Review

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Posted Date: 6 May 2023

doi: 10.20944/preprints202305.0419.v1

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Review

A Survey on Recent Advancements in Magnetic Integration for Power Electronics—Roadmap toward High Density Integration

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Abstract: Lately Silicon Carbide (SiC) and Galium Nitride (GaN) based high frequency power conversion has gained immense popularity which stems from relatively low switching energy, robustness to high temperature operation, wide-band gap and superior thermal limits. While this aspect inherently results in a high-density power stage design, the design of adjoining passive components, particularly magnetics, needs careful attention. This is especially true if the compatibility of core and winding options and their performance is limited with the use of higher switching frequency. In this regard, this paper presents a brief review of existent research conducted in materials, optimization and integration of magnetics for single and three phase applications, ranging from filters, resonant inductors to isolation transformers. Design knobs pertaining to medium voltage (MV) applications, low-voltage (LV) applications, e-mobility sector such as more electric aircrafts (MEAs) and electric vehicles (EVs) are discussed. Guidelines for magnetics design are summarized for each application with a projected roadmap on future trend for magnetics.

Keywords: ferrites; interleaving; indirectly coupled inductors; nano-crystalline; litz wire; magnetic integration; Matrix Integrated Magnetics (MIMs); Monolithic Magnetics (MM); Partial-discharge (PD); shielding

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1. Introduction

Passive components, specifically magnetics consume more than 30% of the power converter volume. Their utility ranges from filtering action, isolation and power flow and line inductors for power factor correction (PFC). Therefore, it is not surprising to see a relatively higher volume contribution.

To address this, a lot of interest has been dedicated towards the optimization of magnetics. Closed form analytical core and winding loss and volume computations allows for faster design process. Form factor manipulation through geometry of cores and winding parameter tuning can be used to further optimize any magnetics design. Knowledge of core material properties, available shapes and vendor limitations is therefore a pre-requisite during any such design process.

Table 1 provides a summary of the available core materials and their typical application areas and frequency range of operation. While Silicon steel has higher saturation flux density, it is not recommended for high switching frequency applications due to poor core loss characteristics. On the other hand, ferrites offer superior core loss curves but poor peak saturation flux. Nanocrystalline cores offers a good balance, but their properties are subjected to severe changes when molded to customized (no-standard) shapes. Powder cores tend to provide higher winding loss due to low permeance. Gapped cores are popular in cases where the eddy current losses due to fringing fields are dominant.

Table 1. Core material properties and application areas.

Core Type	Properties (B_{sat}, μ_r at 10 kHz)	Operating Frequency Range	Application Domain
Ferrites	0.3 T, < 3000	100 kHz – 1 MHz	Transformers, CM-EMI filters (gapped)
Nanocrystalline	1.2 T, < 20000	10 kHz – 10 MHz	CM-EMI Filters
Silicon Steel	1.7 T, 500-1500	< 1 kHz	Grid-side line inductor for PFCs
Amorphous and Gapped Cores	1.5 T, 500-3000	60 Hz -	Line inductor for PFCs Transformers
Powder Cores	1.1 T, < 500	60 Hz – 10 MHz	Line inductors

Besides component level optimization, topological modifications in magnetic circuits are critical for low volt-second (i.e., core volume) and winding loss reduction. Magnetic integration is gaining attention in this regard. The benefits of integration are manifold: Scalability, manufacturability, enhanced impedance, flux-cancellation and loss reduction.

The paper is organized as follows. First, the recent developments in magnetic integration in automotive, server and telecom industries is highlighted. Second, the developments in magnetic integration concepts for harmonics and electromagnetic interference (EMI) filtering techniques for grid-tied applications (LV and MV) is discussed. Finally, key remarks on prospects and typical design examples are shown in detail.

2. Magnetic Integration for e-mobility and telecom/microprocessor applications

Lately transportation sector has picked up significant attention due to the use of WBG power conversion for on-board chargers (OBCs), either single or two stage, auxiliary power modules (APMs) with wide input voltage range and high step-down ratios and traction inverters for propulsion. The magnetics required for these applications are categorized.

3.1. DC-DC converters

3.1.1. Telecom industry: The 48V bus architecture is common standard for the telecom sector, but a transition towards higher efficiency based 12V systems is underway. In this case the LLC converter is heavily used. The matrix transformer concept is adopted. Each elemental transformer is connected with series input and parallel output windings to reduce severe conduction losses and thermals stress on the secondary side [1–5]. To suppress core loss, magnetic integration of matrix transformer is adopted [6]. The idea is simply to combine multiple modular matrix transformers and arrange them into one consolidated structure, such as a common UI core can be achieved using two UI cores through winding reconfiguration on the two limbs as shown in **Figure 1** per [7]. Interleaved primary and secondary windings are adopted to minimize the losses due to proximity effects while shielding layers are embedded to block common-mode (CM) currents between primary and secondary sides. Other aspects such as termination losses, SR conduction losses are discussed in detail. In all the above cases, a leakage inductance is introduced in the primary windings through asymmetrical winding structure [6]. Alternate ways include adding a magnetic shunt as discussed in [8,9].

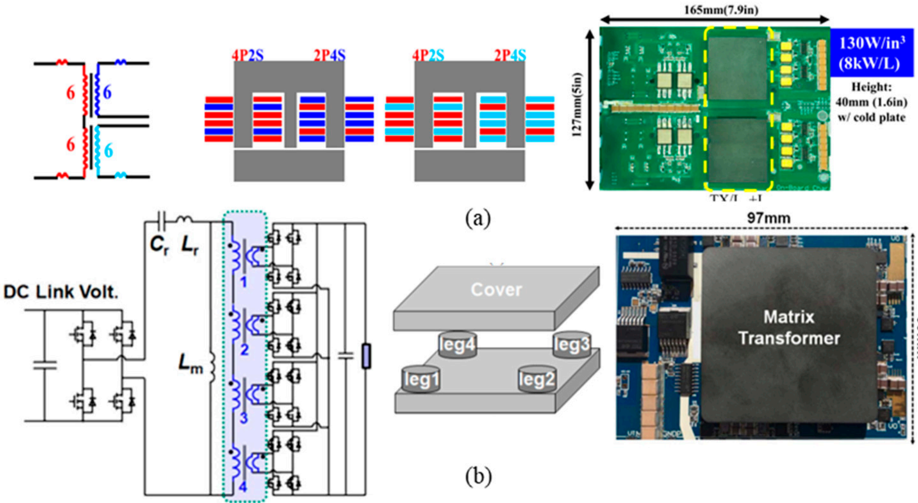

Figure 1. (a) split core MIM for CLLC converter utilizing asymmetric winding distribution for leakage inductance on primary and secondary sides [6] (b) Two integrated MIMs to realize a matrix transformer (shown a 500 kHz 3 kW 48 V-output LLC converter prototype) [7].

In late 2000s, voltage regulator modules (VRMs) to drive microprocessors were investigated to meet the high dynamic transient operation [10]. A multi-phase buck converter with integrated coupled inductors (CI) was proposed to achieve this functionality shown in **Figure 2**. By adding coupling between channels, a high steady state inductance and low transient inductance can be achieved [11–14]. Consequently, the structure was adopted in matrix transformers [15–19]. A dedicated controller was eventually developed to integrate the control architecture within the system. To minimize winding loss for the CI in [11–14] a twisted core concept was introduced in [20], shown in **Figure 2** wherein the core is wrapped around the winding instead of the other way around. To eliminate driver losses, a self-driven, driverless VRM was developed through magnetic coupling in [21]. An interesting point here is the light load efficiency, at discontinuous conduction mode (DCM) which can be improved using saturable cores. To minimize losses at light load, a larger inductance is required while at heavy load a small inductance will suffice to meet transient requirements [22]. This necessitated the use of non-linear inductor integration in the integrated magnetics using saturable core concepts.

The low-profile magnetic concepts were extended to vertical integration. As an example, the 3D integrated solution using low-profile inductor with lateral flux pattern (LTCC material), which can have large inductance density even with very thin core thickness, was explored in [23], also shown in **Figure 2**.

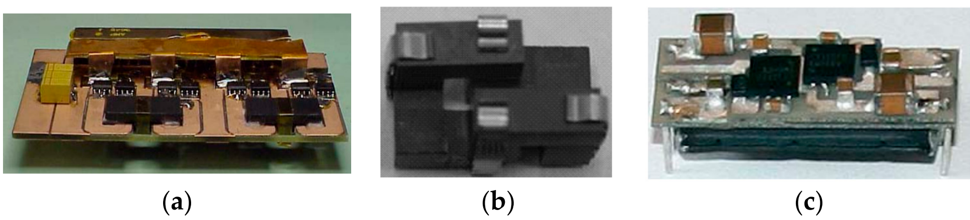

Figure 2. (a) CPES QSW VRM [10] (b) Twisted core coupled inductor implementation [15] and (c) Low profile buck converter using LTCC substrate [23].

3.1.2. Auxiliary Power Module (APMs):

The power requirement for auxiliary systems increases with the increasing use of electronics, multi-media, controls and diagnostics requirements for modern EVs. Typically, full bridge converters with isolated secondaries are employed. On the secondary side, symmetrical output current modes are generated through center tapped or current doubler rectifiers. Herein the elemental transformer concept was introduced in [1,24] where two EI cores or EE cores, shown in **Figure 3,** are stacked and the air-gap and winding arrangement is such that either DC flux is cancelled or amplified at the center leg depending on the loss and coupling requirement. The concept is extended to multi-phase interleaved current doubler [25] through matrix transformers where the center limb is further coupled with adjacent parallel branches to introduce inverse coupled inductor configuration which leads to ripple cancellation [26,27]. To scale to further higher currents, a current tripler structure was proposed in [28] with reduced root mean square (RMS) current stress on secondary side synchronous rectifiers (SRs). Resonant converters are a viable solution for APMs, typically from 400V to 12V conversion, LLC converters are adopted [29–31]. Crucially, integration of SRs on LV side is critical for low termination loss [31] along with the use of embedded shielding layers for low CM noise propagation is critical [32].

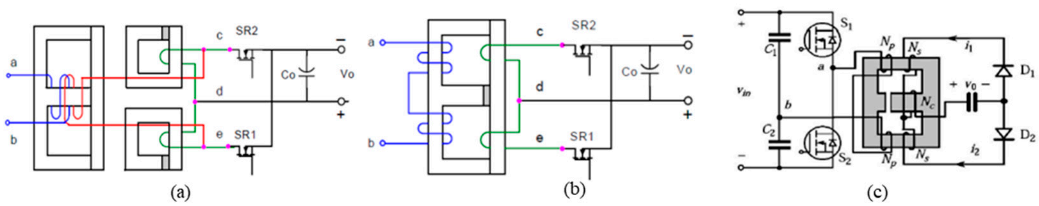

Figure 3. Elemental transformer configurations for current doubler rectifier, (a) discrete solution, (b,c) Integrated solutions [33,34].

3.1.3. On board chargers (OBCs):

Vehicular OBCs must meet the wide input (250-800 V) range, high efficiency and low cost/scalability per CHAdeMO and combined charging systems (CCS) standards [35,36]. This necessitates the use of scalable transformers (galvanic isolation), typically input series output parallel to cater to the wide voltage range. The matrix transformers for single and three-phase LLC(s) [37] and CLLC(s) [38] based resonant converters has been reported in this regard.

In some cases, the APM is integrated with chargers (termed as a three-port solution) for which magnetic and topological integration is required. An example of this is the three-port transformer per [39]. Another example is a wireless integrated charger is presented in [40], where the magnetic coupler is integrated with the high frequency transformer of the isolated DC-DC stage of an OBC. An important consideration is the avoidance of leakage inductance to avoid cross-coupling between three ports (during charge or EV running modes). This is also important for bi-directional operation. A symmetrical structure known as the LCL-T was investigated in [41] to meet this requirement.

3.2. Three phase AC-DC and DC-AC converters for e-mobility applications

3.2.1. Traction inverters:

With increasing torque and power demands, interesting solutions are proposed with adjoining magnetics. The three-phase interleaved converter solution is recommended in state-of-the-art systems [42–44] for redundancy and low output ripple. This necessitates the use of coupled inductors to block inter-channel circulation [45,46]. Typically, circulating current controllers for low frequency are adopted with three phase direct interleaving [47].

3.2.2. Off-board chargers:

Just as in multi-phase VRMs, the inter-channel coupled inductor concepts for three phases are useful in this regard. Novel strategies for three-phase inter-channel coupling were explored in grid tied converters, typically PFCs. The concept of indirect coupling [48–51] which leads to fault tolerance [52] was proposed. Direct coupling using monolithic coupler was also explored in [46,53,54]. Such forms of coupling create avenues to integrate coupled inductors with line harmonic filters using block I cores and star-delta composite Y cores. Gohil et.al. presented a high-density integration for 4 interleaved channels using whiffletree configuration in [55]. Another idea, i.e., localization of circulation using trap inductors was demonstrated in [56,57]. A brief evaluation of such interconnected systems was conducted in [58].

Fast charging is another sector where careful attention to charging profiles is required when it comes to magnetics design. Magnetics for solid state transformer technology has been demonstrated in existing literature. Dual Active Bridge (DAB) based fast charger technology and LLC based technology was demonstrated and compared in [59,60]. The key differentiator in terms of magnetics design consideration is that the isolation transformer in DAB is un-gapped and for LLC is gapped depending on magnetizing inductance and energy storage requirements [61].

Dual inverter charger using open-ended winding PMSM [62] was introduced. A similar concept for propulsion was shown in [63]. In these cases, motor design calls for integration to utilize inductive coupling to cancel circulation of high frequency currents which would enhance device thermal stress.

3. Magnetic Integration for filtering applications

3.1. Single phase systems:

Single phase systems suffer from EMI noise produced by the downstream electronics which requires the use of EMI filters. Magentic integration techniques have been proposed to shrink the filter size. For instance, integration with EE and EIE-type cores was proposed in [64] with CM and DM chokes integrated into one unit. Similarly an integrated CM indcutor (ICMI) was proposed using four amorphous type C cores in [65] and using two E cores with air gap on the center limb in [66,67]. An integrated CM+DM core was proposed using UU type core which was also demonstrated in [68], where the additional beneift of using flexible multi-layer foil (FMLF) was seen in the form of additional DM capacitance between layers. Therefore the structure allowed not only magnetic but also capacitive integration to realize the DM+CM filter. A similar idea was reported in [69]. An extesion of integrated DM+CM structures in planar PCBs is found in [70,71]. A simpler and relatively cost effective approach to integrating DM inductance (block-I core) with standard torroidal chokes was demonstrated in [72].

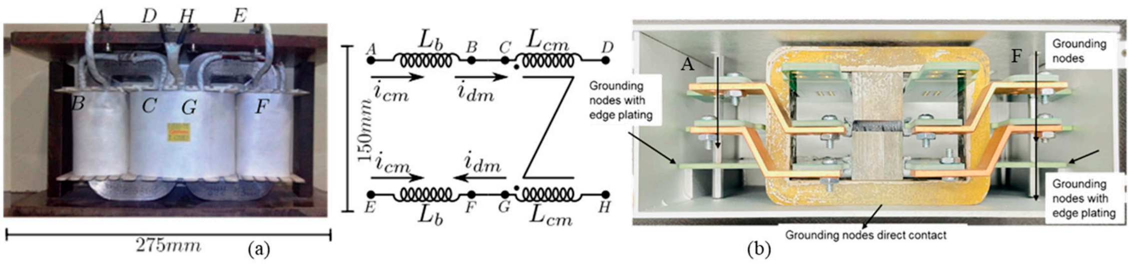

Figure 4. Realization of integrated DM+CM core (a) 2xUU cores [65] and (b) using C + block I core [72].

3.2. Three phase systems:

EMI filters for three-phase systems occupy approximately 30% of the total system volume. Efforts to shrink filter volume through integration are adopted as such. Magnetic integration of CM AC output filter through optimized damping schemes was reported in [73–76] along with reduced CMV schemes for improved bandwidth [77,78]. The DC side filter also requries special attention and integrated DM/CM cores were proposed in [75,79,80]. Critically, designs for high altitude aircraft propulsion require additional control objectives, such as limiting the peak E-field in air. An example of E-field control for an integrated DM-CM filter assembly, rated at 300A was demonstrated in [81]. Other solutions include single turn EMI filters for aerospace and MV applications [82,83] with emphasis on insulation constrained design.

State of the art line harmonic filters have been proposed for LLCL[84] and LCL[85–87] filter where the grid and inverter side inductors are coupled in one common core. The coupling coefficient and winding pattern is tweaked to get the desired equivalent circuit. To solve the attenuation loss

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due to a virtual inductor introduction in the shunt path, an active decoupling winding was integrated as shown in [88], per **Figure 5**. Similarly, an LTCL filter (i.e. a trap LCL filter) was deviced through integration of two E cores [89], resulting in a structure with a high roll off rate. In [90], a clever approach to integrate the LCL filter with the isolation transformer was proposed using leakage inductance of transformer secondary winding to realize grid side LCL filter inductor. This was achieved using the magnetic shunt technique. Ref. [91] shows another example of integrating delta-star transformers to realize multi-level output at the grid side (Point of Common Coupling) PCC through the use of just two-level converters.

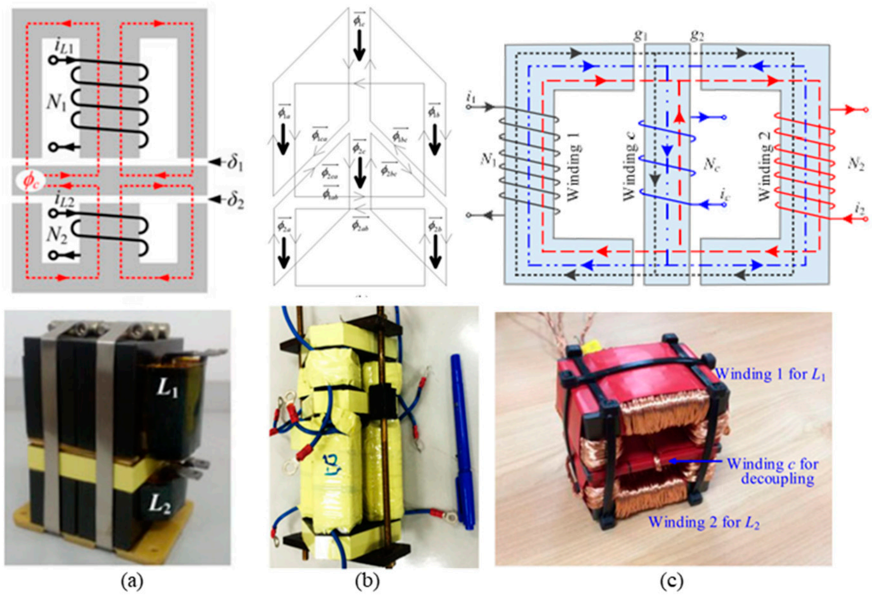

Figure 5. Integrated LCL filter variants (a) Integrated grid side and converter side inductor using 2xE cores and 1xI core [87], (b) similar integration using delta-yoke composite core [86] and (c) Active decoupling of improve attenuation of grid side and converter side coupling [88].

Besides integrated structures for grid side harmonic filter, Xuning and Ohn proposed combinations of AC harmonic filters with the coupled inductor, through the use of amorphous based C cores, either through phase sequence analysis or asymmetric interleaving [92–94]. Other competitive magnetic integration schemes were proposed in [95] to cater to circulation and EMI requirement for three phase systems. **Figure 6** shows examples of magnetically integrated structures for parallel / interleaved converters which address modularity and scalability to higher power rating.

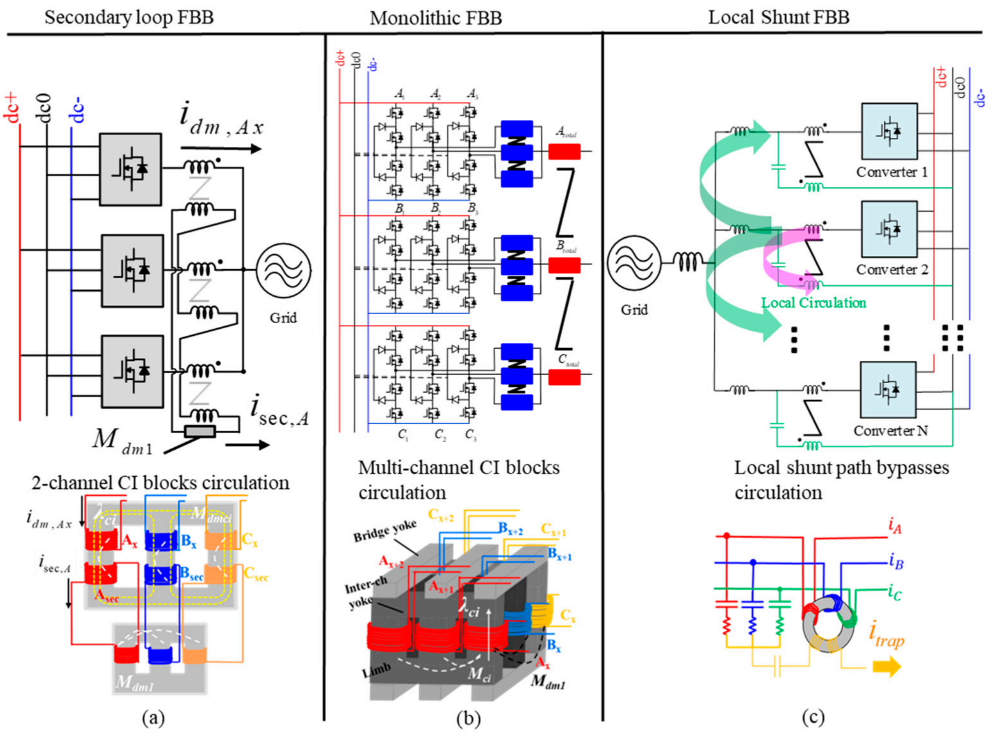

Figure 6. Integration schemes for CI (a) In-direct integration using secondary loop [47] (b) direct integration using monolithic structure [46] and localization using 4-winding CMC [55].

3.3. Integration to desensitize parasitic effects:

An interesting aspect of integration is parasitic control of EMI filters to handle the high frequency EMI noise content effectively. As an example, integration of shielding techniques was proposed in [96,97]. While parasitic capacitance cancellation using embedded layers was discussed in [98]. Other ways to mitigate parasitic effects are discussed in [99] using winding techniques, such as split wound scheme. Appropriate winding and core combinations for flyback transformers was proposed in [100,101]. Such design rules were extended to three phase systems in [102]. Integration to contain radiated emissions was discussed at length in [103–105]. Recommendations to arrange multiple inductors spatially to minimize near field coupling influence on EMI performance was discussed. The most commonly used technique is shielding between primary and secondary isolation layers of the transformer [32] which is achevied using embedded layers in the planar configuration. Typical example is shown in **Figure 7.**

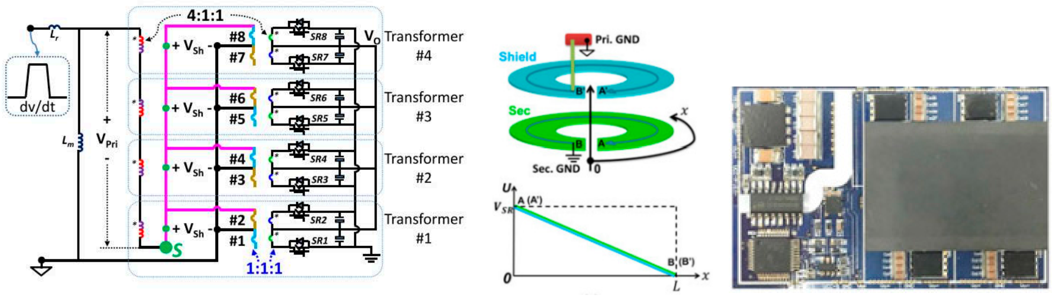

Figure 7. Example of shielding techniques for EMC mitigation in a 4:1:1 input-series output-parallel matrix transformer. Tie the shield to the primary bus results in negligible dv/dt between the primary and secondary side windings, therefore low CM currents [32].

4. Technology Roadmap

Both industrial and automotive grade integration requires novel techniques to integrate core shapes and materials. For micro-converter applications such as VRMs the survey is performed in Table 2. A clear picture on levels of integration from board to package level was provided in [106].

Table 2. Novel and Existent material characteristics and applications [106].

Material	Frequency Range
CoZrNb Amorphous	100 kHz to 5 MHz
NiZn Ferrite	1 MHz to 30 MHz
CoZrO Granular Film	5 MHz to 100 MHz
CoNiFe thin film alloy	
Iron Powder	10 kHz to 1 MHz

In terms of material, an inductor suitable for high-voltage and high-current is the next big thing. Mainly due to the adaptation of EVs, industrial automation and renewable (solar + wind) technologies with the mass inductor demands. A proposal from CleanMag® seems promising in this regard [107]. Immunity to soft saturation due to DC bias can be another promising feature for future materials. Most power converter operation is asymmetric under dynamic transients which can saturate cores due to drop in permeance with DC bias. METCOM and FINEMET provide options with relatively stable inductance drop with DC superposition characteristics [108]. Metal inductors are gaining more attention in this context, although they provide lower permeability, they immunity to DC bias is exceptional [109]. Murata's high current metal alloy power inductors [110] provides almost 80% reduction in footprint area. Additionally, the molded structure suppresses the wire vibrations. A similar concept is utilized in [111] where a method to fabricate an inductor in which the core is realized by molding a magnetic mixture over the circuit board is presented.

A significant emphasis is given to planar technologies such as flexible foil PCB (FPCB) to create windings without increasing the remaining number of rigid layers. To handle higher current, thicker stamped copper turns are typically used [112]. Other technologies such as hybrid PCB and stamped copper foil and pure copper foil windings [113] are gaining attention due to better thermal handling capability. Although, significant work has been demonstrated in low power DC-DC converter applications, high power systems see a huge bottleneck in terms of PCB cost. Heavy copper PCBs are preferred for multi kW high current based converters for better degree of control over parasitics, thermal and peak electric field distribution. But due to the expensive heavy copper technology, industry wide acceptance is still in question.

5. Conclusion

This paper presents a comprehensive review of advancements in magnetically integrated structures catered to a wide range of applications. Based on the recent trend and developments in the field of high frequency power conversion using wide band gap devices, inductor size can be minimized which paves the way for integration possibilities. The tradeoffs, however, need to be carefully investigated prior to any form of integration. It is projected that modular and scalable magnetic integration is possibly going to be of immense importance in the next decade to drive manufacturing and minimize product cost. At the same time, processing and fabrication technologies are expected to adopt these novel integration practices to comply with limited space and high density requirements.

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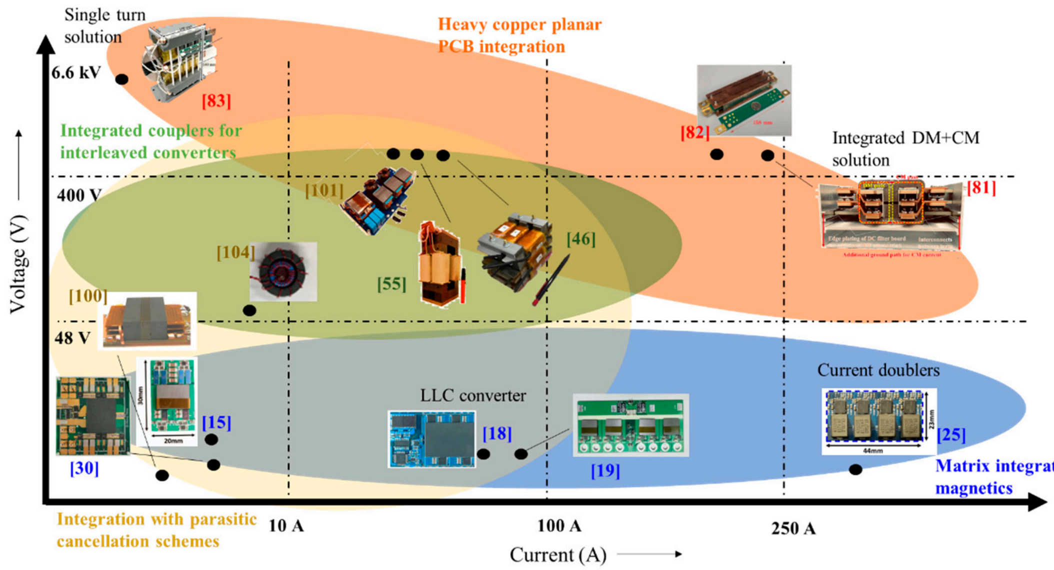

Figure 8. Map of representative integration solutions based on power rating.

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