatively analyze the efficiency performance and power-handling capability between two toroidal cores with the same dimensions but with different material types, namely polycrystalline and nanocrystalline. The dimensions of the toroidal transformer core material were a 40 mm outside diameter by 31 mm inside diameter by 14 mm height.

4.1. Efficiency Comparison of Polycrystalline E Cores

The efficiency performance curves of each obtained standard E shape polycrystalline core material at each operating frequency are shown in Figures 5–8. The measured performance curves generally follow a similar trend. The efficiency curves initially start low at 500 mA loading and then gradually increase as the applied output inverter loading increases before eventually plateauing. Almost all the efficiency curves then start to slightly decline at the end of the load current range. Therefore, these overall efficiency performance curves can be used to comparatively analyze which transformer material core performs the best throughout the half-bridge inverter loading range at a particular set operating frequency.

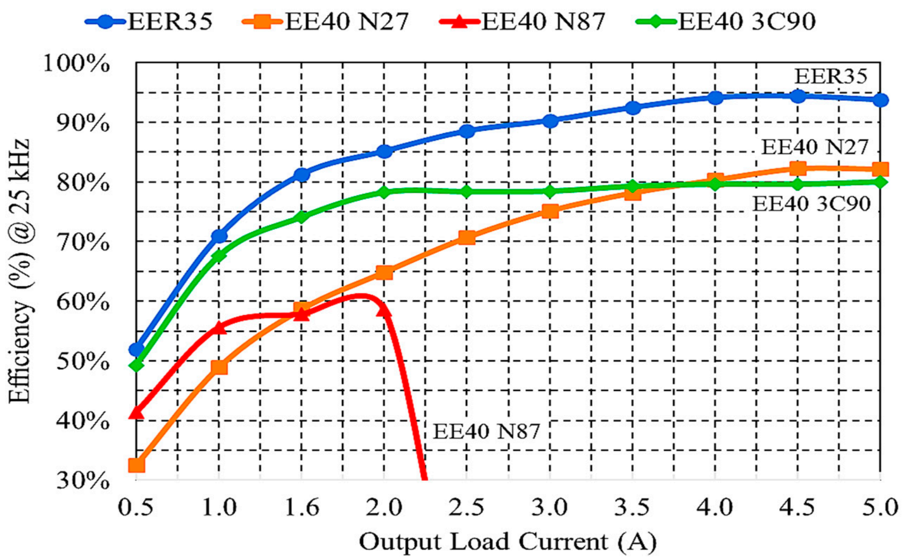

Figure 5. Efficiency vs. output loading of E-cores at 25 kHz.

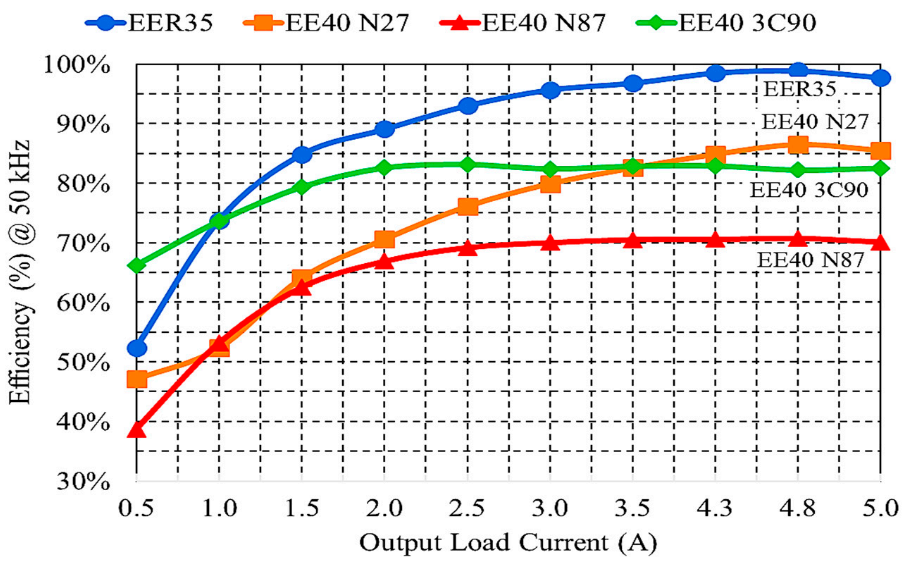

Figure 6. Efficiency vs. output loading of E-cores at 50 kHz.

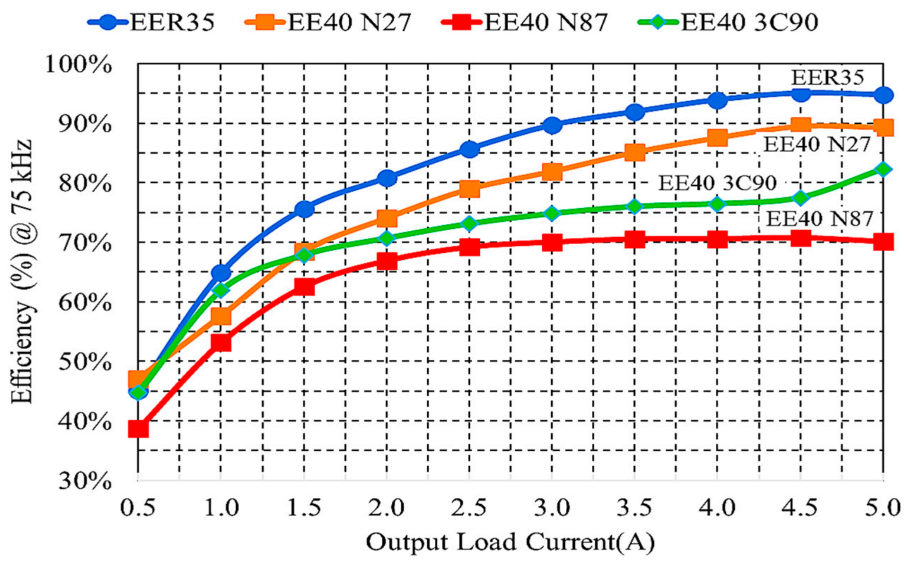

Figure 7. Efficiency vs. output loading of E-cores at 75 kHz.

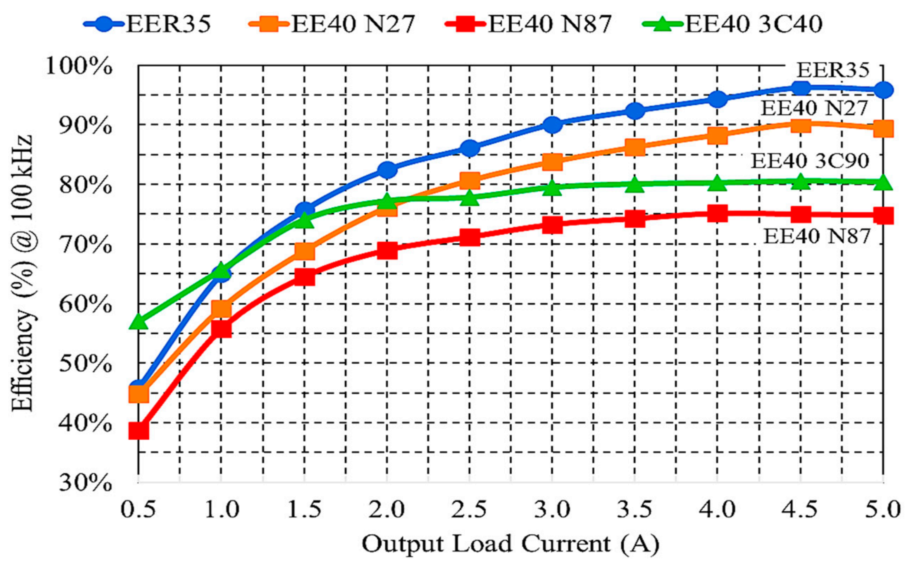

Figure 8. Efficiency vs. output loading of E-cores at 100 kHz.

The EER35 core material is the most efficient at all tested frequencies, while the EE40-shaped cores with N27 and 3C90 polycrystalline materials exhibit similar or closer type efficiency performance trends. The EER-shaped cores have round center legs instead of a square shape, allowing for shorter winding length and therefore improved efficiency. The EER35 core is an unknown material type that was scavenged out of a SMPS used for lead acid battery charging. The SMPS used a QTC3858 PWM controller IC which operates at a frequency of 50 kHz. This commercially used transformer core material has been chosen as a reference or benchmark to compare against the hand-wound EE40 shaped transformer cores with a specific polycrystalline material type.

The obtained performance curves clearly demonstrate that the characterization jig is able to deliver reliable measurements that can be used to comparatively analyze the efficiency of high-frequency transformer core materials. The efficiency curve of the EER35 core suggests that it could possibly be closely related to a 3C90 core-type material because of the closer efficiency curve trends at all frequencies, even though the efficiency of the EER35 core material is higher throughout the loading range.

The N27 polycrystalline EE40 core material follows similar efficiency trends, and its performance improves as the operational frequency increases. The EE40 N27 core material performs best at 100 kHz with peak efficiency around 90% and worst at 25 kHz with peak efficiency around 85%. This EE40 N27-type core material can be recommended for higher inverter operating frequencies, but at 25 kHz, the loading will need to be relatively high to avoid lower efficiency performance.

The N87 polycrystalline EE40 core material was the least efficient at all the tested frequencies and load settings. At 25 kHz operation, the EE40 N87 core material saturates passed 2 A loading, causing its efficiency to drastically drop, as seen in Figure 5. The EE40 N87 core material starts improving its performance at 75 kHz by obtaining a peak efficiency of around 70% and then performs best at 100 kHz by obtaining a peak efficiency of around 75%. The efficiency curves suggest that this core material could perform even better at frequencies above 100 kHz. This is in line with the datasheet for the EE40 N87 material, which shows that it is tested at frequencies greater than 100 kHz. Generally, the efficiency performance cure profiles of all the tested polycrystalline core materials improve as the current loading and operational frequency are increased.

4.2. Output Power Comparison of Polycrystalline E Cores

An output power comparison can reveal the power-handling capability of a material core in relation to its determined efficiency. The inverter output power is determined by multiplying the load current setting with the measured output voltage. Comparatively, a transformer core may be more efficient, but its output power may still be less than a less efficient transformer core that can provide higher output power at a given current load condition. This means that a more efficient core may require lower input power compared to output power requirements, whereas another core can provide a higher output power but then require higher input power, resulting in a lower efficiency. Therefore, output power comparison is just an alternative way to experimentally analyze the performance of a core material in relation to its efficiency. The output power comparison of each polycrystalline E-core at each operating frequency is shown in Figures 9–12.

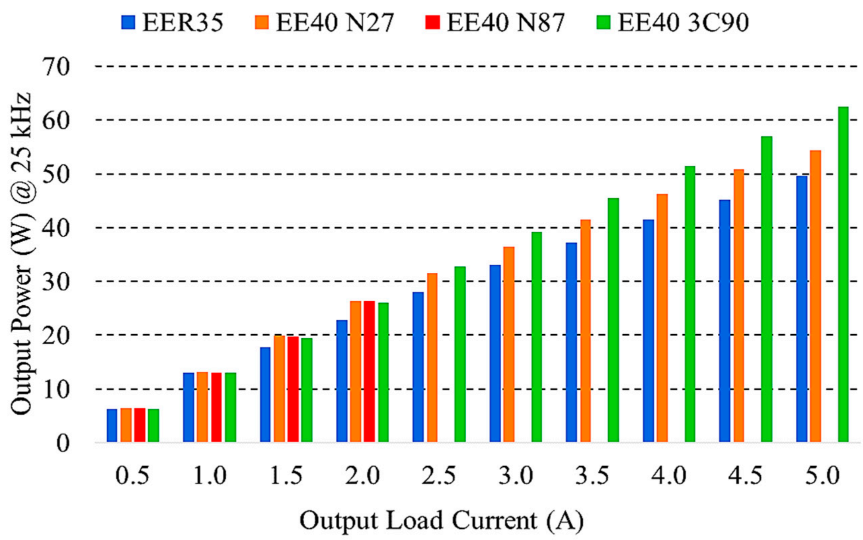

Figure 9. Output power vs. loading of E-cores at 25 kHz.

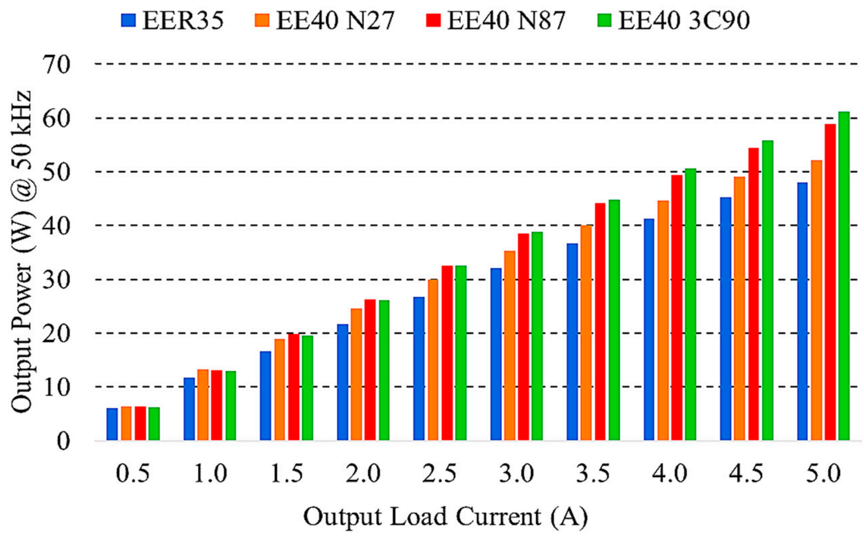

Figure 10. Output power vs. loading of E-cores at 50 kHz.

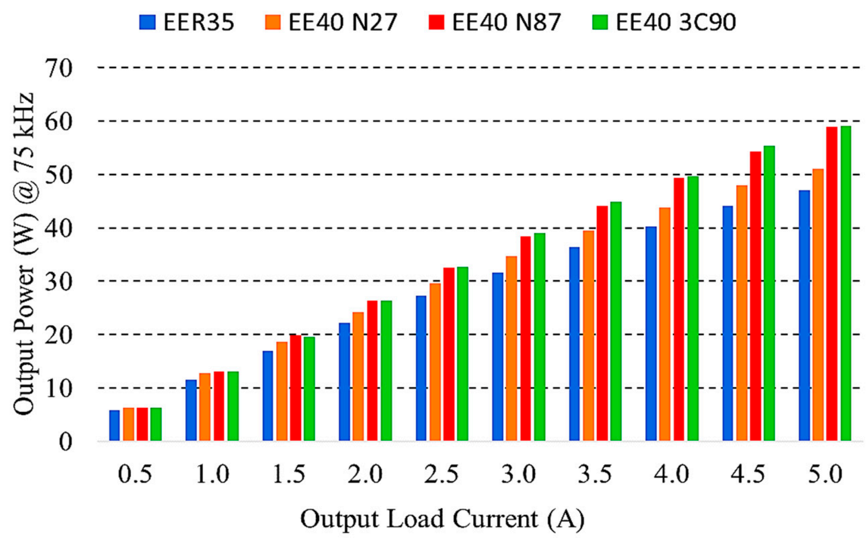

Figure 11. Output power vs. loading of E-cores at 75 kHz.

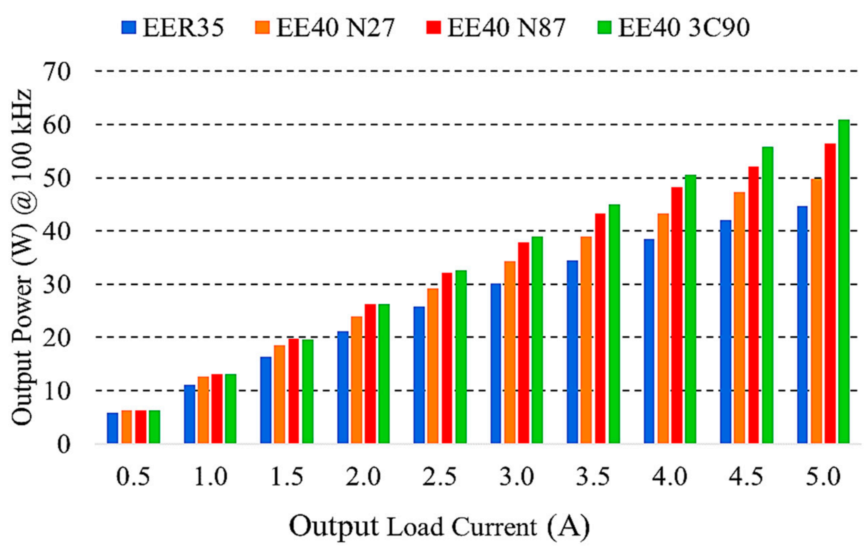

Figure 12. Output power vs. loading of E-cores at 100 kHz.

The EER35 core material is the most efficient but generally provides the least power-handling capability. The EE40 3C90 transformer core material is generally the third least efficient, but it tends to provide higher power-handling capability, especially at 25 kHz and 100 kHz. Therefore, the EE40 3C90 core material could be recommended for high-power converter applications where peak efficiency may not be required. In addition, the EE40 3C90 core material exhibits a more flat efficiency curve throughout the applied loading range, which suggests that this core material is ideal for applications where the loading may continually vary but the core is able to maintain its efficiency. The EE40 N27 transformer core material provides the second highest consistent efficiency curves, whereas the EE40 N87 transformer core material provides the second highest power-handling capability, except at 25 kHz. Generally, the surface temperature rise of all the tested transformer E-cores follows a common trend and is almost static throughout the loading range.

4.3. Efficiency of Polycrystalline vs. Nanocrystalline Cores

The obtained efficiency performance comparison curves of toroidal core-shaped R polycrystalline and K1-107B nanocrystalline materials at each operating frequency are shown in Figures 13–16. Again, these transformer core materials generally follow a similar trend as observed with the standard polycrystalline or ferrite E-cores. Initially, the efficiency starts low and improves as the loading increases before it plateaus and then either falls or remains the same at the end of the loading range. The efficiency performance of the two tested toroidal core materials generally tends to improve at higher current loading and operational frequency.

The efficiency performance of the toroidal core with R polycrystalline material starts low—for example at around 27% for 25 kHz and 50 kHz; then, it peaks around 70% at almost all tested operating frequencies. The toroidal R polycrystalline material core is the least efficient at 25 kHz and 50 kHz; then, it is most consistently efficient at 100 kHz. The toroidal core with K1-107B nanocrystalline material performs with the best efficiency at 75 kHz and the worst at 25 kHz operating frequency. The toroidal core K1-107B nanocrystalline material at peak efficiency is on average about 20% more efficient than the toroidal core R polycrystalline material at all operating frequencies. Only at a 100 kHz frequency does the efficiency performance difference between the two toroidal core materials start to decrease as the loading increases.

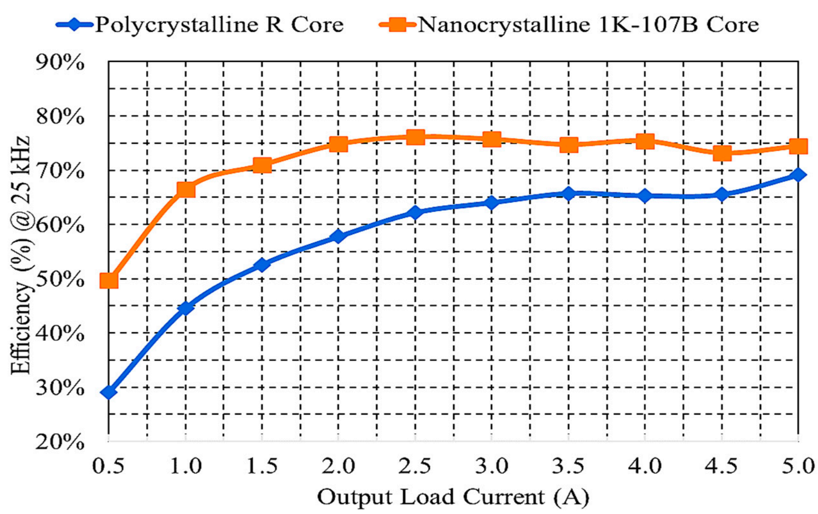

Figure 13. Efficiency vs. output loading of R and 1K107B cores at 25 kHz.

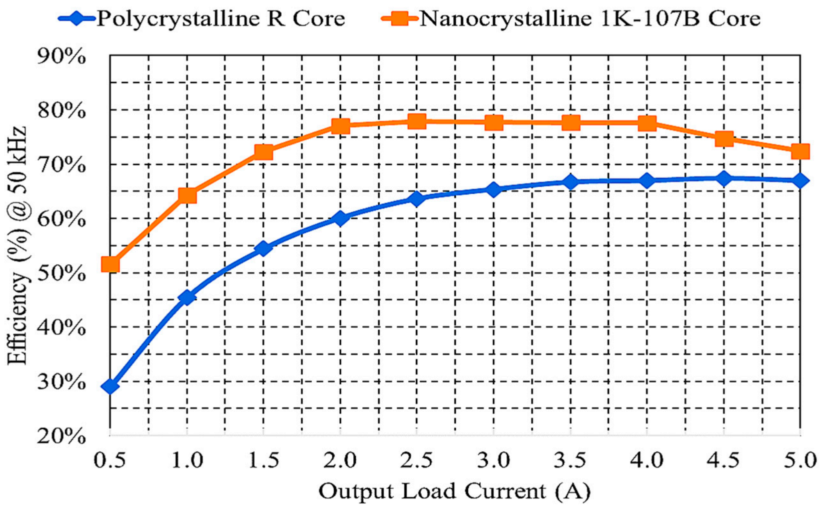

Figure 14. Efficiency vs. output loading of R and 1K107B cores at 50 kHz.

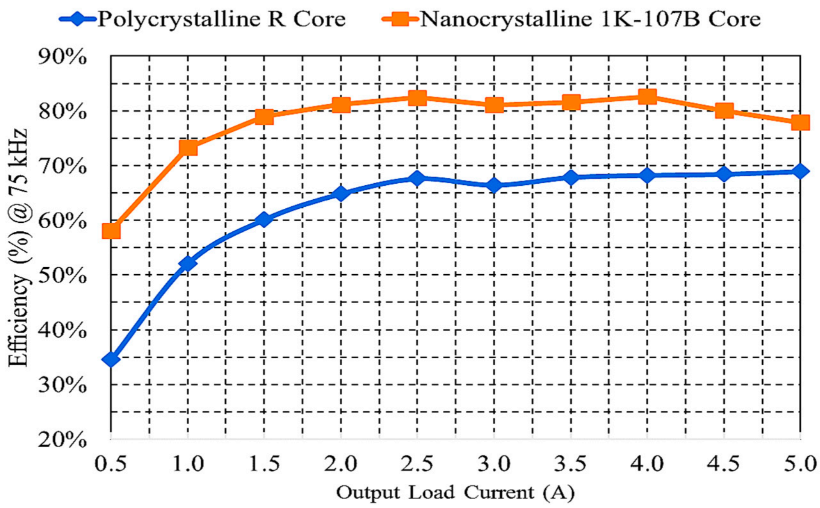

Figure 15. Efficiency vs. output loading of R and 1K107B cores at 75 kHz.

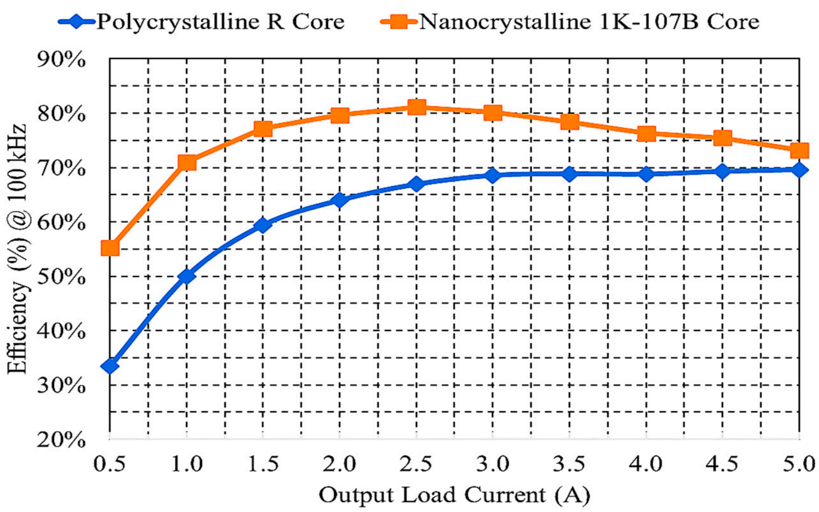

Figure 16. Efficiency vs. output loading of R and 1K107B cores at 100 kHz.

Transformer nanocrystalline material cores are generally preferred over transformer polycrystalline material cores in high-power applications because of the ferrite core size limitations [10]. Compared to polycrystalline materials, the core loss of nanocrystalline materials is two to three times lower with a reduction in volume of around 60% [12]. Therefore, the nanocrystalline core materials are more suitable for frequencies up to 100 kHz, while polycrystalline or ferrite E-core materials are more suitable for frequencies above 100 kHz [17]. The nanocrystalline core materials are generally preferred for operating frequencies from 10 to 25 kHz, while materials are also available for low-power applications around 100 to 200 kHz [18,19]. Experimental results reveals that even though the nanocrystalline is more expensive than polycrystalline material, it can still be an ideal replacement for power converter applications that operate between 25 and 100 kHz because of the higher efficiency and similar output power capability. Again, the obtained characterization jig efficiency performance measured curve trends are validated because it clearly reveals and confirms that nanocrystalline is more efficient than polycrystalline transformer core material for a 25 to 100 kHz operating frequency range.

4.4. Output Power of Polycrystalline vs. Nanocrystalline

The polycrystalline R and nanocrystalline K1-107B toroidal core output power at each loading for all set operating frequencies is shown in Figures 17–20. The core with nanocrystalline material is more efficient than the core with polycrystalline material, but its output power-handling capability is almost similar to the polycrystalline core at all tested frequencies throughout the loading range. The efficiency performance of the toroidal nanocrystalline core is not as high as the characterized polycrystalline or ferrite E-cores, but its output power-handling capability is higher. Note that a lower output voltage drop occurs when there is a more flat efficiency curve throughout the applied loading range. This nanocrystalline material characteristic makes it ideal for applications where the load may continually vary but the core is able to maintain its efficiency. Therefore, transformer nanocrystalline core materials should be considered as an appropriate option for higher power converter applications with operational frequencies between 25 and 100 kHz.

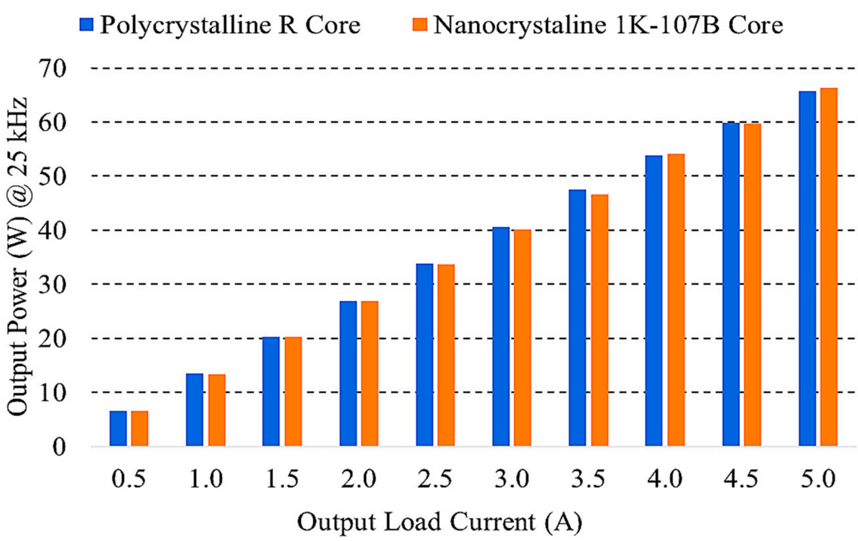

Figure 17. Output power vs. loading of R and 1K107B cores at 25 kHz.

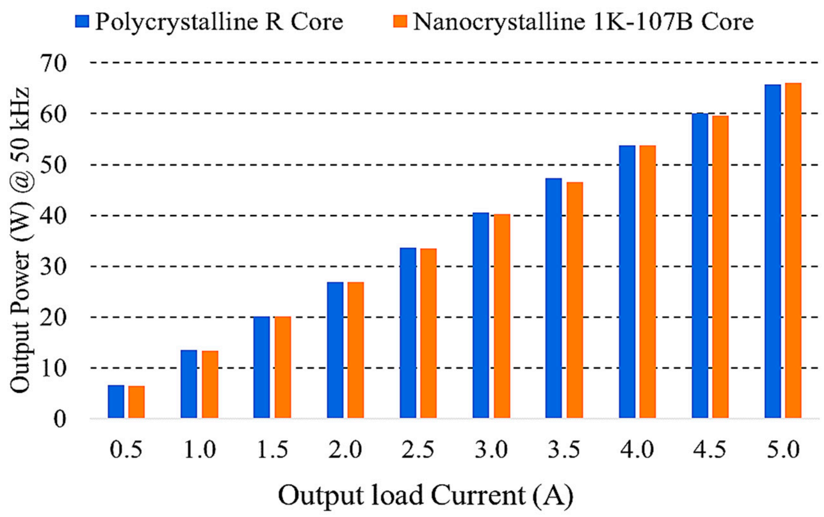

Figure 18. Output power vs. loading of R and 1K107B cores at 50 kHz.

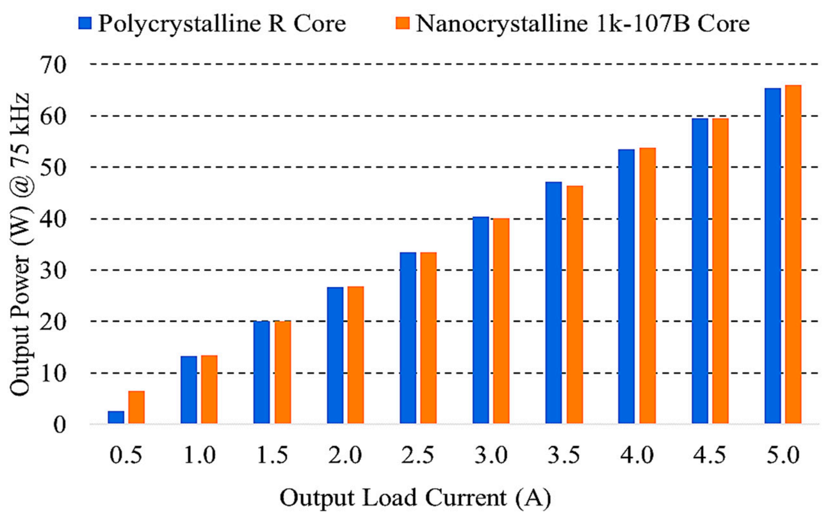

Figure 19. Output power vs. loading of R and 1K107B cores at 75 kHz.

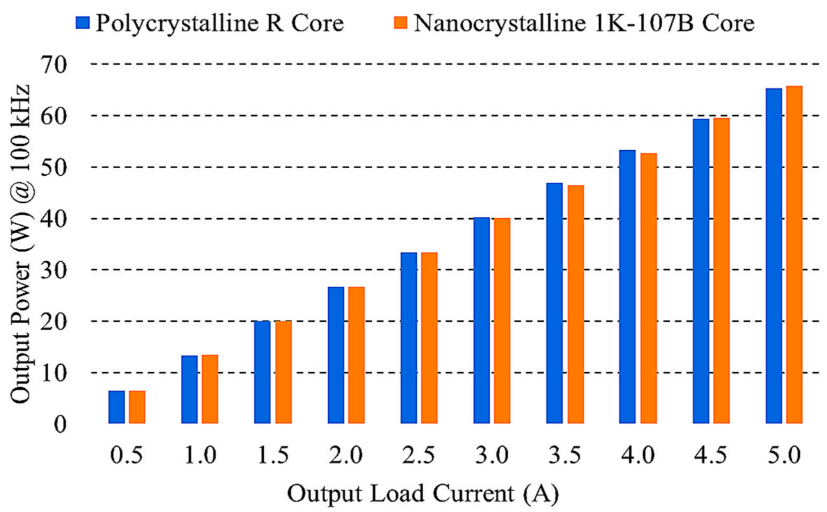

Figure 20. Output power vs. loading of R and 1K107B cores at 100 kHz.

4.5. Temperature Rise of Polycrystalline vs. Nanocrystalline

The surface temperature rise of the R polycrystalline toroidal core at the different operational frequencies as the output load current increases is shown in Figure 21. A DS18B20 temperature device sensor was attached to the surface of the core material under test and therefore does not measure the internal temperature, which could possibly be at a higher temperature. However, as can be clearly seen, a relationship exists in which the temperature rises as the applied load current and the operating frequency are increased.

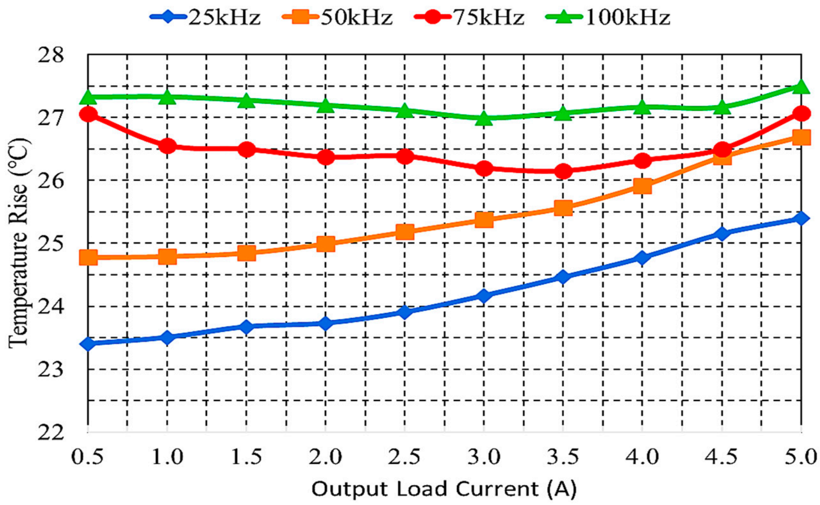

Figure 21. Temperature rise of polycrystalline R toroidal core.

The temperature rise of the R polycrystalline toroidal core explains why its efficiency only peaked at 70%. Increased heat generation is considered wasted power with respect to the core conduction losses. These losses can be attributed to the type of core material used and possibly influenced by how the core was wound. Winding inefficiencies may occur if the core was wound by hand, and this is true for all tested core materials in this study except for the scavenged EER35 core, which had the highest efficiency performance curves. Therefore, dissipated heat is related to winding efficiency and core material losses. The temperature rise of the K1-107B nanocrystalline toroidal core at different frequencies as the output load current increases is shown in Figure 22.

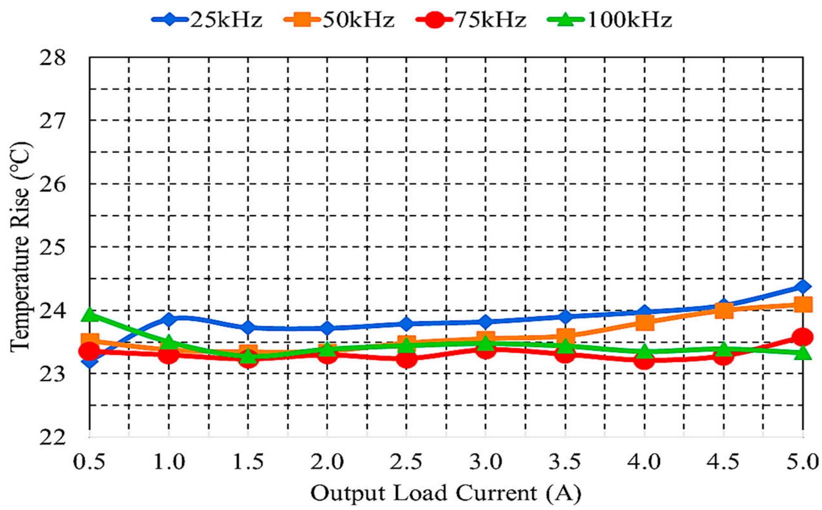

Figure 22. Temperature rise of nanocrystalline 1K-107B toroidal core.

The temperature rise of the nanocrystalline toroidal core seems to be insignificant as comparatively observed with the polycrystalline or ferrite E-cores. In addition, as the operational frequency increases, the surface core temperature slightly decreases. At 75 kHz, the nanocrystalline toroidal core surface temperature ran cooler, and at 25 kHz, it ran hotter throughout the loading range. This directly correlates with the nanocrystalline toroidal core efficiency performance curves, whereby at 75 kHz, the core was at its most efficient, and at 25 kHz, it was at its least efficient. Therefore, as the toroidal core and winding losses increase, the surface temperature rises and the efficiency decreases.

The polycrystalline material has a lower flux saturation density of 0.39 T, and the nanocrystalline material has a higher flux saturation density of 1.2 T [11]. The significant flux saturation density of the nanocrystalline material, which is around three times that of the polycrystalline material, can explain why it is more efficient: because it operates at a lower temperature. This is evident in the core surface temperature rise of the materials at the different set operational frequencies throughout the loading range, where the polycrystalline toroidal core heated up more than the nanocrystalline toroidal core.

5. Conclusions

High-frequency transformer core material efficiency performance is either analyzed by using FEM software or by using experimental models. However, the purpose of this study was to design an empirical experimental approach that can quickly determine the actual efficiency and output power performance so that comparison analysis between two different high-frequency transformer core materials can be conducted. The experimental approach used a standard half-bridge inverter topology in order to ensure that the entire hysteresis loop of the high-frequency transformer is activated during characterization. The actual input voltage and current including output voltage and current measurements were used to determine the transformer core material efficiency performance throughout a defined output constant current load range that was operated at different set switching frequencies.

The characterization jig operation was validated because it revealed that standard polycrystalline or ferrite E-core materials including a commercially scavenged SMPS core material exhibit similar measured efficiency performance curve trends. Observation of the measured profile curve trends also revealed that a definite relationship exists between the operational switching frequency, output current loading and efficiency performance even with different types of transformer core materials. In addition, the reliability of the characterization jig was verified by its consistent and repeatable measurements throughout the output constant current loading range.

The usefulness of the characterization jig was then demonstrated by comparatively analyzing the performance of polycrystalline and nanocrystalline toroidal transformer core materials. As confirmed by the literature, the results concluded that the nanocrystalline material has a higher efficiency performance than an equivalent-sized polycrystalline material transformer toroidal core.

Therefore, the designed experimental approach provides an empirical method that can be used to quickly determine the actual efficiency and output power performance difference between two compared high-frequency transformer core material types. The contribution of this paper is significant, because newly produced core materials can be rapidly analyzed by comparing their efficiency and output power performance against a known core material type. By using this experimental approach, a fast identification of new improved core material performance can be achieved. The proposed approach could be further improved in order to operate at higher frequencies and output current loading so that a larger range of high-frequency transformer core materials can be characterized.

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