A Survey of Phasing in Electric Motors

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Abstract

The purpose of this paper is to survey the recent advancements in poly-phase motor construction and their control, particularly those with greater than three phases. Recent advancements in control technologies, semiconductors, materials, and manufacturing have led to lower costs for high quality motors, inverters, and controllers. Moreover, increased incentives for efficiency and the growing adoption of electric motor controls across applications such as robotics and mobility are set to accelerate the demand. This paper summarizes the findings of greater than three phases on the output performance and control characteristics of electrical motors. A discussion of common electric motors and control paradigms is discussed, such as induction, switched reluctance, and permanent magnet switched reluctance. This is followed by a survey of the effects of phasing in these common motor types. In addition, the permanent magnet analogue of halbach arrays is discussed.

1 Introduction

Electric motors are a critical component in modern industrial development. In recent decades, sophisticated motor control and design has opened a wide array of applications that were previously not possible. A prime example of this is low-cost 3D printing, which was enabled by a rapid decrease in cost of multi-axis synchronized motion control using stepper motors. [1] As the world moves to improve sustainability and ecology, electric motors will begin to supplant internal combustion engines in the automotive industry as well.[2] For simplicity this discussion will focus on rotary motors, rather than including linear motors.

There is likely significant growth in demand for electric motors over the coming years. In 2017 the global market for electric motors was estimated to be around USD 100 Billion and had experienced around an averaged 6.3% compound growth over the past decade. [3]

Similarly, efficiency incentives have been put into place by the European Union and the United States to encourage industries to adopt more efficient motor installations and save power. Beginning in 1992, the U.S. Congress established minimum efficiency requirements for induction motors. This was followed by the European Union in 1998. These efficiency incentives targeted household appliances and industrial applications, with minimum targets of 80.4% efficiency requirements in the EU beginning in 2009 and 2015 in the United States.[4] Figure 1 shows the efficiency mandate as a function of power output under EU and US regulations.

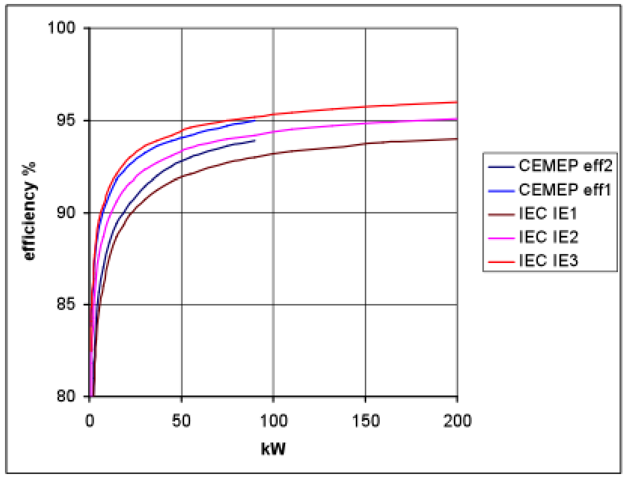

Figure 1: Mandated efficiency as a function of power under the European Committee of Manufacturers of Electrical Machines and Power Electronics and the International Electrotechnical Commission

As the cost of manufacturing of motors and supporting electronics decreases due to density improvements and automation, advanced motor designs will become more feasible and can deliver significant performance improvements to efficiency and reliability.[5] One area in that shows promise to improve several motor factors is the increase in motor phases. A motor phase may be thought of as the potential-generating component in a motor. Generally, these are electromagnets made by winding wire around a magnetically conductive core. The most common material for an electromagnet is copper wire wound around an iron-based core, with additives such as silicon or carbon to reduce weight and allow for ease of material processing. In order to convert electrical potential to rotating motion, the electromagnets are commutated. Through this process, electrical potential is converted to magnetic potential, then finally into mechanical motion. The process of commutation is the control process through which each grouping of electromagnets, known as a phase, receives a controlled flow of power through each coil. This process thereby continually rotates the magnetic potential in the motor to continue rotational motion.

1.1 Historical Electric Motor Development

The development of the electric motor is tightly coupled with some of the early experiments in electromagnetics. It is widely believed that in 1740, Andrew Gordon first discovered the electro static motor. However, concrete understanding of the relationship between current and electromagnetic fields was discovered in 1820 by André-Marie Ampére, who later developed the solenoid. A year later, Michael Faraday observed electromagnetic rotation in a magnet suspended in an electric field. For the next decade several inventors discovered different constructions of electromagnetic oscillators, until Moritz von Jacobi developed the first practical rotating electric motor in 1834, which was later tested to propel a boat. Beginning in 1861, James Maxwell publish his key equations which formalized electromagnetism. Throughout the late 19th century, several scientists and engineers worked to refine the design and theoretical underpinnings of the electric motor. These techniques were applied to early machine tools, automotive, and power generation. However, critical interest began in 1885 with the discovery of the induction motor, which had great promise for power generation and industrial machinery. Throughout the 20th century, the work on motor design continued, ultimately reaching a watershed moment with the development of the transistor. Modern motor development now focuses on control paradigms using fast-switching transistors to control a motor with precision and efficiency, often times coupled with sensor feedback for closed-loop control. [6] [7]

2 Common Polyphase Electric Motors

2.1 Induction Motor

The induction motor was the first widely commercialized form of electric motor. The first patents were filed for the device in 1985 by Nikola Tesla and Galileo Ferraris. As the name implies, the rotating motion of the rotor is introduced through electromagnetic induction, without the use of permanent magnets. This property allows for brushless operation and simple commutation through alternating currents. This is demonstrated in Figure 2, where three phases may be used to induce a rotating magnetic field.

In addition, the absence of permanent magnets reduces production costs of the motor and does not suffer for varied performance from demagnetization. When used as a generator, the induction motor yields good efficiency and naturally produces AC voltage which is suitable for use in power transmission. The most common type of industrial motor uses three phases. Since three phase power is tightly coupled with the modern electric grid and industrial motors, this technology has received most analysis and has the most availability for a given application. The rotations per second of an induction motor given in Equation 1 is a function of the frequency applied to the phase, f, and the number of magnetic poles in the rotor, p. For single speed operation powered by grid power, it is common to vary the specified pole count to change the speed of the motor.

$$n_s = \frac{2f}{p} \tag{1}$$

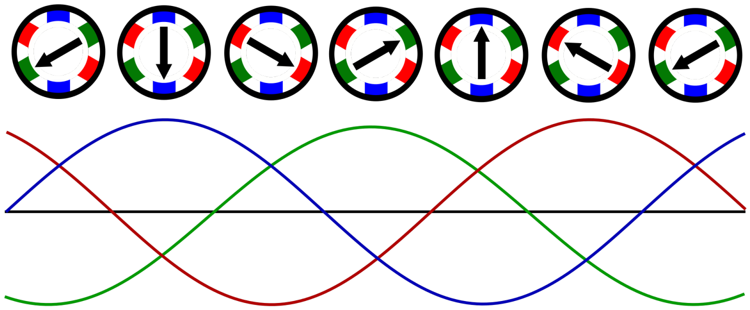

Figure 2: Visalization of rotating magnetic field using three phases. Note that the direction of the magentic field rotation is aligned with the peaks of the waveform.

2.1.1 Three Phase Induction Motor

The induction motor became widely popular as a generator and motor for industry. Most of the induction motors used in household appliances are based on one or two phases of power. In contrast, industrial applications almost always use three phases. This is due to high efficiency and self-starting properties. This contrasts with one- and two-phase induction motors will use capacitors to introduce a phase shift, thereby creating an additional phase to start and continue motor rotation. By far the most important property of three phase power is the Y, or "Wye", termination of the three phases. This is a consequence of the sum of the voltages in all three phases being always equal to zero. Therefore, all wires used in a three-phase system are used for power transmission and a ground line is not required. For high power applications, this saves cost on wiring and connections. In Figure 3, we can see this property graphically. For example, at 90°we can see phase 1 has a value of 1, whereas phase 2 and 3 both have values of -0.5, for a total of 0.

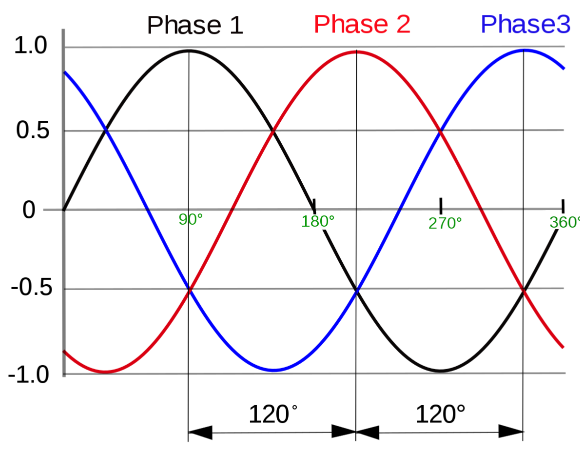

Figure 3: Three phase power waveform

2.1.2 Variable Frequency Drive

The first poly phase motors used three-phase power, due to simple wiring in the stator. This principle of operation made three-phase motors highly popular in industry due to high efficiency and cost-effective designs. However, the growth of automation technologies beginning in the last half of the 20th century have created greater emphasis on speed control techniques. Digital Variable Frequency Drives (VFD) have become highly popular in industry to control electric motors at user-variable or programmed speed profiles. It is important to note that VFDs operate using semiconductor technologies using computer-controlled transistors. A simplistic model will have AC-DC rectifying diodes and filters to produce a controllable DC voltage. Computers will then control transistors at high frequency to control the current through a given phase at a specified rate. This rate-control of current through a given phase gives the "Variable Frequency" component of the name. Figure 4 illustrates the circuit diagram of a three phase VFD, and the transformation of a single output phase.

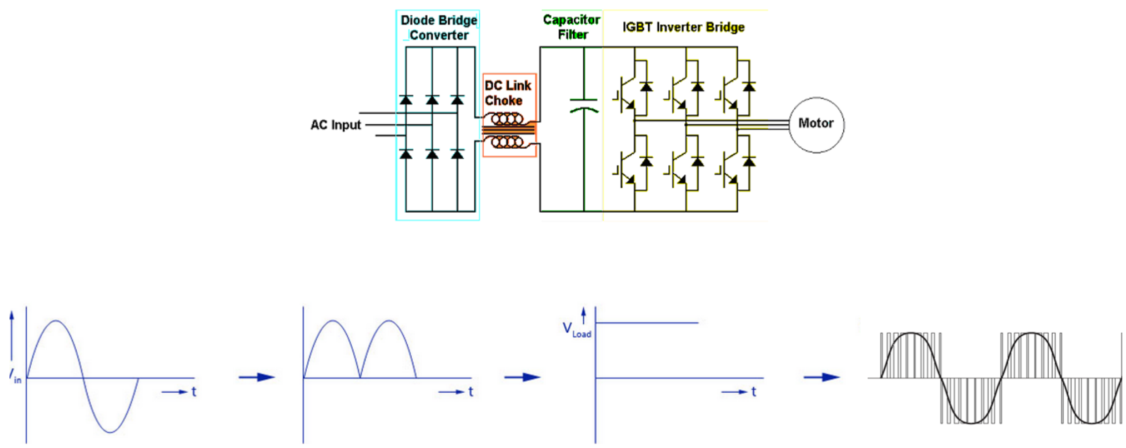

Figure 4: Operational circuit diagram for a three-phase VFD and waveform transformation process for a single phase

2.2 Stepper Motors

Stepper Motors are a form of Brushless DC (BLDC) motor, but have higher pole counts of around 20-1000. This higher pole count allows for precise motion. Similarly, stator electromagnets generally use high winding counts to give greater holding torque. These combination of elements in a stepper motor make them ideal for low-cost precision motion control in applications such as robotics, manufacturing, and computers. Most importantly, a stepper motor does not require commutation via sine wave interpolation. This property allows for a motor to rotate with continuous voltage alternating between the two phases. The commutation of a stepper motor between two phases is seen in Figure 5.

The early CNC machines developed by MIT in the late 1950's adopted steppers motors, since relay logic could control these motors. [8] This simplicity has allowed for stepper motors to be widely applicable to positioning systems without the development closed-loop controls. Contemporary applications include printers (2D and 3D), CNC, and optical disk drives.

The natural frequency of a stepper motor is given by:

$$f = \frac{100}{2\pi}\sqrt{\frac{2pM_h}{J_r}} \tag{2}$$

where M_h is the holding torque, p is the number of holding pairs, and J_r is the rotor inertia. We can therefore see that the natural frequency of the stepper motor can be controlled with proper specification of the pole count and holding pairs given in Equation 2. This is important is precision motion applications as stepper motor controllers frequently employ a technique known as micro-stepping. In this process, an alternating current is applied through the stator electromagnetic coils, thereby allowing for the rotor to maintain a position between steps. This use of micro-stepping helps to minimize much of the acoustic noise generated by the stepper but sacrifices deterministic positioning between the states. [9]

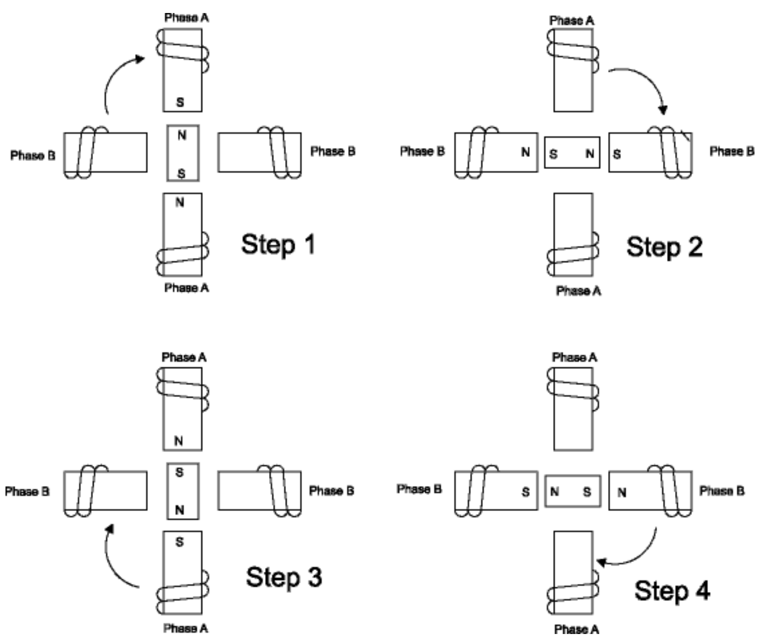

Figure 5: Stepper motor operation phasing[1]

3 Increased Phase Count Motor Design and Control

3.1 Induction Motor

There is on-going research into the introduction of different phase counts on induction motors. Studies have been focused on both the efficiency and performance aspects of these motors,

[1]Courtesy of PC Control: https://www.pc-control.co.uk/step-motor.htm

particularly the introduction of six phase control schemes. In 2002, Lyra and Lipo developed formalized mathematical models for a six-phase induction motor. They also noted theoretical torque density improvements of up to 1.4 times in their models in comparison to three phase windings. However, they noted a theoretical ability of the six-phase motor to control harmonics of the third order via adjustments to current and frequency in three of the six phases. Experimental tests showed that harmonic adjustments generated unwanted spurious emissions that affected the operation of nearby machines and electronics. [10] The results of this study were also experimental confirmed in 2012 by Nanoty and Chudasama who showed that by rewiring a three-phase motor to six phases, a torque output improvement of 1.4 times was achieved. In addition, the team made use of two three-phase VFD drives connected in parallel to drive the six-phase motor, without developing new control algorithms of circuitry. They note that due to the doubled cost of two VFDs, the economics of such systems do not scale properly with the performance. However, marginal benefits occur through fault tolerance and redundant control of the motor.[11] Similar modeling was performed in 2012 by Venter, who demonstrated a six-phase system using three phase control via capacitive phase shifting for the other three phases. Here the need for additional control circuitry is minimized. In addition, the key result of the study was minimization of high inrush currents that typically occur during startup of a three-phase induction motor.[12]

3.2 Five Phase Stepper Motors

One promising development has been the five-phase stepper motor. This motor adds three additional phases to the traditional stepper motor, and therefore has several interesting properties and benefits. We can see using Equation 2 that for equal pole counts and rotor inertia, a five phase stepper will have a 58% greater natural frequency. This increase in natural frequency helps to reduce mechanical resonance. However, in practice, five phase stepper motors often have much greater pole counts so the natural frequency is much greater. [13] The effects of a higher natural frequency are compared in Figure 6, with data produced by Oriental Motor. Here we can see the benefits of the natural frequency increase to avoid the low resonant frequencies produced by mechanical components such as bearings. Similarly, the effects of torque ripple are mitigated with five phase operation. Torque ripple is the change in magnetic flux density as a motor pole rotates between phases. At high loads, oscillations or resonance may be introduced as rotor inertia changes through the rotation. In Figure 7, we can see that phasing increase of the 5 phase motor reduces the gap in magnetic flux from roughly 29% in a two phase stepper, to 5% in a five phase stepper.

[2] Courtesy of Oriental Motor USA Corp.
[4] Courtesy of Oriental Motor USA Corp.

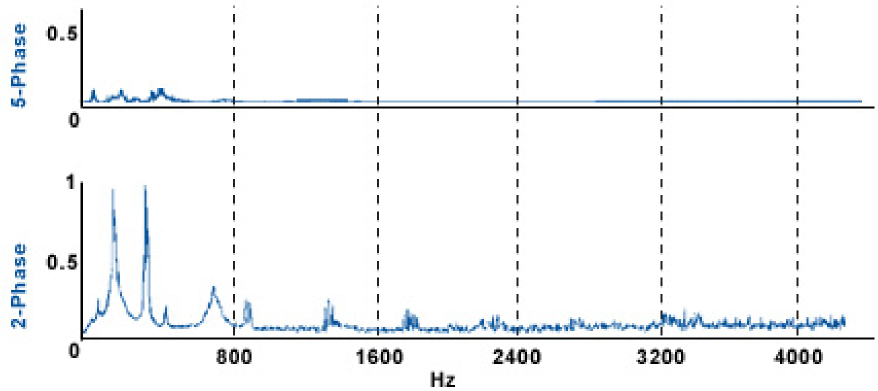

Figure 6: Vibration comparison of two and five phase steppers a 5K steps per revolution [2]

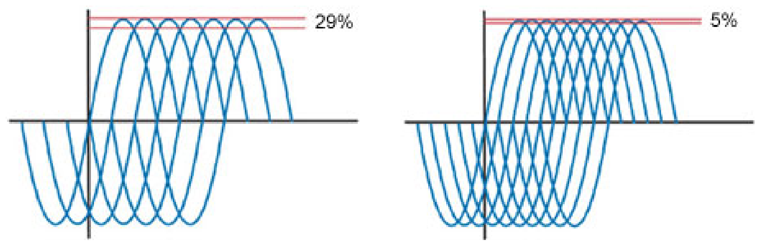

Figure 7: Torque ripple comparison of two phase (left) and five phase (right) stepper motors. [4]

3.3 Fault Tolerence

The addition of five or more phases to a motor has a significant advantage for reliability and fault tolerance. As previously mentioned, greater phase counts reduce the current load on a given conductor, and therefore generate less heat. This factor helps to reduce damage to wire enamel and demagnetization of permanent magnets. Moreover, increased phasing allows for a high degree of fault tolerance when a single phase is damaged. With five or more phases, a motor may still start and operate, albeit at a lower efficiency and with resonance. However, such fault tolerance may be desirable is certain applications such as power generation, defense, and mobility where complete failure puts human safety or operational requirements at risk. Levi et al. introduced algorithms for five and six phase induction motor control with fault tolerance.[14] They note that several applications as of 2007 were exploring six and greater phase systems for fault tolerance, such as a 15-phase motor to power stealth ships and submarines. [15] Oprea, Martis, and Karoly demonstrated control algorithms for fault tolerant six phase control of a brushless DC motor used in power steering applications. They presciently noted in 2007, when the paper was published, that autonomous vehicles would require high degrees of fault tolerance for public safety. [16] In addition, seven phase fault tolerant control of a brushless DC motor was published by Vu, Nguyen, and Semail in 2018 to provide additional control of harmonics and suitable safety measures. They also note that seven phases help to mitigate some spurious emissions during operation caused by control of third order harmonics. [17]

3.4 Halbach Arrays

Halbach arrays are an arrangement of permanent magnets that increases the magnetic field in a single direction. The design was first formalized by Klaus Halbach of Lawrence Berkeley National Laboratory as a means of focusing particle accelerator beams. [18] Niche applications have begun to make use of Halbach arrays to greatly improve power density of the electric motors. However, due to the inherent difficulty of assembling magnets with opposing forces, they have remained somewhat limited in availability. The most common application of halbach arrays in mobility are in linear induction motors used for trains and monorails.

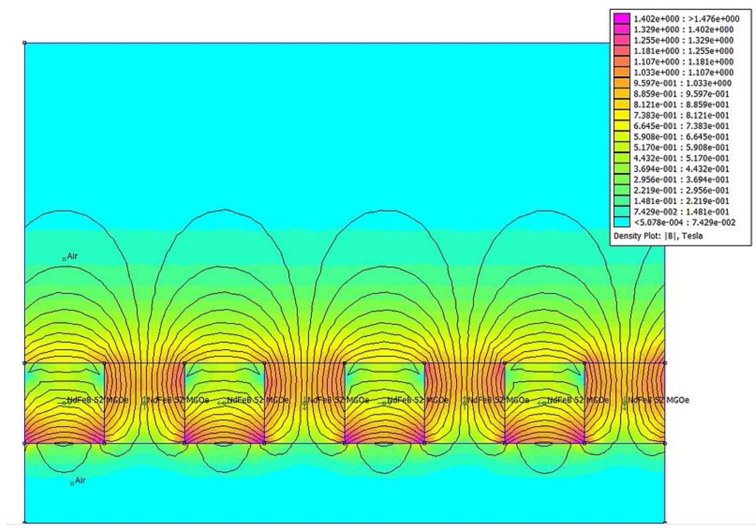

Figure 8: Halbach array magnetic field visualization [5]

A study out of Lawrence Livermore National Laboratory in 1995 formulated analytical realizations of a Halbach Array motor systems. They noted that the benefits largely include a reduced requirement for back iron and laminations, thereby significantly reducing the weight of the motor. [19]

Halbach arrays greatly help to improve the power density of an electric motor. Launchpoint Technologies has developed a high-power density electric motor for use in Unmanned Aerial Vehicles that has a power density of 5.1 KW/Kg, accomplished through use of halbach arrays.[20] The team at Launchpoint has received several rounds of SBIR grant funding by the NSF and is currently engaged with the United States military to pursue experimental applications and larger scale designs. A design study by an Italian team showed similar scaling of halbach array designs to high powered electric turbo pumps. However, in addition to Halbach designs on the permanent magnets, the team demonstrated a winding method to

[5] Courtesy of Teapeat: `https://commons.wikimedia.org/wiki/File:Halbach_array_field.jpg`

use similar principles on the electromagnet coils.[21] A study in 2016 by a Turkish and UK team applied genetic algorithms to the design of a halbach motor and traditional permanent magnet motor. They noted their algorithm created a halbach array motor with 5% greater torque output across all loads. However, they noted the algorithm used 25% more volume of magnets and suffered greater iron losses. The team also noted a high degree of temperature sensitivity on the performance, with severe demagnetization occurring at 80°C[22] A joint Korean and Chinese team recently developed numerical simulations to parameterize a hub motor design and demonstrate numerical proof of improved power density and performance characteristics over torque and speed curves. In this study the team demonstrated similar performance output between conventional hub motors and halbach array hub motors. However, they we successfully able to design a motor with 76.1% less overall mass and 79.6% moment of inertia in the rotor.[23] It is possible from these studies to surmise that halbach array motors are promising in applications with good cooling and large surface area. Most importantly, existing design principles must be revisited to create optimal parameters for magnet arrangement in these motors.

4 Conclusion

Given the increase in computing power, and high-density power electronics, it is likely that research and production of polyphase motors will grow. Particularly, high torque applications are likely to see immense benefit from high-order phasing to provide overall net efficiency increases. There are several applications for higher-order polyphase motors and controllers. In the general case, current applications are well served by three phase systems. Certain applications where vibration, fault tolerance, or torque are of concern may be well served by implementing greater than three phase systems. It is likely that within commercial applications, the three-phase setup will remain popular, primarily due to simplicity, wide availability of ASIC systems, and well understood design and operation parameters.

Since modern motor control systems rely heavily on Application-Specific Integrated Circuits (ASICs), it is unlikely four or greater phased motor control systems will become cost effective until such ASICs become available. Current software implementations are limited by realtime processing power of micro controllers. It is possible that the application of Field Programmable Gate Arrays (FPGAs) can provide an avenue for addressing such processing limitations.[24]

Since every application has different requirements, it is likely that no motor design will be superior to all others. This is most recently illustrated by Tesla Motor's decisions to use permanent magnet BLDC motors in the rear drive unit and induction motors in the front drive unit of the Model 3.[25] In addition, several teardowns by Monroe Associates of the Model 3 motor design have shown the integration of halbach arrays into the rotor design. Overall, it is possible that the greatest benefit of greater phase counts will be seen in permanent magnet halbach array motors. Similarly, large diameter motors such as hub motors used on electric cars, bikes, and scooters, provide sufficient surface area to see benefits from a greater quantity of phases. Coupled with halbach arrays, high phase-count hub motors could provide a high level of efficiency and control that is currently not available when limited to three phases.

In the age of semiconductors, advanced software control systems, and computer optimized design, it seems as though electric motor development is still nascent. There are several opportunities to present marginal performance improvements to a wide variety of applications. Due to the near ubiquity of electric motors in industry and mobility, such marginal increases can yield great effects on overall energy consumption. Most importantly, power density and reliability improvements can greatly improve usability in robotics and space applications where such factors are of paramount concern.

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