Abstract—The structural and functional integration of passive components, power electronic converters, heat sinks and mechanical sub-systems is required to make an efficient and power dense electric motor-drive system which is essential for traction, aerospace and marine applications. The Integrated Motor Drives (IMD) has been at focal point with growing interest in power electronics research industry over past few years. Passive components such as filter inductors and capacitors entail significant amount of space in aerospace and automotive drive systems and have added penalties of high losses and weight. The integration of passive components in such systems offer many benefits such as power dense design, reduction in cost, mass, size and eases the manufacturing processes.

This paper continues with reviewing available capacitor technologies and their thermal capabilities, selection and sizing of capacitors for drives, a brief overview of filter inductor integration already designed and presents some potential future approaches on integrating the output filter capacitor in the same PMSM drive.

Keywords—Integrated Motor Drive (IMD), PMSM, Filters, Inductor, Capacitor.

I. INTRODUCTION

Passive assemblies (inductors, capacitors) impose an obstruction to meet an ever increasing high power density demands in power electronic systems for electric drives employed in More Electric Aircrafts (MEA), Electric Vehicles (EV), Hybrid Electric Vehicles (HEVs), Marine Applications etc. which require close physical and functional integration of various electrical and mechanical sub-systems for reduced weight, size and costs targets.

The assemblage of passives for power electronic systems is voluminous due to sizeable and disjunctive modules coming from different manufacturers with distinct technologies and large number of miscellaneous packaging parts, thus lending them geometrically un-optimized for high power density integration.

Passive components for the filters usually occupy tremendous space of the whole drive system employed in electric transportation applications. This is because they are separately conceived and devised after other drive components such as converters, gate driver circuits, control circuits and machine itself have been developed leading to distinct sub-systems which calls for novel integration approaches [1, 2, 3].

II. LITERATURE REVIEW

A. Capacitors for Drive Applications

In VSI drives, capacitor (both for dc-link and output filter) presents to be one of the expensive and massive passive components. In power converters, its main function is to stabilize the dc bus voltage and to counterbalance the load difference between the input source and the output. They do so by absorbing the large ripple currents and restraining the voltage transients which occur due to switching action of the converter and thus providing a low impedance path for the switching harmonics. They can also be used to smooth battery current if used for traction drives.

However, for large scale application of IMDs, one of the existing challenges among others is the designing of capacitors under high temperature and high frequency operations for use in power electronics in DC-link filters and AC filters.

The main capacitor types available requiring research attention in Integrated Drives include: Ceramic Capacitors, Multi-layer ceramic capacitors, Electrolytic capacitors, Film Capacitors. The ideal requirements for Integration in a Drive System expects capacitors to possess high capacitance, compactness, operation at high temperatures, high voltage and/or current ratings, high energy densities and low cost to meet the challenges of increased power densities, thermal management and manufacturing for economically Integrated Drive systems. It is merely impossible to expect a passive component to have all such attributes, hence a trade-off has to be established between the applications and attributes. In the previous research undertaken, some novel approaches have been worked out to integrate the output filter inductor in a Permanent Magnet Synchronous Motor (PMSM) while leaving the filter capacitor and damping resistor outside the machine. This section highlights the properties, current trends and
advancements in aforementioned capacitor types used for filters in terms of thermal capabilities, operation, ratings and their pros and cons with respect to drive applications.

1) Ceramic Capacitors

Ceramic Capacitors are the most widely used components in modern electronics which can be used in high voltage and high temperature applications. The plenty of ceramic compositions and their manifold dielectric behavior have made them pervasive in many extreme environments. Custom-made ceramic capacitors also exist to cover potential gaps in other capacitor technologies such as high voltage capacitors with ratings from 50-100 kV [4]. High temperature ceramic capacitors that can bear temperatures up to 250°C can be found. The disadvantages are low energy density, high costs and brittle nature, therefore the catastrophic failures requires extra caution in circuit design. Shocks and vibrations are usually notable in traction drives which raise reliability concerns over their mechanical firmness [1].

Ceralink™ is now developing an advanced ceramic capacitor technology which can operate both as dc-link and snubber capacitor as a compact element by locating the capacitor in close proximity with the semiconductor switch in the converter design. It is made with anti-ferroelectric material that can offer high capacitance at operating voltages, low losses at high temperatures and low parasitic values of Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL) [5]. It has magnificent lifetime at temperatures above 125 °C due to high insulation level where hardly other capacitors can be used [6]. This technology can save the space in converter and increase power density. Some commercially available wide dielectrics for ceramic capacitors fabrication along with their properties are listed in Table I.

2) Multi-layer Ceramic Capacitors (MLCCs)

MLCCs are distinguished for their high capacitance and compactness [7], high energy density, very high ac current ratings, high temperature operation up to 200°C [1], and is the dominant form of ceramic capacitors. They feature small size, low cost, large capacitance per unit volume and is very little affected by environmental factors [8]. MLCCs are now acquiring wide spread attention in aerospace electronic equipment and automotive applications.

<table>
<thead>
<tr>
<th>Dielectrics</th>
<th>Dielectric Constant</th>
<th>Dissipation Factor</th>
<th>Brand/Types</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I</td>
<td>Low (5 to few hundreds)</td>
<td>Low (&lt;0.01)</td>
<td>Porcelain, Steatite (talc), Mica and other silicates. Simple oxides, e.g., TiO₂ (rutile) and perovskite titanates, e.g., CaTiO₃ and modified (Ca,Sr)</td>
<td>Linear temperature coefficient of permittivity from zero to several thousand ppm/°C</td>
</tr>
<tr>
<td>Class II</td>
<td>High (1000 to &gt; 200000)</td>
<td>0.01-0.03</td>
<td>Barium Titanate (BaTiO₃), Relaxors [Pb(Mg₁/₃Nb₂/₃)O₃ and large number of its compositions</td>
<td>Moderate to high temperature dependence of dielectric constant</td>
</tr>
</tbody>
</table>

The ongoing trend of increasing the number of dielectric layers while reducing the dielectric layer thickness in MLCCs to increase volumetric efficiency is becoming a major concern for Class 2 dielectrics (BaTiO₃) which are used in MLCCs manufacturing. The thinner dielectric layers in the submicron range could be problematic for next generation MLCCs as the dielectric properties of BaTiO₃ are highly dependent on their grain size [9]. Secondly, the electric field is becoming sufficiently high with decreasing dielectric layer thickness thus making it a concern of voltage dependence on dielectric properties [10].

MLCCs are also seen replacing tantalum electrolytic capacitors in order to resolve its transient failure problems which are becoming prominent with its increased use [8]. The reasons is that with the increase in frequency of operation, the MLCCs offers much less impedance and ESR values than the tantalum capacitors which leads to much lower ripple current. And the capacity of MLCCs has no noticeable change while that of tantalum capacitors decreases rapidly with increasing frequency. Therefore, MLCCs can support large ripple currents and breakdown voltage tolerance and also own a long operating life [11]. The robustness of MLCCs against cracking has also been considerably improved by installing MLCCs with metal stent which is able to absorb the bending stress on PCB plate and improves its capacity and reliability [8].

3) Electrolytic Capacitors

Electrolytic capacitors are the cheapest and the most in demand option among others with higher storage densities and low current ratings. Maximum operating temperature observed is up to 120°C and practical maximum voltage limit is 600V [1].
They are the preferred choice for dc-link in conventional VSI-fed drives. High ESR and ESL values in electrolytic capacitors pose a limit on their maximum frequency of operation and are polarity dependent. The life of modern electrolytic capacitors is short because of chemically triggered thermal degradation. Their limitations of low current and temperature handling restrict their ubiquitous integration in drives but some effort for integrating electrolytic capacitor technology has been done in the recent past which is discussed in the section ahead. The different modern electrolytic capacitors present in market along with their dielectric properties are listed in Table II.

Earlier electrolytic capacitors consisted of Al electrode in electrolyte bath. They were bulky and heavy. It was until the invention of wound construction aluminum foil capacitors that became the model for all modern electrolytic capacitors. Power supply filters are the most common application of Aluminum capacitors. The vast range of voltage ratings and capacitances is the outstanding attribute of these electrolytic capacitors. The wide range of sizes in terms of (diameter × height) for low voltage capacitors can be found to be (3×5) mm and (90×210) mm for high voltage power capacitors [12].

Tantalum on the contrary is a valve-metal which can form extremely thin and protected oxide layers with higher permittivity, thus rendering themselves as good choice for electrolytic capacitors. They have high specific capacitance than Al e-caps. In the past, tantalum capacitors were built with sintered anode body as axial capacitors with a liquid electrolyte. They were relatively heavy and expensive [13]. Tantalum capacitors are now being widely used in power filters, by pass channel circuit, for coupling and decoupling [8]. Their favorable characteristics include low impedance, minimal leakage current, highly resistant, excellent high frequency performance and good operating life [14]. The failure rate of tantalum capacitors has also considerably improved since its presence.

Niobium is also a valve metal which is produced using the same processes as tantalum capacitors; therefore it exhibits similar chemical properties. Niobium pentoxide offers 40% greater dielectric strength than tantalum pentoxide but with 30% lower voltage, implying that approximately same C×V value can be obtained from same amount of material [15]. The energy density however is not competent enough with that of tantalum capacitors. Hence, they are larger in size. Maximum temperature of operation is limited to 105°C, leakage current is 5-10 time more than tantalum e-caps and cannot operate reliably over 10 volts DC. They lean to be less expensive than tantalum e-caps for higher capacitance where the amount of material is large [13].

4) Film Capacitors

Today capacitors are mainly manufactured with film technologies based on Polypropylene or Polyesters. Film capacitors come with a merge of properties which makes them desirable for high stress applications. Plastic Film capacitors are polarity independent unlike electrolytic capacitors and work very well under high currents and voltages [1]. Plastic/Polymer films are favored for energy storage applications because they hold high dielectric breakdown strengths, low dissipation factors and good stability over broad frequencies and temperatures range. Metalized Film Capacitors are also captivating alternate to electrolytic capacitors. They possess high reliability, high RMS current and small capacitance change what may be the operating voltage. Besides, their characteristics are acutely dependent on operating frequency [16]. The table below presents a comparison of dielectric properties of commonly used film technologies.

<table>
<thead>
<tr>
<th>Dielectric for Film Capacitors</th>
<th>Relative Permittivity</th>
<th>Breakdown Voltage (kV/mm)</th>
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<tbody>
<tr>
<td>Polypropylene (PP)</td>
<td>2.2</td>
<td>600</td>
</tr>
<tr>
<td>Polyethylene Terephthalate (PET)</td>
<td>3.3</td>
<td>500</td>
</tr>
</tbody>
</table>

The PET and PP dielectric films have some restrictions to handle high temperatures. For example, the nominal working temperature of metalized polypropylene technology is reported to be 85°C hot spot at full load and therefore requires derating of voltage for operation at higher temperatures [17].
On top of that, SiC semiconductor switches operation temperatures are in the range of 175°C and above, requiring dc-link film capacitors to function at temperatures above 105°C [18]. Hence, the downside of PP film technology is its limited temperature range proclaimed up to 115°C during continuous operation. Although, the benefits of Polypropylene films are good self-healing capabilities, lower density and are preferred for high voltage applications. Power capacitors are based on PP films mostly since these films can operate at high specific voltages (150-200 V/µm) [19].

On the contrary, PET operates at 125°C but with low specific operating voltage in capacitors and consequently has limited access in power applications. The maximal operating temperature and higher permittivity of PET than PP can allow manufacturing of very thin films resulting in better volumetric application which is a desirable feature for integration in aerospace applications where size and weight are critical factors [20].

Reliability issues of electrolytic capacitors have urged traction drive manufacturers to replace them with self-healing film capacitors. The bothering point of present film capacitors is that their ripple current handling capability decrease quickly with rising temperatures which could lead to increase in capacitor’s cost, volume and weight as outlined in [21].

The need for working under high temperature environments demand all passive components manufacturers to seek for new materials and processes to meet power electronics requirements of miniaturization and high power densities. As said earlier, a trade-off has to be built between the applications and required attributes.

B. Capacitor Selection for Drives

The size of filter capacitor and dc-link capacitors is determined by the amount of energy it must absorb to support a right amount of current ripple and the RMS current level it can tolerate. The value of total capacitance, ESR and ESL are paramount factors that need consideration while sizing the capacitor as they are highly dependent on operating temperature and frequency [22].

Electrolytic capacitors had been a dominant interest because of low cost/farad associated. The high ESR, low ripple current handling capability, shorter life span, weight and mounting difficulties have compelled manufacturers of electric drives for traction and aerospace applications to turn towards film capacitors technology because they don’t have these limitations associated with them. Film capacitors however do cost more per farad than e-caps.

Before evaluating the size and volume of capacitor, it is essential to note that the size of electrolytic capacitors is limited by their RMS current rating rather than capacitance. To meet the application demand of desired current rating, the capacitance of electrolytic capacitors will be immensely larger than the necessary owing to their low current ratings and high capacity. Having an excessive capacitance could also present safety concerns because of large amount of energy stored thus entailing additional circuitry for quick and safe discharge. In contrast, film and ceramic capacitors have appreciably smaller capacitance/volume than e-caps and large RMS current ratings. Hence the size is not dictated by the ripple current to be handled. Instead, it is the maximum voltage ripple desired which govern the capacitance needed. It is shown that film capacitors have advantages of size, efficiency, weight, lifetime, cost and capacitance over e-caps [23].

It is also reported in [24] that the electrolytic capacitor volume does not change noticeably with the increase in switching frequency while the capacitance and size reduced significantly for film capacitors.

C. Integrated Capacitor Technologies

One potential lead for the integration of passives that has proven to be productive for implementing high frequency resonant circuits and EMI filters is the principle of electromagnetic integration [25]. In [25], this rationale has been extended for high energy density applications and was put through electrolytic capacitor technology in a 2.2 kW industrial drive for integrating DC link filter. The electromagnetic integration rule exercises by raising the capacitance in the windings with the insertion of a dielectric layer between wound conductors as shown in fig.1. In this way, inductor is integrated in the same component with the capacitor with improvements in THD of input current. This work resulted in volume reduction of 45% for total passive components.

![Fig. 1. Integrated LC Filter (a) Foil Windings and Equivalent Circuit (b) C Core Inductor](image)

Integrated Modular Motor Drive (IMMD) is however another method to help with gaining the advantages of high power density and high efficiency whilst lowering the manufacturing and maintenance cost [26]. The modularized design brings about curtailment in the transmission cables, reduces the overall IMMD price with superior radiated EMI performance and fault tolerant capability. The heat sinks and de-link capacitors being the weighty and prime occupants of the power electronic converter volume limit the performance of...
traditional IMMD designs because of their size and height. Hence, traditional IMMDs cannot fully integrate them which otherwise would cause physical vibrations.

In [21] [27], researchers developed an IMMD design by segmenting the inverter switches for reduced voltage and motor winding branches into two fundamental winding configurations suitable for IMMD. The lessening of dc link capacitor voltage makes the selection of low voltage capacitors adaptable and capacitor optimization easier. This is shown in the fig.2. It was demonstrated that splitting the traction drive inverter and motor windings into two or more parts to form multiple parallel connected drive units and using the technique of gate signals interleaving for PWM switching of the inverter segments will cause cancellation of some of the large ripple current components while reducing others in the dc-link. This significantly impacted the size of dc-link capacitors required for ripple currents filtering. The work culminated in dc-link capacitor size reduction of about 55-75%.

![Fig. 2. Traditional IMMD with inverter modules in parallel](image)

The drawback with this configuration is that dc-link voltage usually comes from the passive frontend rectifier which is decided by the power grid voltage levels. For that reason, low dc voltage is unavailable for many applications other than that supplied by either a buck converter or active frontend.

This design has been further refashioned in [24]. The proposed topology reduced the inverter segment voltage by connecting them in series and employing wide band-gap devices such as GaN MOSFETS to eliminate IMMD heat sinks and optimizing the choice of dc-link capacitors as shown in fig.3. The same gate interleaving procedure is applied but instead of reducing the total dc-link current ripple, the dc-link voltage ripple has been minimized for each inverter segment which adds up. The reductions in total dc-link voltage ripple making equivalent frequency to be twice the switching frequency. The decrease in voltage ripple reduced the capacitor size and increase in frequency brought down the capacitor volume.

![Fig. 3. Redesigned IMMD with inverter modules in series](image)

Very compact IMMD design was reached with the approach emphasized in fig.3 where the PE converter and associated circuitry can be seen fitted between the stator back iron and end plate in fig.4. It can be noticed that semiconductor devices and the machine sharing the same heat sink, hence it is necessary that semiconductor devices must have high class efficiency and high junction temperature than silicon power devices. This requirement can only be met by adopting wide band-gap devices such as GaN.

![Fig. 4. IMMD with Power Electronics Integrated between the back-iron and end plate](image)

For further reductions in the cost of the drive, an inverter-motor packaging scheme has been investigated, designed and fabricated in [28] using different heat-sinks, capacitor board designs and IGBT modules of different ratings for the aforementioned integrated segmented drive system. This eliminated the connection cables between the inverter and the motor completely. Two prototypes of ring-shaped segmented inverters suitable for integration into cylindrical motors were produced. The first design employed block discrete capacitors while the second design used a cylindrical capacitor which much better utilized the space and reduced the inverter height. The fig.5 illustrates this design concept in which IGBT power module, gate driver board, capacitor board and heat sink are all made in cylindrical shapes and are tightly packaged into motor
housing. Paper [29] confirms that Power Ring Film capacitors have superior ripple current capabilities and have benefit of space saving in this design that cannot be acquired with block like inverter designs. This integrated packaging scheme greatly increased the power density of the drive.

### III. MOTOR WITH INTEGRATED FILTER INDUCTOR

The author of [2] has proposed a Permanent Magnet Synchronous Motor (PMSM) with integrated filter inductor. This integrated motor uses the inherent motor magnetics as filter inductance instead of introducing an external inductor between the inverter module and the motor terminals. Fig. 6(a) and Fig. 6(b) show both conventional and integrated motor drive systems respectively.

![Fig. 5. Inverter-Motor Packaging into cylindrical shapes](image)

From Fig. 6, it is clearly seen that the motor with integrated filter inductor does not include an external inductor which is traditionally located outside the motor. Hence eliminating the external filter inductor losses and its associated weight and volume. Filter capacitor and damping resistor are placed separately between the motor windings to form an integrated RLC output filter using the inherent inductance of motor windings as shown in Fig. 7.

![Fig. 7. Per Phase Equivalent Circuit of the motor with integrated filter inductor](image)

The value of the filter inductance ($L_{abc}$) can be varied by varying proportion of motor winding used as filter and varying the capacitance of the integrated RLC filter for the same resonance frequency. The motor is divided into two branches; filter branch and the motor branch. The motor branch windings will see the filtered sinusoidal currents, whereas PWM switching currents will flow through the filter branch winding, which is the fraction of the motor winding.

The FEA model of the motor with integrated inductor is illustrated in Fig. 8 which uses a part of motor windings as a filter inductance. The vectors A1, B1 and C1 represent the filter branch windings, whereas the vectors A2, B2 and C2 correspond to the motor branch windings. The value of filter inductance is fixed by the filter design process as explained in [2, 30] which is half of the entire motor windings.

In [2], the research has been undertaken entirely on the integration of filter inductor whereas the filter capacitor and damping resistor outside are placed outside. The next section will explore different viable ways to integrate the RC branch into the motor housing which will result in a complete integration of RLC output filter.

![Fig. 8. Winding formulation of 12 Slots 10 Poles integrated permanent magnet synchronous motor](image)
IV. POTENTIAL FUTURE APPROACHES FOR FILTER CAPACITOR INTEGRATION

From the above discussions, the need for integrating filter and dc-bus capacitors for large scale implementation of Integrated Motor Drive System is evident which demands the manufacturers of drives and passive components to seek for new materials, processes and methods for meeting power electronic system requirements of miniaturization and increased power densities under high thermal and frequency operations.

In this section, some potential future approaches to integrate output filter capacitor and dc-link capacitors in above PMSM drive with already integrated filter inductor are presented to cope with this existing tough challenge. It should be noted that the above PMSM integrated the filter inductor inside the motor housing as a motor-shaped rotational inductor and motor-shaped rotor less inductor [3].

A. Wrapped Capacitor on the Stator

The first idea is to wrap the conducting layers of an appropriate capacitor type with a right dielectric in between (suitable for motor operating conditions) on the stator of the integrated motor-shaped inductor (fig.9) or on the stator of motor itself (Fig. 10).

The prospective of integrating the capacitor on the motor stator as opposed to the integrated inductor stator is that axial length of the motor is greater than that of integrated inductor. Therefore, for a given operating value of capacitance for this PMSM drive, radial cross-section area required will be less. Moreover, most of the drive applications do not usually prefer the RLC output filter after the inverter. In that case, it is possible to integrate the dc-bus capacitor on the motor stator using this notion. The integration of output filter passives inside the PMSM housing would result in considerable space savings resulting into a compact and power dense overall design.

From the integration of filter inductor inside the motor housing as discussed is Section III, it was observed that the natural air cooling mechanism limited the inductor from achieving higher current densities. With this new approach of integration, both passive components can be placed as a single entity into the motor housing which will not only allow them to use the same heat sink mechanism but will also have the advantage of increasing the inductor current density and losses that the capacitor can handle since losses are inversely proportional to mass and space.

B. Integrated LC Filter

Another possibility is to use the concept of electromagnetic integration employed in [25] as shown in Fig. 11. But instead of using a traditional C core on which foil windings are wrapped to get distributed and integrated LC as shown in fig.1, we can use motor shaped integrated inductor core. The windings in shape of foil will be wound around with a layer of dielectric substituted between the foils. In this way, we can get distributed but integrated capacitance just like in conventional e-caps. The inductor will be formed by using cathode and anode foils of the capacitor and the integrated filter inductor core to implement the windings. Such structures can be implemented in various technologies such as electrolytic capacitors, film capacitors, and ceramic capacitors [31]. This integration option would result in a significant space reduction by placing the integrated filter capacitor and inductor inside the motor housing as opposed to placing it on a PCB of the inverter, thus making an effective overall power dense drive.
V. CONCLUSIONS

Latest available capacitor technologies for drive applications have been presented in this paper. The pros and cons of each capacitor technology have also been discussed in terms of thermal, operational and structural limitations specific to applications for electric drive requirements for transport applications. The paper also reviewed available integrative options for passives with a brief discussion of the work done to integrate the filter inductor inside the PMSM drive. It then proposed some prospective integration options for integrating the filter capacitor inside the same machine by either wrapping it on the stator of motor shaped inductor or on the stator of the PMSM itself, which can draw lot of research attention in aerospace and marine applications where integration is a prerequisite.

VI. FUTURE WORK

These conceivable prospective integrative options of filter capacitors requires a detailed mathematical and finite element modeling and analysis along with its experimental validation, which the authors aim to document in future publications.

VII. REFERENCES