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Advanced Ferromagnetic Materials in Power Electronic Converters: a State of the Art

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ABSTRACT Currently, the design of power electronic converters (PECs) is in a stage which looks increasing its efficiency and reducing its dimensions from basic topologies through precise analysis of losses in each device that conforms. Although there have been important advances to improve the active components of PECs, passive components, particularly inductors, have changed very little since several decades ago, and those begin a limiting factor, when a high efficiency at very high power and switching frequency, are required. It is for the foregoing that this paper reviews new ferromagnetic materials to construct inductors and achieve a substantial increasing in efficiency through magnetic permeability and hysteresis improvements. Therefore, the main objective of this work is to position the reader in the state of the art of advanced ferromagnetic materials used in PECs. Details about how they are constructed and qualitative comparison of their dynamic behavior are provided. Also, estimation methods of energy losses, applications for different types of material, and its influence on the performance of some basic PECs are presented.

INDEX TERMS Amorphous magnetic materials, magnetic materials, power conversion, soft magnetic materials.

I. INTRODUCTION

SINCE the beginning of the electronic, digital electronic has been a huge step in human evolution, achieving to reduce the size of its components. However, the design of power supplies that feed the electronic boards is still a frequent development topic [1]. Many electronic components, including the aforementioned, use inductors with magnetic cores, so a reduction in their size and improvements is desirable. Also, the manufacturers require that the selected material must be accessible, easy to manipulate and cost-effective [2]. Currently, a lot of devices require at least one power conversion stage, from daily things like wireless screwdrivers or cell phone chargers, to electric vehicles, only for mentioning some examples [3], [4], [5]. The necessity for improving efficiency and performance in power electronic converters has been an important growing area worldwide.

Nowadays, the most common requirements on PECs' design are: low number of magnetic components, size and weight reduction, low cost, wide range of conversion, output regulation, high performance and major reliability [6]. One way to minimize the dimensions and weight of PEC, without affecting it's performance, is through semiconductor devices built with materials that allow a high-frequency commutation with small energy losses. At present, the semiconductor devices based on silicon carbide (SiC) and gallium nitride (GaN) are widely used [7], [8], [9], [10], [11]. Some characteristics about the principal semiconductor devices are given in Table 1, including general-purpose diodes (GPD), high speed diodes (HSD), Schottky diodes (SD), TRIAC (Triode for Alternating Current) and different thyristor and transis-

TABLE 1. Comparison between semiconductor and commutation devices.

Dispositive	Frequency [Hz]	V_{max}/A_{max}	V_{on}/R_{on} [V]
GPD	Low, 2 k	High, 10 kV/5 kA	Low, 1-2
HSD	Medium, 12 k	Medium, 3 kV/1 kA	Low, 1-1.5
SD	Medium, 20 k	Low, 50 V/50 A	Low, 0.5-1
Thyristor	Low, 1 k	High, 3-7 kV/5 kA	Low, 1-3
TRIAC	Low, 1 k	Medium, 1 kV/50 A	Low, 1-3
GTO	Low, 1 k	High, 6 kV/6 kA	Low, 1-3
MCT	Medium, 30 k	Medium, 3 kV/2 kA	Low, 1-2
MOSFET	High, 1 M	Low, 0.2-1 kV/ 1 kA	High, 8-15
BJT	Medium, 10 k	Low, 1.5 kV/ 1 kA	Low, 1
IGBT	Medium, 80 k	Medium, 1.7-6.5 kV/2.4 kA	Medium, 1-4

TABLE 2. Cut-off frequency in MOSFETs of Si, SiC and GaN.

Kind of MOSFET	Cut-off frequency [Hz]
Si	1 M
SiC	3.5 M
GaN	5 M

tors types as GTO (Gate Turn-Off Thyristor), MCT (MOS Controlled Thyristor), BJT (Bipolar Junction Transistor) and IGBT (Insulated Gate Bipolar Transistor). Nevertheless, the maximum frequency that these devices can achieve is of 1 MHz due to being built with Si, so their performance altogether with ferromagnetic materials in high-frequency applications will be limited [12], [13], [14], [15].

The cut-off frequencies of metal-oxide-semiconductor field-effect transistors (MOSFETs) building with Si, SiC and GaN are showed in Table 2; these devices shown an increase until 3.5 times of SiC respect to Si and 5 times of GaN compared with Si, this feature in their manufacture together with ferromagnetic materials achieve to improve the PECs' performance [16].

These components together with ferromagnetic materials allow improving the performance of PECs

Nowadays it is estimated that magnetic components of a PEC operating at high-frequency can be more than 50 % of the total system weight [17], [18], [19]. For this reason, the design of magnetic components requires a high accuracy fabrication. For instance, geometric characteristics are in function of electrical excitation signals, current density, magnetic flux, energy losses, among others [1], [20], [21]. Currently, there are three kind of materials leading the fabrication of transformers and inductors; these are: ferrite, powder core, and nanocrystal alloy [22]. PECs' magnetic components usually employ ferromagnetic materials, that is, ceramic magnetic materials with spinel structure like ferrite [23].

Ferrite is low-price and due to its high resistivity, it has low energy losses at high-frequency, and it is available commercially in many geometric shapes and sizes; these features make it the leading material in low power electronic applications. However, during the design of ferrite magnetic components, to enhance the saturation point, an air gap is used. Unfortunately, the air gap raises the ferrite core reluctance, producing the need of a high magnetic field intensity to reach the density saturation level of the magnetic field [24], [25]. The Eddy current losses arise the square to the frequency and are direct proportional to electrical material conductivity; this implies an eminent impact in high-frequency applications [26], [27], [28]. Additionally, ferrite has a low magnetic saturation (0.4 T), which is a limitation on high power applications and physical size reduction. It is necessary to mention that advances in ferrite cores are growing, in these day researchers are working in order to improve their magnetics properties with different types of alloys and materials. The reader interested in ferrite cores can read relevant information about the in [29], [30], [31], [32], [33], [34], [35], [36].

Up to date, there are materials with higher saturation point than ferrite, which can achieve high power levels. Those alloys are based on metallic elements (Si, Ni, Cr and Co). This kind of materials is known like ferromagnetic materials and those are based on iron (Fe). Ferromagnetic materials are an available option to substitute ferrimagnetic materials in the market of magnetic components. This is because iron is the predominant element in their alloys, which is one of the eight more abundant elements on Earth [37]. For instance, an available option of ferromagnetic alloys in PECs is on the fabrication of electric vehicles (EVs) and hybrid electric vehicles (HEVs), in particular the nanocrystal alloys (usually the FeSiBNbCu family) [26], [38], [39], [40]. Indeed, it is expected that the use of ferromagnetic materials will reduce the following characteristics of PECs: a) weight, b) volume and c) core losses [41]. Unfortunately, one limitation of ferromagnetic elements is their electric conductivity, which results on excessive Eddy current losses at high frequencies. To overcome this limitation, an air gap is used, however, this last can generate hot points due to Eddy current losses generated by linkage magnetic flux in air gap [24], [25].

In view of the new challenges to design high-efficiency PECs, this paper provides to the reader the state of the art in magnetic materials alternatives to ferrite. The content of this work is organized in the following sections. In Section II principal properties of magnetic materials are described. In Section III, the reader will find information about ferromagnetic materials, their classification and characteristics of each one of them as well as their limiting parameters. In Section IV the different kinds of energy losses in magnetic components design are reviewed. In Section V a comparative between applications and different magnetic materials used in the PECs is given. The discussion of this work is presented in Section VI; and finally in Section VII conclusions are provided.

II. FUNDAMENTALS OF MAGNETIC MATERIALS

Before to proceed with the description of ferromagnetic materials used in PECs, it is necessary to provide some fun-

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damentals and properties. The materials that have magnetic moments derived from the electrons' rotation and orbital angular moments are called magnetic materials. This kind of materials exhibit magnetic polarization, as soon as those are exposed to an applied magnetic field [42], [43]. Magnetization phenomenon (M) is given by the alignment of the magnetic dipoles within a material to the applied magnetic field. A magnetic material is represented by several magnetic dipoles and, therefore, by many magnetic moments. In the absence of an applied magnetic field, the magnetic dipoles are oriented in an aleatory way; as a result, the addition of moments plus and the magnetic polarization is equal to zero. Once a magnetic material is subjected to a field, the dipoles of many materials will line up in that direction [42].

The value of M represents the effective magnetic contribution of the overall material atoms, likewise, the magnetization process can occur by two ways, domain wall moves and domain rotation [44]. It is known as saturation magnetization M_s, to the maximum value achieved once the overall magnetic atomic moments are aligned in parallel [45], [46]. In contrast, magnetic remanence (M_r) refers to the residual magnetization that stay in the material once the applied field is restored to zero [1], [6]. On the other hand, the inverse field necessary to reduce the magnetization to zero is known as coercivity (H_c) [37].

The magnetic characterization of a material comprises to measure the magnetization M, and the flux magnetic density B or polarization J as a function of magnetic field H [47], [48]. The correlation between B and H is a combination of empty space contributions (μ_0H) and the material or substance response (μ_0M). This is, $B = \mu_0(H+M) = \mu_0 H + J$, where μ_0 is the vacuum permeability expressed in Henry per meter H/m, B in Tesla T likewise magnetic polarization J; note that $J = \mu_0 M$, and the units of H and M are Ampere per meter A/m [45].

The variables of magnetic susceptibility, $\chi = M/H$ and permeability $\mu = B/H$, are used to classify materials in different magnetic families by considering their temperature response once a magnetic field is applied [45]. Starting from the permeability definition, $B = \mu H = \mu_r \mu_0 H$, $\mu_r = 1 + \chi$ is defined as relative permeability. It is necessary to mention that, with exception of some materials, many materials have a μ_r very close to unity [42]. The magnetic response of a material is commonly described by μ_r, and often, in ferromagnetic and ferrimagnetic materials this is a frequency function (complex permeability) [42], [45], [49].

On the other hand, magnetic material properties are represented by a hysteresis curve of each material, and it can be provided in terms of B and H, or to M and H [37], [50]. The variables until now described can be obtained directly from this curve, whereas in the case of the permeability and magnetic susceptibility, only their initial values are considered [29]. Moreover, depending of the material composition, different behaviors can be observed in presence of external parameters such as temperature, pressure, direction the applied field, among others [48].

A magnetic material possesses magnetic anisotropy, which means that its internal energy relies on the direction of its spontaneous magnetization with respect to crystallographic axes [51]. Magnetic materials typically present some kind of anisotropy in diverse magnetic properties such as: resistivity, coercivity, permeability, magnetostriction, etc. [45]. Three principal anisotropy sources are associated to the sample shape, crystalline structure and atomic structure or micro scale [37].

Magnetostriction effect (λ) is related to the length variation(Δl) that suffers a material once it is exposed to a magnetic field, and it is defined as $\lambda = \Delta l/l$, where l is the material length, so the fractional change is just an effort. The λ value depends of the magnetization grade, and the applied field. Indeed, many of the length changes related to this property take place during the domain rotation [29], [44] [38], [48]. It is well known that the material's magnetic properties change with temperature [52]. The temperature (T) increment generates an atom vibration inside the material.

Besides, if it is applied enough thermal energy, then the magnetic energy will overcome, and the material will become paramagnetic over by a certain umbral called Curie's temperature (T_c), or Néel's temperature for antiferromagnetic materials [37], [44], [45], [53]. Weiss proposed a model that describes this thermal phenomenon assuming that a stronger internal magnetic field takes control beyond the T_c umbral, and it allows the coupling of atomic moments despite of the thermal effects. In other words, T_c is the temperature that separates the well-ordered state ($T < T_c$), where intern field dominates the thermal effect, of the disordered state ($T > T_c$), where the disorder thermal effects predominate [54].

III. FERROMAGNETIC ALLOYS

Depending on magnetic moments arrangement, structure, texture, composition and properties, magnetic materials can be classified in different trends, some of these are [8], [50].

1) According to the arrangement of magnetic moments:
   a) Ferrimagnetic materials.
   b) Ferromagnetic materials.
2) According to the magnetization easiness:
   a) Hard magnetic materials (high coercivity).
   b) Soft magnetic materials (high permeability).
   c) Semi-hard materials.

The magnetic properties of ferrimagnetic materials are intimately related with the temperature at which those are exposed. That means, at environment temperature those are easier to magnetize; typically, these are ceramic materials that tend to behave as good isolation materials and those are used in diverse high-frequency applications [55], [56].

On the other hand, a ferromagnetic material is characterized due to its atoms are aligned in the same direction that its magnetic domains, in other words, big ordered magnetic regions allow an energy store reduction in the magnetic field [45].

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In the absence of a magnetic field, ferromagnetic material domains are oriented aleatory, and those do not show any magnetic property. If the material is subject to a magnetic field, its magnetic domains are aligned in the same direction of the field and those will have magnetic properties even in its absence [57], [58]. This kind of material respond at high changes of B, while μ_r values for some materials can reach up to 1 M [45]. Fe, Ni, Co and their alloys are some examples of these materials [59]. Ferromagnetic materials contain atom alignments, which can be paralleled and anti paralleled with respect to the magnetic domains, causing a magnetic response reduction on certain grade [45].

Hard magnetic materials (H_c >400 kAm^{-1}) are permanent magnets, so those have a high coercivity (magnetic field intensity that must be applied to reduce its magnetization to zero, after the material has been magnetized until saturation), and those can support demagnetizing fields [57]. On the contrary, soft magnetic materials (H_c <10 kAm^{-1}) have high permeability allowing its use in electrical machines and electric devices.

Semi-hard magnetic materials (10 kAm^{-1} < H_c <400 kAm^{-1}) are considered a special kind of permanent magnet material, and those are mainly used on analog and digital magnetic recording [37], [60].

It is necessary to mention that the development of magnetic materials is in function of industrial needs, as well as the technology advancement to obtain materials with new compositions, micro-structures and manufacturing techniques [60], [61]. Fig. 1 [1] shows a ferromagnetic material classification used in the inductor cores of PECs.

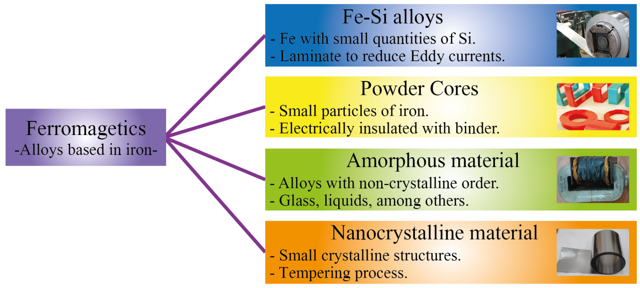

FIGURE 1. Magnetic materials used in PECs cores.

A. FE-SI ALLOYS

Fe-Si alloys are a combination between efficient design (due their magnetic properties) and reasonable cost. In these alloys the Si has several benefits such as: increment of resistivity (reduction of Eddy current losses), high permeability, decrease of magnetostriction, augmentation of mechanical strength, and alloy stiffness [50], [60], [65]. These alloys do not need to have more than 4.5 % of Si, otherwise the material obtained will be fragile and impossible to manipulate. It is necessary to mention that alloy magnetic materials are normally founded in the market like laminations. This last to reduce the material's Eddy current losses [35].

Magnetic properties such as energy core losses and magnetic saturation point rely on the sheet thick. Regularly the sheet thick is of few millimeters (0.3 and 0.7 mm) and with a longitude up to 1 m. The Fe-Si main applications are in the cores of many kinds of transformers that operate in frequencies of 50 or 60 Hz, sometimes at 400 Hz, and in low-medium frequency applications [60]. These cores can be made in several geometries, E and C shapes are the most popular [35].

There exist two kind of Fe-Si alloys: grain non-oriented sheets (GNO) and grain-oriented sheets (GO), both have different applications and characteristics, being Fe_{96-99}-Si_{1-4} and Fe_{97}-Si_3 the most representatives [50], [60], [61].

Robert Hadfield and his son developed in 1900 the grain non-oriented silicon steel. There are two types of this material: complete processed sheets, enriched with Si and Al that allow low losses; and semi-processed sheet, which is cheaper than complete processed sheets, and has several induction levels [50]. Nowadays this material represents 80 % of electrical devices market, mainly in the magnetic core manufacture.

On the other hand, the grain-oriented silicon steel was developed by the american metallurgic Norman Gross, in 1933. He discovered that, in contrast to hot lamination of the silicon steel, cold lamination with intermediate anneals plus a final high temperature annealing produce a sheet with better magnetic properties in the same lamination direction. This improvement was a consequence of a favorable magnetic texture, produced by secondary recrystallization during high temperature annealing [60]. The GO sheet arrived into commercial production around 1945, and since then its properties have been continuously improved in order to be produced, nowadays, in routine form [52], [60].

B. POWDER CORES

Powder cores represent the most recent advances in magnetic materials area; those are fabricated from metallic powders, typically iron. Although those can be composed with alloys such as Fe-P, Fe-Si and Fe-Co [66], [67]. The powder cores also are known as soft magnetic composites (SMC).

This kind of cores is used in applications that require special geometry cores, because those present greater versatility in their manufacturer process compared to thin sheet cores (Fe-Si alloys). Also, powder cores are also suitable for medium frequency applications (from frequencies lower than 1 kHz up to tens of kHz) [8], [61].

One of the most attractive characteristics of powder cores is the relative permeability variation according to the magnetic field intensity. In addition, those have the following characteristics [36]:

1) *High magnetic saturation point*: this property allows windings endure high current levels reducing the size of cores and handling great power. In this kind of cores,

[1] Source: Adapted from [62], [63], [64]

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the saturation flux is generally high (around to 1.5 T) [36].

2) *High Curie temperature*: the powder core Curie temperature is between a range of 400 $\sim$ 700°C [36], [68].
3) *Highly flexible magnetic structure*: the manufacturing process of powder cores consists in spreading a dough all over a preformed mold, apply pression to compact the material and leave it in an only piece, this allows powder cores have many different geometric forms. This is one of the most attractive characteristics, because the thermal resistivity can be reduced if the area of the magnetic component surface is increased [36].
4) *Soft saturation*: also called gradual saturation. This variable indicates at which point the inductance significantly falls if the polarization current is increased. In the case of powder materials, the speed at which inductance will fall is gradual compared to ferrite cores, and it relies on the core shape function [36], [68]. Gradual saturation also can be observed through the change of their initial permeability in DC bias conditions. Powder cores are composed of materials that possess a uniformly distributed structure by thin spaces, which allows to achieve a soft saturation. In other words, each particle does not allow simultaneous saturation [69].
5) *Fringing flux elimination*: powder cores, contrasting magnetic ferrite cores, do not require an air gap to avoid magnetic saturation because powder cores are made from very thin particles of magnetic material. Those particles generate small air gaps (pores) within the powder core's structure, which removes the need for an external air gap, and it decreases the energy losses [24], [36].

In terms of the material used for fabrication, those can be classified into four groups, shown in Table 3. This Table also includes properties and characteristics [69], [70]. As it can be seen from Table 3, Sendust cores are also known as "Kool Mμ™". These cores have mechanical hardness and remarkable magnetic properties like low energy losses at high frequencies, magnetostriction close to zero, and high permeability [71], [72]. The particle size of these cores is around 125 μm with a coercivity of 56 A/m [73]. In this kind of cores, the high content of Si and Al reduces the saturation magnetic flux ($\sim$1.2 T). Therefore, it is not frequently used in power transformer applications [49].

Powder cores are mixed with a binder or insulating material, which can be made of organic or inorganic material. This combination reduces magnetic losses at high frequencies because dust particles are isolated from each other [74]. However, those also present low resistivity, which increases Eddy current losses. Besides, the low resistivity causes the skin effect to be shorter than the metal particles used as cores, thus increasing material losses. The frequency operation of powder cores is below 100 kHz [37] and the permeability is low due to the isolation concentration [68].

TABLE 3. Powder cores classification in terms of their composition.

Iron Powder Core (Fe)	Very small Fe particles with purity greater than 99 %. Great rentability overall powder cores. Available in two types: Fe carbonyl and Fe reduced in H. Permeability range of 1 to 100. Magnetic density flux of 0.8 T. Resistivity $\sim$10 $\mu\Omega$m.
Molybdenum Permalloy Powder Cores (Ni-Mo-Fe)	Also known as MPP. Composed of 81 % Ni, 2 % Mo, and 17 % Fe per weight. High fabrication cost. Normal effective permeability between 14 and 350. Magnetic density flux of 0.3 T. Resistivity $\sim$ 55 $\mu\Omega$m.
High Flux Powder Cores (Ni-Fe)	Composed of 50 % Ni and 50 % Fe powder alloy per weight. Permeability range of 14-160. Magnetic density flux of 2.4 T. Resistivity $\sim$ 25 $\mu\Omega$m.
Sendust Cores (Fe-Si-Al)	Called also as "Kool Mμ™". Powder produced from a ferrous alloy of 85 % Fe, 6 % Al and 9 % Si per weight. Cheaper than MPP or high flux cores but more expensive than Fe powder cores. Permeability range between 26 to 125. Magnetic density flux of 1.1 T. Resistivity $\sim$ 110 $\mu\Omega$m.

C. AMORPHOUS MATERIAL

In the 60's, it was discovered that some families of alloy that cooled from the liquid state at very high speed, solidified as non-nanocrystalline materials. That is, once their atoms were solidified those were not organized in a regular, repetitive and compact structure; these materials are known as amorphous alloys or metallic glasses [55].

In 1967, Duwez and Lin reported the first amorphous magnetic alloy with shape like a disc. In 1969 Allied in U.S.A. started the first amorphous alloy tests, which are now part of Metglas ® [29], [75].

Alloys of magnetic importance contain approximately 80 % of particles of Fe, Ni, Co and their combinations; and 20 % of metalloids particles or glass formed elements (C, Al, B, Si and P) mainly B and Si [35]. Additionally, alloys are very strong and hard, but also ductile [52], [60]. Table 4 shows different kinds of amorphous alloys with their characteristics [35], [76].

In general, the magnetic saturation point is in range of 1.5 at 1.9 T, the magnetic anisotropy is very low, and its Curie temperature is around 300°. Its fabrication process conforms small sheets from 5 to 50 μm thin and up to 25.4 cm wide, these are translated in core losses reduction.

These materials do not have thermal stability, as a result its saturation point decreases up 30 %, have high permeability and their frequency operation varies from 0.4 to 250 kHz. Nonetheless, some alloys can operate in a frequency range from 10 kHz to 10 MHz [29], [35], [52].

Amorphous alloys are very thin sheets and relativity narrow, which difficult the design and construction of big transformers. Thus, those are generally used as wound cores [77]. In terms of price and magnetic properties, these alloys are competitive compared to powder cores and Fe-Si alloys [78]. These alloys can be found as high-power inductors, pulse transformers, magnetic amplifiers, low and medium frequency transformers (alloys based on Ni-Fe), specific applications (Co alloys) and inside automotive power trains [35]. As well as iron powder cores, its low material resistivity is a limiting factor for their use at high frequencies. In this material, mainly produced by the wide sheets and their conductivity, the skin effect starts to have repercussions at frequencies above 100 kHz. As a result, its' Eddy current losses do not make them candidates in high-frequency applications.

D. NANOCRYSTALLINE ALLOYS

In 1988 a new steel-based alloy class was introduced, whose magnetic behavior was shown to be superior to materials used until then. This relatively new quasi-tropic material (term applied to laminated materials whose layers are longitudinally oriented in 0°, ±45° and ±90°) consists in an Fe-Si ultrathin grain alloy with an average diameter of 10-15 nm [41], [79]. Time later a few quantities of Cu and Nb were added, being born FeSiBNbCu nanocrystals family, the alloys composed by $Fe_{\sim 74}Si_{13-16}B_{6-9}Nb_3Cu_1$ are known as Finemet and Vitroperm [41]. This unusual combination favored the optimization of ultrathin grain structure and magnetic properties.

TABLE 4. Properties and characteristics of amorphous alloys.

Amorphous alloy	Properties and characteristics
Fe-Si-B	Losses six times smaller than traditional materials. Resistivity of 130 $\mu\Omega$m. Permeability range of 500 to 50000.
Fe-Si	First alloy dedicated to produce distribution transformers. Magnetic flux density up to 1.5 T. Resistivity of 130 $\mu\Omega$m. Permeability range of 5000 to 50000.
Alloys based on Co	Typical alloys are 71% Co-4% Fe-15% B-10% Si and 67% Co-3% Fe-12% B-16% Si-2% Mo. High permeability (60000 to 1000000). Low coercivity. Magnetostriction near to zero. Low Curie temperature. Low magnetic polarization. Magnetic flux density of 1.0 to 1.2 T. Resistivity of 120 $\mu\Omega$m.

Nanocrystals combined the high permeability of amorphous materials and the ferrite's low energy losses, making them promising materials in power electronics area for frequency applications between 10 kHz and 200 kHz. In this kind of material, the grain size determines the relationship between the functional frequency spectrum and the material magnetic properties [41]. The manufacturing process of Nanocrystals alloys is very similar to amorphous alloys, i.e. sheets with wide around of 20 μm are produced [80]. Since their discovery, different alloys have been developed, and in terms of their behavior and magnetic properties, these are divided into four categories: Finemet, Nanoperm ($Fe_{90}Zr_7B_3$), Hitperm (alloys of Fe-Co-M-Cu kind where M can be Zr, Nb or Hf) and Nanomet ($Fe_{85}Si_2B_8P_4Cu_1$) [81], [82], [83], [84].

Nanocrystals materials have magnetic saturation fluxes up to 1.3 T, low coercivity, frequencies above 100 kHz, good thermal stability because they can continually work at temperatures over 150°C, high electrical resistivity ~115 $\mu\Omega$cm and low hysteresis losses, allowing achieve small cores. Nonetheless, these materials are susceptible to air gap losses inducing Eddy currents inside core sheets and causing overheat, which limits the range of high operating frequencies and the possible core size [17].

However, they have a good combination of high permeability ($10000 \leq \mu_r \leq 300000$), high magnetic saturation flux, low losses, good behavior at medium frequency, and good thermal stability; these features allow reducing size cores and components weigh [41], [85]. Some of their applications are medium frequency transformers, sensors, inductors, among others [81]. Nanocrystals are materials with high mechanical hardness and extremely fragile, hindering their manipulation and increasing their price [29].

IV. ENERGY LOSSES

For high power applications, it is desired that the magnetic material of passive components has a good performance in frequency, permeability, coercivity and high-frequency; while Eddy currents and hysteresis losses should be as low as possible. As it can be noticed, material selection is a fundamental step on magnetic component design [2].

For magnetic material selection, the following parameters must be considered [86]:

- Relative permeability.
- Magnetic saturation point.
- Temperature operation range.
- Energy core losses.

In addition, it should be always kept in mind that the material performance also relies on other factors such as: quality control in the manufacturing process, concentration and particle size of the materials used in the alloy, size, volume and shape of magnetic component, losses under different waveforms, frequency operation range, and magnetic material thick, among others [67], [86], [87], [88].

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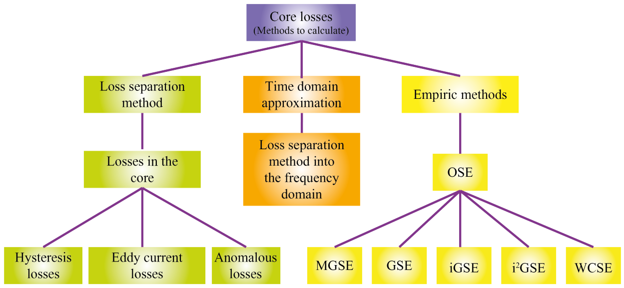

FIGURE 2. Methods to calculate core losses.

For instance, the magnetic dispositive performance is affected by various types of losses. These include losses due to the operating temperature range caused by the decrease in the magnetic saturation point. Additionally, hysteresis losses in the core are low with a high-frequency operation and low ripple [78]. For an in-depth study of core loss factors related to the magnetic material characteristics, the interested reader is referred to [89].

In general terms there are three methods to calculate energy losses: loss separation method (LSM), empiric methods (EM) and time domain approximation (TDA). In [35], [86] and [90] more details can be found, and those are listed in Fig. 2.

The separation of losses and time domain approximation methods are considered like high accuracy theoretical methods; however, they need several values and parameters for their calculation. On the other hand, empiric methods are easy to calculate, because the information required to use them, it is provided by manufacturers and its precision degree is comparable to the theoretical one [90].

Hysteresis losses are defined as the energy loss when the magnetic material ends a complete cycle. These kinds of losses can produce additional problems in the final application, due to the heat that they can generate [33], [89]. Hysteresis losses are defined in terms of the magnetization curve area (of the magnetic material), the frequency applied at the core, and its volume [35].

On the other hand, Eddy currents are produced when a conductor is inside a time variable magnetic field, the flux lines pass through the core, inducing electrical currents and generation heat [29], [89]. In magnetic devices, the Eddy current losses are quadratic in terms of frequency [91]. Anomalous losses occur once the Eddy currents induce very small currents at high frequencies during the material magnetization process. This phenomenon generates a difference between hysteresis static losses (or continuous current hysteresis) and classical Eddy current losses [86].

In accordance with the separation losses method, total core losses are the addition of the losses mentioned above. Please note that hysteresis losses are dominant at low frequencies, while Eddy current losses are dominant at high frequencies [29], [86]. On the other hand, in the approximation time domain approach core losses are calculated by volume unit (it is the separation losses method given into the frequency domain). Finally, core losses in empirical methods are calculated by volume or weight.

The Steinmetz equation proposed in 1892 is the foundation of empirical methods. This equation calculates the magnetic losses inside a material by using only the maximum value of induced magnetic density flux. This equation is known as Original Steinmetz Equation (OSE) and it can only calculate the core losses considering a sinusoidal excitation [86], [92].

Over time, modifications to OSE have been made, developing Modified Steinmetz Equation (MSE) [93], General Steinmetz Equation (GSE) [94], Doubly Improved Steinmetz Equation (Improved-Improved Steinmetz Equation, i^2GSE) [95] and Waveform-Coefficient Steinmetz Equation (WCSE). By using those proposals, it is possible to estimate the magnetic core losses on any arbitrary excitation voltage waveform [35], [86], [96], [97], [98]. The researched losses efforts for different ferromagnetic materials are summarized in Table 5.

By looking Table 4, it can be noticed that many works based on numerical software such as ANSYS, MATLAB or LabVIEW, applied the models listed above for core sizing or modelling [90]. Indeed, this table summarizes some key parameters such as: duty cycle (D), frequency (f) and excitement signal period (T). On the other hand, nanocrystalline and amorphous alloys are the most demanded materials for high-frequency applications [104]. A comparison between those materials and powder cores is reported in [105]. Iron powder cores have specific energy core losses relatively high, likewise low relative permeabilities, thus this magnetic material is not the first option for high-frequency and power applications [86], [106].

V. COMPARISON OF FERROMAGNETIC MATERIALS USED IN PEC

To select the right magnetic material in the design of a PEC application is not an easy task. Generally, a set of parameters from material and final application must be combined to determine the most feasible option. Some design restrictions are listed to follow: maximum power, stability, efficiency, input and output voltage levels, operation frequency, thermal stability, system cooling, portability, energy losses and cost [1], [78].

Table 6 summaries the most relevant parameters [52], [61], [69], [77], [78], [89], [99], [107], [108]. Please note that parameters showed in Table 7 are provided for a specific alloy and its manufacturer provider. Therefore, it is common to find variations of these data in literature, but this can be considered as a good starting point. The electrical, magnetic and mechanical characteristics of a material depend on the preparation and processing of the elements that compose it. Additionally, the material's purity degree, size and shape of its particles influence the general magnetic response [109].

Ferromagnetic materials are frequently used in direct current applications (DC) and alternating current (AC) selecting a material for each of them depends on specific factors

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TABLE 5. Research on ferromagnetic material losses.

Description	Magnetic material	Characteristics	Model	Reference
Transformer core losses	Nanocrystal alloy. (Vitroperm 500F).	High-frequency. Non-sinusoidal waveform signal. f=5 kHz	LSM. TDA. MATLAB data processing.	[86]
	Amorphous alloy. Nanocrystal alloy.	Medium frequency. 50 Hz≤f≤250 Hz	LSM. Finite Element Method (FEM) 2D and 3D. Simplorer.	[99]
	Amorphous alloy (Metglas 2605SA1 AMCC-80). Ferrite (3C94). Nanocrystal alloy (Vitroperm 500F W630).	Medium and high-frequency. f=10,20,50 y 100 kHz 12.5 %≤D≤50 % Rectangular waveform signal.	GSE and iGSE.	[27]
	Amorphous alloy.	Litz-wire. High-frequency.	Theoretical. FEM 2D.	[100]
	Amorphous alloy (AMCC 25). Ferrita (3C94). Nanocrystal alloy (W156-03).	Medium and high-frequency. f=5,10 y 20 kHz D=20,40,60,80 y 100 % Rectangular waveform signal.	GSE, iGSE, MSE. Experimental.	[101]
Waveform losses	Aleación Fe-Si GNO Fe-Co sheets. Nanocrystal alloy. Ferrita Mn-Zn.	Symmetric and asymmetric waveform signals: triangular, rectangular and sinusoidal. f= 1 MHz 0.1≤T≤0.5	Statistical loss theory.	[102]
Iron losses in a synchronous permanent magnet motor	Nanocrystal alloy (Finemet). Fe-Si GNO alloy (35H300).	Iron loss check in 75 %. Two test motors.	Experimental. Finite Element Analysis (FEA) 2D.	[103]
Magnetic, thermal and core losses	Nanocrystal alloy. Iron powder core.	Dynamic and static materials' characterization. Toroidal cores.	LabVIEW characterization. TDA.	[24]

TABLE 6. Characteristics of magnetic materials used in PECs.

Magnetic material	Magnetic flux density $\mathbf{B_S}$[T]	Operating frequency $\mathbf{F_{Op}}$[Hz]	Curie temperature $\mathbf{T_C}$[°C]	Coercivity [Oe]	Number of geometries available	Relative cost
Fe-Si (GO)	2.0	0.05-1 k	740	0.008-0.6	>5	High
Fe-Si (GNO)	2.0	0.05-1 k	740	0.008-0.6	>5	High
Iron powder cores	1.0	100 k-100 M	770	5-9	>10	Very low
MPP	0.3	10 k-1 M	450	0.3	–	High
High Flux powder cores	1.5	10 k-1 M	360	1	–	Medium
Kool Mμ™ powder cores	1.0	1 M	740	0.5	–	Low
Amorphous alloy	0.5-1.6	0.4-250 k	200-380	0.008-0.04	–	High
Nanocrystal alloy	1.3	0.4-150 k	600	0.02-0.04	>5	Very high

[109]. For instance, in DC applications, a desired magnetic flux is generated when a magnetic material is energized through an external field. In contrast, in AC applications, the material is magnetized and demagnetized continuously

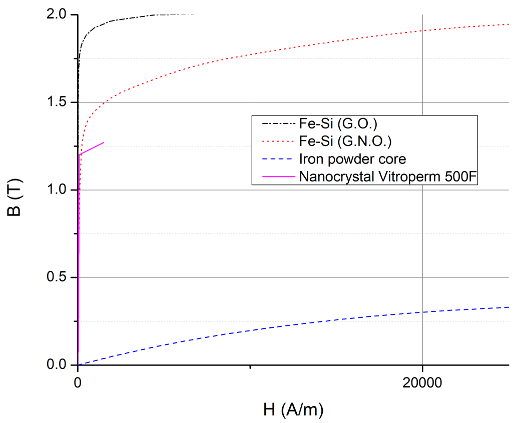

FIGURE 3. BH curve of magnetic materials used in PECs.

following the frequency of the alternating current that feeds the device [49]. The parameters that are generally considered in DC applications are coercivity and magnetic flux density. Whereas AC applications require a high induction and low Eddy current losses therefore, permeability, magnetic flux density, and material losses are key factors [109].

A exhaustive comparison between different ferromagnetic materials is achieved considering factors such as BH curves, energy losses, flux density and operation frequency. Fig. 3, 4 and 5, graphically summarizes those factors for the main ferromagnetic materials [110].

Fig. 5 was separated for each kind of material: rolled alloys 2605-SA1 of METGLAS (amorphous material), M-19 of AKSteel (Fe-Si GNO), M-6 of Allegheny Technologies (Fe-Si GO) and Hiperco50A of Carpenter Technology (Fe-Co). This figure also includes losses per cubic centimeter (cc) for different kind of Magnetics powder cores, energy losses graphs for Finemet 500F and Vitroperm nanocrystals alloys

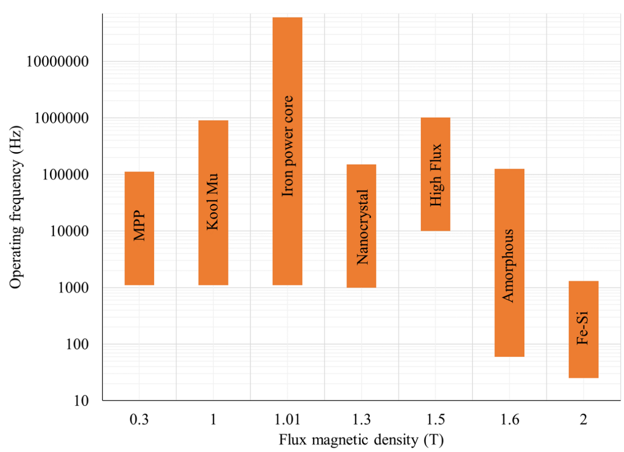

FIGURE 4. Magnetic materials' operating frequency and magnetic flux density.

[110], [111], [112], [113].

Please note that each type of ferromagnetic material has distinctive characteristics that determine its viability and use for certain applications. For instance, Fe-Si alloys are by far the most widely used materials worldwide. It is estimated that their annual production is ten million tons, that is, 80 % of the market. These alloys offer high flux density and low price; recently there have been metallurgical advances focused on the optimization of textures and impurities. However, Eddy's current losses remain as a main limitation in its performance [49].

In contrast, amorphous and nanocrystal alloys are unique due to their exceptionally low coercivity and Eddy current losses. However, they are extremely fragile and lack of high magnetization flux density [114], [115]. Recent advances in these alloys improved one or several of the following topics: manufacturing processes, thermal stability, isotropic structure and magnetization flux density [49]. The interested reader on nanocrystal alloy can find more details in [116] and [117].

On the other hand, powder cores are materials that have versatile magnetic characteristics and those are excellent candidates for replacing materials such as ferrite and steel sheets in electric machines applications [109]. The most recent advances in this type of material are presented in [118], [119], [120], [121]. The powder cores can be found in alternators, transformers, generators, low-frequency filters, induced field coils, electrical components of the aircraft engine, and in DC engines, among others [109]. A current field of research is the study of new powder material alloys. That is, the study and feasibility of mixing ferromagnetic materials (nanocrystal, amorphous, soft ferrite and Fe-Si alloys) with powder cores to obtain alloys with better magnetic properties, such that the resulting combination overcomes their individual limitations.

Currently, the use of ferromagnetic materials has a huge impact on electronics for energy conversion, distribution, generation, and storage [122]. Additionally, it can be found on automotive industry (EVs, HEVs) and solid-state transformers (SST) [123], [124], [125]. Table **??** summaries references related with the design of inductors and transformers for high-frequency PECs, machines design, and electrical devices.

Another field of research on ferromagnetic materials is the design of PECs with different input power supplies, in which an amorphous or nanocrystalline core material is shared to achieve better performance. Within this scope, the conditions of the power sources (amplitude, frequency, and phase) must be considered [129], [133].

A comparison between different medium-frequency transformer cores is showed in Fig. 6 [99], [129], [134], [135], [136], [137]. By looking this figure, it can be noticed that Nanocrystal alloys can be used in applications of high operating frequency and power. For the interested reader, the design of high-power transformers using this material is reported [108], [115], [138], [139], [140], [141].

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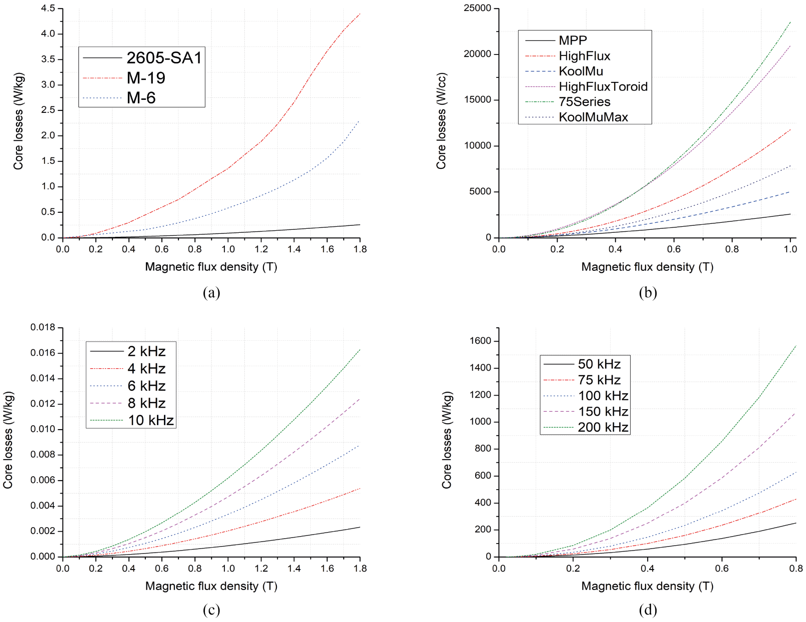

FIGURE 5. Energy losses' curves to materials: (a) laminated, (b) powder cores, (c) Finemet® 500F and (d) Vitroperm®.

TABLE 7. Relation between magnetic materials and applications.

Aplication	Materials type	Reference	Remarks
Properties comparison (physical, magnetic or microstructure)	Iron powder core and nanocrystal alloy.	[24]	Nanocrystal alloys have lower losses than other materials, but their cost is higher too.
	Powder core conformed by amorphous and nanocrystal alloys.	[126]	Relation behavior-cost is attractive in iron powder cores. Research field open to new powder core alloys to improve their magnetic properties.
Transformer design for DC/DC converters	Nanocrystal alloy.	[127] [108]	Powers of 0.8 kW at 5 kHz and 100 kW to 200 kW at 20-30 kHz. Stable performance and compact designs in volume and weight, using nanocrystalline alloy.
	Mn-Zn nanocrystal alloy.	[128]	Research field open to new nanocrystalline alloys.
Renewable energy systems connected to the grid	Amorphous alloy.	[129] [130]	Utilized SiC and GaN with amorphous material, multilevel converters and algorithms to connect micrograds to the grid.
Medium frequency transformers design	Amorphous alloy.	[99]	Inverter monophasic simulation of three levels to verify the feasibility of using amorphous material.
High-density flux with two inductors coupled	Nanocrystal alloy.	[131]	Nanocrystal alloy with low permeability that allow reach output currents at 30 A.
High power magnetic components design	Nanocrystal powder core.	[22]	This alloy has a stableμ_r, low energy losses and the possibility to improve a great number of magnetic parameters.
Electrical machines and devices	SMC.	[132]	Developing research field principally in themes as material selection and factors that influence the electrical machines and devices manufacture process to minimize their dimensions, make efficient their motors and expand the reach in electrical applications.
	SMC, CoFe, NiFe and amorphous alloy.	[67]	

VI. DISCUSSION

The applications field of power electronics in recent years has taken a great relevance by the inclusion of alternative energy sources. Some of its most significant areas of application is in the generation, transmission, and storage of energy. New emerging technologies in this area demand highly portable circuits, low energy consumption and high-power output without a price increment. Up to date, fast switch electronic

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devices based on SiC and GaN seems to be a solution to the current demands. Additionally, it is expected that in near future those will reach lower energy losses, increased voltage and current ratings, as well as higher operating temperature.

However, the need for the use of high-performance magnetic devices in power electronic converters remains. In an electronic circuit the magnetic components are the biggest and heaviest elements. The challenge to develop, design and validate magnetic components like inductors and transformers to operate in high-frequency, requires developing adequate core materials with the purpose of new alloys, geometries and sizes. For years ferrite has been, the material used regularly, because it is a low-price material with high accessibility, and high-frequency range. However, it is a heavy material with low magnetic flux density and high energy losses, which limits its use on high power inductors and transformers.

Ferromagnetic materials are an alternative to ferrite. These can quickly change their magnetic polarization by applying a small field, also these can reach power level comparable to, and inclusive bigger than, ferrite with a lower size and weight. These magnetic materials are principally composed by Fe, which is one of more abundance Earth elements. This feature makes them profitable materials. The principal ferromagnetic materials used in PECs are based on Fe-Si GO and GNO, amorphous alloys, powder cores, and nanocrystal materials. Each one of them has specific magnetic and physic features that are fundamental to determine their feasibility. Nonetheless, in many applications the magnetic flux density, frequency operation range, temperature, energy losses, and price are the principal characteristics to be considered.

Nanocrystal, amorphous and Fe-Si alloys are the materials more used in power electronics and have been widely studied. From them, nanocrystal materials have lower energy losses and high performance in PEC applications. According to the state of the art, nanocrystal alloys used on the construction of medium and high-power transformers show a volume and weight reduction of almost 50 % compared to ferrite. That is why alloys are currently in great demand, despite their high cost. Magnetic features of amorphous and Fe-Si materials are like nanocrystal characteristics at accessible prices. Most of the applications of these materials are in the design of medium and high-power transformers and electrical machines. Amorphous materials and nanocrystalline alloys have low energy losses but they are highly fragile, which limits the design of magnetic components.

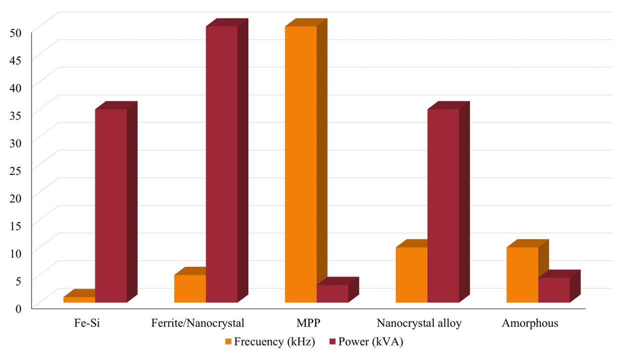

FIGURE 6. Magnetic materials comparative used in transformers.

On the other hand, Fe-Si alloys lead the electronics market for their high magnetic flux density. However, they exhibit too many losses and, their manufacturing process is actually focused on improve their performance. Based on the reviewed material, in the authors' opinion, powder core seems to be the most versatile soft material. Therefore, nowadays, powder core seems to be a serious candidate to be used as replacement of rolled alloys in the design of electric machines. Another open research area is the fabrication of hybrid alloys based on the combination of different ferromagnetic and ferromagnetic materials. This last, aims to improve their performance and overcome their individual limitations by varying particle size, insulator, shape, and size of the magnetic device.

VII. CONCLUSIONS

This paper summary the ferromagnetic materials currently used as core in magnetic devices. To this end, an extensive review of the state of the art was carried out, adding quantitative and qualitative data to highlight advantages and limitations of each of these materials at different working frequencies. Indeed, the reader can compare ferromagnetic materials presented quickly and effectively using the BH and losses curves. These curves provide essential information, such as permeability and saturation points.

Energy losses are the main restriction to use a magnetic material due to its increment with frequency. Indeed, some materials, within a frequency range, have more losses than others. Based on the state of the art and the authors' knowledge, there is no a single work that reports a full characterization of energy losses in a ferromagnetic component, which is an open niche for new proposals.

For medium and high-frequency applications nanocrystal materials are preferred despite their high price because they have low energy losses and excellent performance. Amorphous and Fe-Si alloys are more affordable than nanocrystalline materials and those are an attractive option in electrical machines. Amorphous alloys have low energy losses and low magnetic flux density too, instead, Fe-Si materials have high energy-losses and high magnetic density flux.

On the other hand, powder cores are materials with a wide range of prices. Their manufacturing process allows them a variety of shapes and specific magnetic properties. This material does not need an air gap, and has a variable inductance according to the applied field and its frequency operation range. These characteristics have made it a serious substitute for laminated materials in the design of electrical machines.

Powder cores are materials with a wide range of prices. Their manufacture process allows them a variety of shapes and specific magnetic properties. In magnetic components design, their variable inductance according to the applied field, their frequency operation range, and the fact that an air gap insert is not needed have made them in materials of increasing interest, mainly in electrical machines design as a substitute for rolled materials.

This work provides the reader with an overview of the magnetic materials currently used in magnetic devices, comparing their principal characteristics. This last to select the most suitable material for an application, without the need for the reader to perform a thorough search in the literature about its characteristics, advantages, and disadvantages among them.

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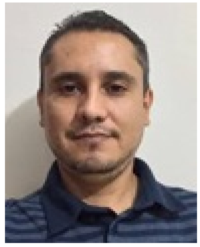

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