Maximizing Electric Motor Energy Savings Under Real-World Conditions and Constraints

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Abstract. Achieving high electric motor efficiency in real-world applications is difficult for a variety of reasons. This paper details many of these issues and suggests a motor design approach to address many of these challenging application problems with a low-cost, high-efficiency motor. Data is presented on the design approach and prototype testing results.

Keywords: Electric Motors, Energy Efficiency, Amorphous Iron

Electric motors currently consume about half of all electricity generated worldwide. This percentage is rising, due to the electrification of building heating and water heating with heat pumps, electrification of transportation with electric cars and bikes, automation use in factories, and increased cooling needs with air conditioning. Making sure that motors are efficiently using electricity is extremely important, but it is also difficult given the widely varying applications where motors are used.

This paper will describe the numerous factors that limit motor efficiency in real-world operating conditions and will then present a motor that would overcome many of these issues. FluxDynamics, Inc. has recently developed a prototype motor that successfully addresses many of the factors that limit efficiency in motor-driven systems, as well as the factors which limit the widespread adoption of ultra-efficient motors. The design, materials, and other attributes of this motor are presented in detail. Performance metrics from this prototype technology are provided.

1 Factors Limiting Motor Efficiency in the Real World

In real world motor applications, there are numerous factors that affect motor operating efficiency and the efficiency of the motor-driven application. Each of these factors can result in motor operation that is not as efficient as it could be. Many of these factors are presented below.

Currently, electric motor efficiency is usually only given for a motor's rated operating point. In most cases, however, the motor is rarely operated at that point. Motors are typically less efficient when operated much below or above their rated operating point. This is especially true of induction motors, but generally applies to most motor designs.

Oversized Motors. The first important factor is that almost all motors are oversized for the job they are doing. This is because the operating load is often not well known in advance and can change over time, with operating environment variations and with changes in application requirements. Selecting a motor that is too small can lead to the motor not working as desired or not working at all. The easiest way for the application engineer to ensure that the motor will always operate is to select a motor with a higher power rating.

Furthermore, even when the load can be determined, engineers often select the largest value for the operating load that is expected, and then add an additional safety factor on top of this maximum predicted load. This again is the easiest way to ensure that the motor will always operate. However, by using a motor that is oversized, the application will not be as efficient as it would be if its motor were more precisely matched to its operating load. Induction motors are especially notorious for becoming less efficient when they are operated below the load at which they have been rated – which is how they will run most of the time when an oversized motor has been selected.

A paper by Werle, Brunner, and Tieben [1] presented data on motor oversizing, and a figure from that paper clearly illustrates this tendency for motors to be oversized (see Figure 1).

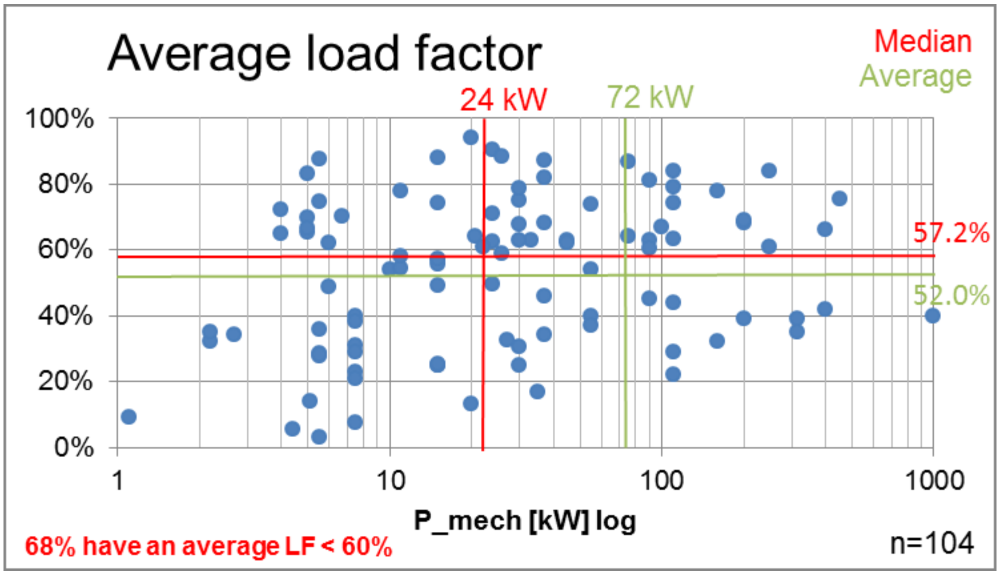

Fig. 1. Motors are commonly oversized. Load measurement results of 104 motor systems. Source: S.A.F.E. 2013.

Undersized Motors. On the other hand, in some cases, to save cost, system manufacturers use motors above their rated point. This is especially true for induction motors. A manufacturer may know that they can use a 2.2 kW rated motor at 3 kW or higher. The motor may get hotter and not last as long, but in some cases pushing the motor to a higher specification makes financial sense for the OEM company manufacturing the application. Motor efficiency drops in cases like this, but this increased electricity consumption cost affects the user of the equipment, not the manufacturer.

Fixed-speed Motors. Most low-cost motors, such as line-operated induction motors, are fixed, single-speed devices. Often the speed that the motor operates at is not the ideal speed for the application. This leads to real efficiency losses in that the process being operated by the motor will not be as efficient as it would be if the motor's speed were more closely matched to the application.

Gears and Pulleys. When the optimum speed for the motor does not match the speed needed for the process, often gears, pulleys, or other speed-changing devices may be employed, but each of these also has efficiency losses and extra costs associated with them.

Line Voltage Issues. Another issue that affects motor efficiency is that for line-operated motors, the line voltage may be lower than rated or unbalanced. This especially occurs in rural pump applications where the power line to the pump may be quite long. Running a motor at a voltage lower than the rated voltage decreases the motor's efficiency. This problem can be alleviated by using a variable frequency drive (VFD) to operate the motor, but this increases the cost and adds complexity to the installation.

Motor Cost. Inexpensive, fixed-speed induction motors generally have lower operating efficiencies than higher cost motors. Motor efficiency regulations can keep out some of the very cheap, low efficiency motors, but some still are used as part of final products which are not always covered by efficiency regulations. As a rule, higher motor efficiency comes with higher motor cost.

Cost and Complexity of VFDs. Variable frequency drives (VFDs) can be employed to achieve variable speed motor operation, but the cost of the VFD, the complexity of setting up and operating the VFD, and the necessary cabling and VFD mounting tend to limit the use of variable speed operation to a subset of motor applications.

Permanent magnet (PM) motors generally offer better operating efficiencies than induction motors, but generally cost more and require the use of a VFD to operate them. The extra complexity and additional cost of the PM motor and VFD limit the application of PM motors.

Cost of Rare Earth Magnets. Most very high efficiency motors (IE4 and better) are permanent magnet motors and most likely use rare earth magnets sourced from China. Rare earth magnets are costly and their prices have swung wildly over the last couple of decades. The additional cost for rare earth magnets results in a higher price for motors using these magnets and also limits the applications that use these high efficiency motors. Also, these days, any product that is solely sourced from China has an issue with stable long-term availability.

Age of Motor. Most motor users do not replace a motor unless it fails. This means that motors in operation are often quite old. Older motors are usually not as efficient as newly produced motors. This is especially true since motor efficiency standards have been adopted. The chart below, again from Werle, Brunner and Tieben [1], shows just how old motors tend to be.

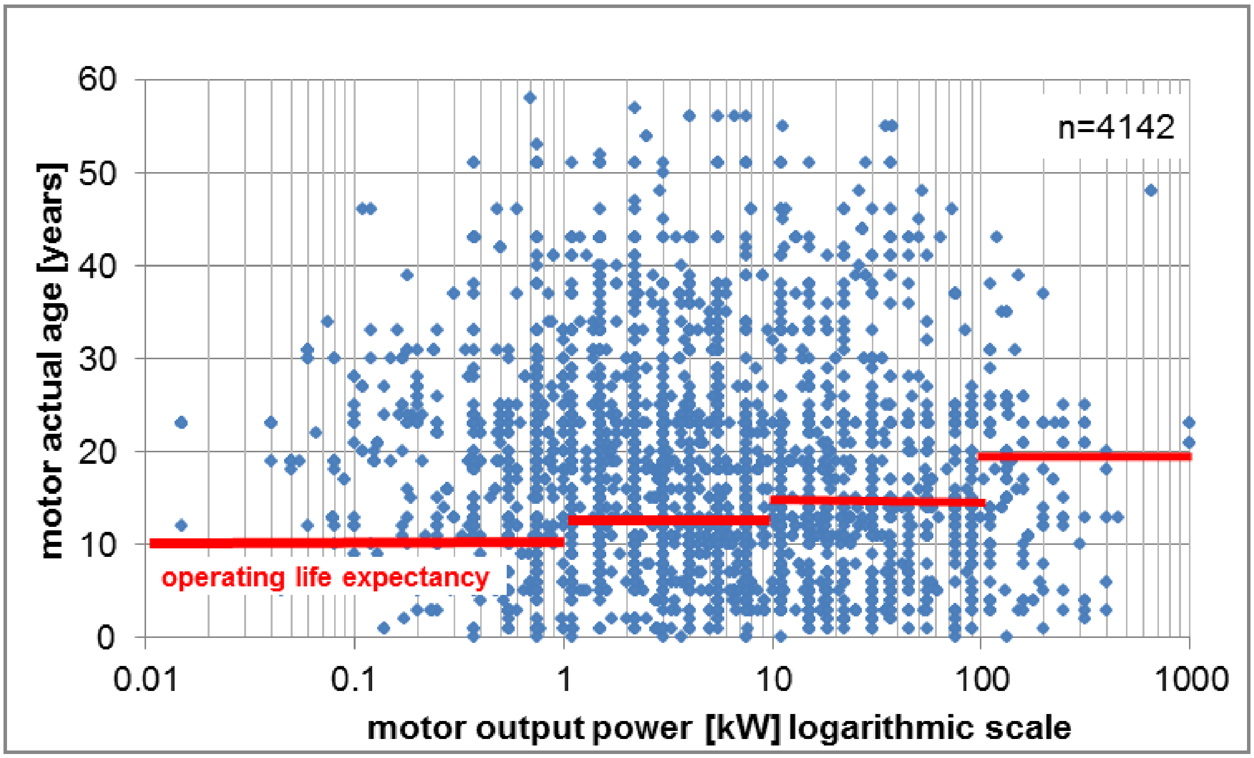

Fig. 2. 56% of motors are older than their operating life expectancy. Source: S.A.F.E. 2013 [1].

Replacing Older Motors. In applications that have been operating well for the user, if a motor needs to be replaced, the safest choice is to replace it with the exact same motor type and model that is currently in use.

When a motor needs to be replaced, it is often hard to substitute a higher efficiency motor because the higher efficiency motor may not be in the same form factor or may need an external VFD or may not run the same way that the low-cost, low-efficiency existing motor operates. It is also likely to cost more, and initial purchase price is often a highly weighted factor since the maintenance budget is often separate from the operating budget.

Another issue that discourages a user from replacing an older motor with a more efficient motor is that the energy savings is generally not known or predictable. Because of varying operational conditions and times, the operator doesn't reliably know just how much energy and cost savings the more efficient motor would provide. Without this savings data, it is harder to justify buying a more expensive high efficiency motor to replace an existing motor.

If a plant manager could easily know that replacing older, inefficient motors would quickly save operating expenses and improve the company's bottom line and that it could be easily accomplished, then the likelihood of older motors being replaced would increase. This type of information can be provided by an integrated motor drive system, as explained later in this paper.

A lack of technical motor knowledge can also limit a facility manager from replacing inefficient motors with higher efficiency units. This can be partially addressed with motor systems designed to be easy to install and use.

Manufacturer Pays for Motor, but Not its Operating Cost. Finally, and of great importance, most equipment manufacturers that buy motors that are incorporated into the equipment they sell do not pay the operating cost of the motor. Their incentive is to buy the cheapest motor that does the job, and this is rarely the most efficient motor that could be applied.

Summary of Issues. These are all practical problems facing anyone who is concerned about overall energy savings from motors. Current approaches to motor specifications and regulations do not readily solve many of these real-world application issues.

In summarizing the above factors that limit real-world motor efficiency, three issues stand out.

Cost. The first is the cost of the motor and the variable speed drive, if it is required. If a higher efficiency motor is available at the same (or lower) cost than a lower efficiency motor, then there is very little reason an OEM manufacturer would not choose the higher efficiency motor. The same goes for replacement motors, but the second major factor is likely even more important when older motors are replaced.

Ease of Use. The second factor is ease of use. This includes motor form factors, operating voltages, connections required, learning curves regarding the motor's installation and use, and other associated issues. Here, an integrated drive and motor combination with proper pre-programmed setup could make a significant difference. This is especially true if extended features like real-time cost savings and induction motor emulation are part of the total system package.

Motor Technology and Integrated Electronics. The third factor is motor technology. There needs to be a way to achieve high efficiency over wide ranges of speeds and torques with a motor whose initial cost is highly competitive with less efficient motors. Ideally, the motor's rated operating point would be highly efficient (IE4 or above), and the motor's efficiency would be even higher at lower loads and also stay high as load and speed vary. Integrated electronics would prevent motors from being misused at operating points higher than specified or that are otherwise not appropriate. The same integrated electronics could provide cost of operation savings and induction motor emulation, as well as motor condition and operating statistics.

While these three factors do not cover everything, they do address the majority of real-world issues that prevent wider adoption of superior electric motor efficiency.

2 A Motor to Address these Efficiency-Limiting Factors

With all these real-world factors working against achieving the highest possible motor operating efficiency, what would an ideal motor to address these issues look like? In my opinion, the ideal motor to address the efficiency-limiting issues described above would include the following:

- Have a high efficiency (IE4 or greater) at the rated operating point
- Maintain high efficiency over a very broad range of torques and speeds
- Expensive materials or sole-sourced materials would not be required
- Compete in production cost with induction motors

- Allow for variable speed as well as fixed speed operation
- External VFD or motor cabling would not be required
- Available in both industry standard IEC and NEMA frame sizes
- Would be a drop-in replacement for induction motors
- Provide the user with cost savings and motor performance data

Currently, there isn't a motor on the market that will meet all the above requirements.

An appropriate question to ask is: Can the above goals be met by a single motor design? Is it even possible with currently available materials and processes? FluxDynamics, Inc. was founded with the mission to create such a motor. The rest of this paper outlines the approach FluxDynamics used to address these motor design goals.

Developing a motor design that achieves both low cost and ultra-high efficiency is an extremely daunting endeavor. Everything must be considered, including basic motor design and form factor, materials to be used, manufacturing techniques and costs, as well as the design and placement of any control electronics.

High motor efficiency is achieved when the motor losses are minimized. There are a number of losses in a motor, but there are only two major losses: conduction losses and iron losses. To achieve high motor efficiency, both of these two major sources of loss need to be addressed.

Conduction losses are most easily addressed by providing more volume for conductors, thus lowering the overall resistance of the motor winding. This generally will make the motor larger and heavier, and therefore can increase cost. The reduction of iron losses generally requires the use of higher quality material, which again can increase motor cost. So, the changes that would improve efficiency typically increase costs. The choices are not easy, and some characteristics must be traded off though an iterative design process.

2.1 Axial vs. Radial Design

One of the keys to FluxDynamics' development process was to move from radial motor topology to an axial design. While radial designs dominate the current motor industry in terms of number of motors manufactured, axial designs have some unique advantages.

Axial motors have historically not been given much attention, even though they were common in the early development of electric motors. Two seminal books on permanent magnet motors only briefly mention them. In "Design of Brushless Permanent Magnet Motors" by Hendershot and Miller [2] only two pages out of a 300-page book are on axial designs. In "Brushless Permanent Magnet Motor Design" by Hanselman [3], three pages out of 250 mention axial motors. Good coverage of axial motors is available in a book "Axial Flux Permanent Magnet Brushless Machines" by Gieras, Wang and Kamper [4], published in 2004 and since updated. Peter Leijnen also does a nice job of summarizing axial motor advantages in his blog post [5]. Recently there has been a major revival of interest in axial motors and axial motor design. This is especially true for in-hub wheel motors for vehicle applications.

Some of the advantages of axial motors are presented below.

One of the primary advantages of axial motors is that the torque increases with nearly the cube of diameter. This is because the area of the motor increases with the square of the radius, like the area of a circle. Also, the torque lever arm increases linearly with the radius. Taken together, this area increase and lever arm increase results in the cubic function. Of course, not all the area available is appropriate to use, so the real gain in torque is a little less than cubic.

Axial motors in general have a larger magnet area and a longer torque arm than radial motors of similar diameters. This is the result of not having an external yoke for the flux return path. The stator flux path is also straight, which allows the use of higher performance grain-oriented materials. In some designs this straight flux path can be shorter than in a radial motor of equivalent power. Overall, axial motors use less permeable material in the stator than an equivalent radial motor, leading to lower weight, reduced cost, and less iron loss.

Many axial motors do not use pole shoes on the stator poles and use concentrated windings. This allows the windings to be assembled on a bobbin and then inserted in mass onto the stator poles. This can increase conductor packing factor, as well as reduce winding costs. It also can improve heat transfer within the coil due to the near-perfect conductor winding.

Also, there are no end turns in the coils of an axial motor winding. This means all of the conductor is active, which can reduce the total amount of conductor used in the motor. This saves both cost and weight and the additional conductor loss.

Another advantage of axial motors is that the rotor positioning is not critical with respect to concentricity. With an axial motor, the rotor is not inside the stator as it is in a radial motor, so the concentricity of the rotor to the stator is not so critical. Of course, having good concentricity is an advantage, but in a radial motor with a 0.5 mm air gap, being off by even 0.1 mm is an issue. With an axial motor, being off axis by as much as 0.5 mm does not create any real problems for motor operation.

While there is no yoke in the stator of an axial motor, the rotor does have back iron. However, since the rotor carries the permanent magnets and rotates with the stator field, the field in the back iron never reverses and is of limited magnitude. This means that the losses in this rotor back iron are minimized. They can be further reduced with slit or wound back iron.

In terms of heat dissipation, an axial motor has a large portion of the windings on the outside diameter of the stator, resulting in good heat transfer from the coils to the case. However, if there is significant iron loss, heat generated in the stator cores is difficult to remove. This calls for the use of low-loss magnetic materials for the cores of axial motors. In the past, soft magnetic composites (SMC) have mostly been used to reduce eddy currents. However, SMC materials have high hysteresis losses. In some applications grain-oriented electrical steel has been laminated into a core shape. This provides better performance than the SMC solution, but this axial form of lamination is difficult to produce. The FluxDynamics approach is to use amorphous iron or other thin magnetic ribbon materials, which provide the ultimate in low hysteresis and eddy current loss.

While nearly all radial motors are manufactured with stamping, axial motors are manufactured with multiple methods. These include using pressed powder soft magnetic composites, stacks of individually cut laminations, and continuously wound laminations.

There are, of course, also disadvantages to the axial motor design. One of the biggest is that there are high magnet forces in the axial direction which need to be accommodated. This high axial force requires special handling equipment to be used when installing or removing rotors of the machine.

Another disadvantage of the axial motor design is that both the axial positioning and the perpendicularity of the rotor to the stator are critical dimensions. This also means that larger rotor diameters need to be mechanically stiff and the flatness of the rotor needs to be maintained.

Concentrated windings and lack of pole shoes can lead to torque variations. Proper choice of pole-slot combinations and dimensions is important in order to minimize this issue. Also, with surface-mounted magnets on the rotor, only a limited amount of field weakening can be accomplished.

A particular characteristic of axial motor designs is that the rotor diameter is larger than for radial motors. The larger rotor diameter means that the centrifugal forces are higher and the stresses on the rotor are higher. This results in a lower maximum speed for an axial motor as compared to a similar power radial motor. This larger diameter also results in high inertia, which may be an advantage or a disadvantage, depending on the application.

An additional disadvantage of axial motors is that they have very limited performance and are difficult to manufacture in small diameters, say less than 25 mm.

2.2 Selection of Materials

The first principle of achieving a low-cost motor is to look at every material available for motor construction on a performance per cost basis. When one does this, with current material pricing, one can determine the most effective materials to use for the core material, conductors, and magnets.

Choice of Magnetically Permeable Material for Motor Stator. The choice of magnetically permeable material is one of the most critical decisions in attempting to achieve a high efficiency motor with low production costs. For a radial topology motor, the choice is almost always a non-oriented electrical steel. The choice for other motor designs is typically between non-oriented and grain-oriented silicon electrical steels. However, this ignores the possibility of using amorphous iron or other similar materials that have significantly better magnetic properties. This matters because in order to increase efficiency, both iron losses and conduction losses must be addressed. Amorphous iron is a much better permeable material than either of the traditionally used electrical steels. It has higher permeability, low hysteresis loss, and higher resistivity, which results in substantially lower iron losses than any of the other choices.

Amorphous iron has been available for nearly 50 years but has still not been applied at any scale to electric motors. Numerous small companies and university labs have built prototypes of amorphous iron motors, but none of them have reached commercial sales and survived.

Hitachi has made the most progress, having built both axial and radial motors from amorphous iron ribbon with various cutting and stamping processes. They even have a compressor product that incorporates one of their amorphous iron motor designs, however this motor is not for sale outside of Hitachi.

The appeal of amorphous iron is its magnetic properties. It has close to zero hysteresis loss with an extremely square loop when processed properly. A BH curve for properly processed amorphous iron is given below in Figures 3 and 4, which have different X axis scaling. This data is from a core with a 70 mm internal diameter and a 160 mm outer diameter and a width of 25 mm. This core weighs 600 grams and the properties were measured by Metglas, Inc., which used to be part of Hitachi but is now owned by Proterial. A comparison to a grain-oriented electrical steel (GOES) and a high quality non-oriented electrical silicon steel used in high efficiency motors is also shown below. A low-cost, general-purpose motor would be manufactured with steel with even worse magnetic properties than the 35H230 Nippon steel shown in the figure.

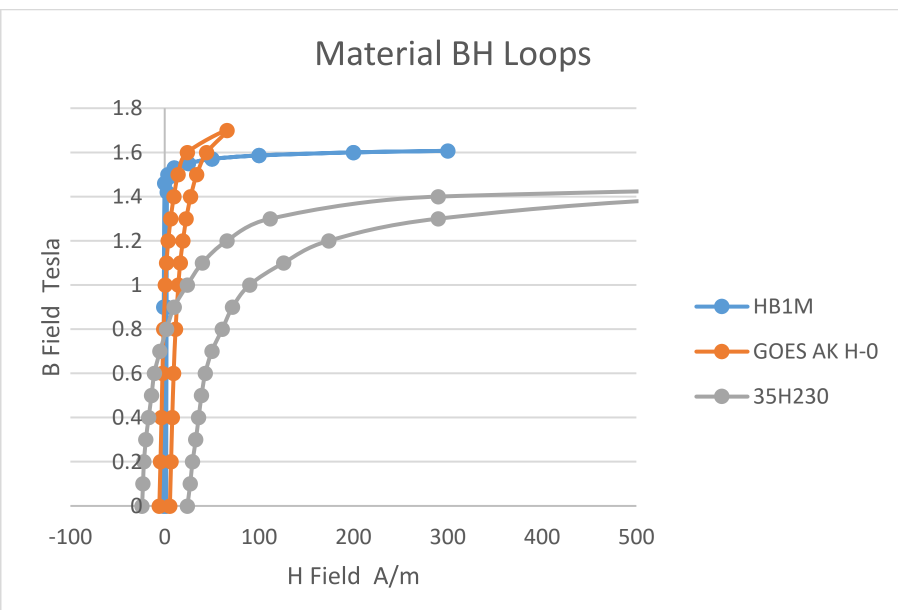

Fig. 3. BH loops of amorphous iron (HB1M), grain-oriented electrical steel (GOES), and good quality non-oriented electrical steel (35H230).

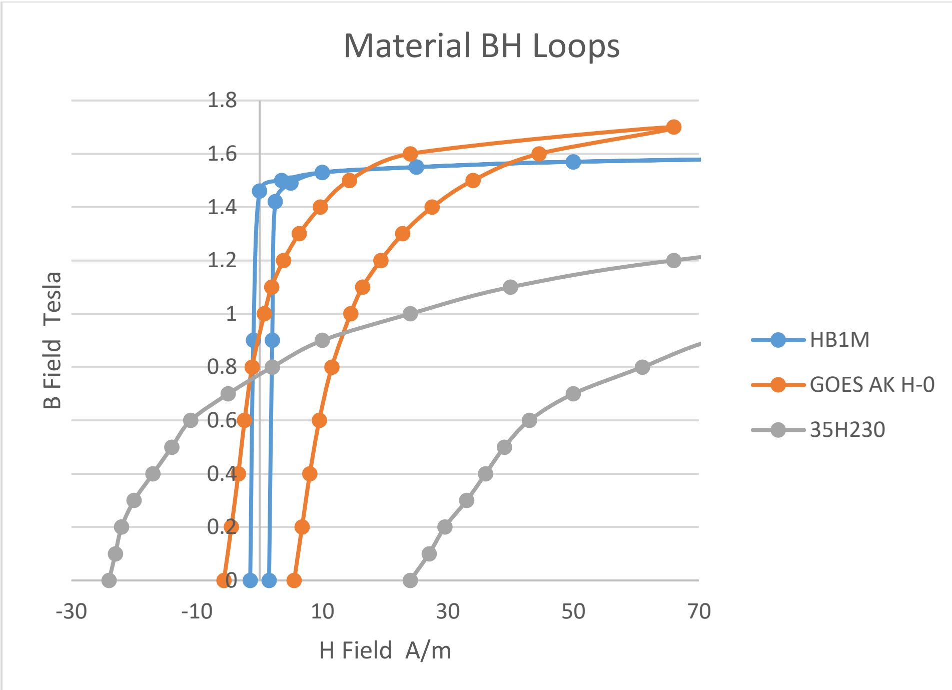

Fig. 4. BH loops of amorphous iron (HB1M), grain-oriented electrical steel (GOES), and good quality non-oriented electrical steel (35H230), with expanded X axis scale for clarity.

Amorphous iron can reduce hysteresis losses by an order of magnitude. In its annealed state, the hysteresis loss is extremely low. In addition, because it is manufactured in a very thin ribbon form, only 25 microns thick, and it has nearly twice the resistivity, the eddy current losses are nearly zero compared to standard existing motor laminations.

Also, the production process for amorphous iron is much simpler and requires lower capital cost than the production of high-quality electrical steel. While currently produced only in low quantities, the process of scaling up production to industrial motor material requirements is relatively easy. While the current cost of amorphous iron is somewhat higher than non-oriented silicon steel, as the volume grows, this pricing gap will decrease and may disappear.

The only real downside of amorphous iron is that it is exceedingly difficult to get this material formed into a stator for a motor. However, FluxDynamics has developed a commercially viable manufacturing method for making an electric motor stator from thin, flexible ribbon material, such as amorphous iron.

In most motors, because iron losses and conduction losses are generally both large sources of loss, designers often balance these losses to obtain the optimum motor design. Usually decreasing iron losses involves increasing conduction losses and vice versa. Amorphous iron stator cores can nearly eliminate iron losses in the stator, thereby opening up a number of design possibilities that focus on reducing conductor losses. This includes making a motor larger or longer to allow for additional conductor volume.

Choice of Permanent Magnet Material. For the magnets, the two dominant options are rare earth magnets and ferrite magnets. If you look at flux per dollar, ferrite easily wins as the most cost effective, as shown in Table 1. Another advantage of ferrite magnets is the material is non-conducting. This results in the elimination of eddy currents in the magnets, which are troublesome with rare earth magnets. While the rotor magnet back iron in an axial motor can be a source of eddy current losses, the flux in this back iron never reverses and the change in magnitude is limited. Thus, the eddy currents are relatively small, and this loss can be further reduced with partial circumferential slits in the back iron or with wound back iron structures.

Table 1. Permanent Magnet Performance Ratio

Magnet type	Flux available	Cost $/Kilogram	Performance Ratio in KGauss/$
Ferrite (FB6)	4 K Gauss	$10 USD	0.4
Neodymium (N45)	12 K Gauss	$80 USD	0.15

Choice of Conductors. For the conductors, when conductivity per unit cost is considered, there really are only two good conductor choices: copper and aluminum. These two materials are widely used in the power and electronics industry. For making a high efficiency motor at low production cost, aluminum is the clear winner, as shown in Table 2. Pricing was obtained from the London Metal Exchange in March 2024 [6].

Table 2. Conductor Performance Ratio

Conductor Type	Conductivity Siemens/m	Density kg/m^3	LME Pricing $/Kilogram	Performance Ratio Siemens-m^2/$
Aluminum	36.9×10^6	2700	$2.34 USD	5.84×10^3
Copper	58.7×10^6	8960	$8.55 USD	0.77×10^3

Similar data was presented in a paper presented by me at EEMODS in 2022 [7]. At that time, the key performance ratio of conductivity per dollar for aluminum was about 6.4 times better than copper. At present prices, that performance ratio for aluminum has improved to 7.6 times better than copper.

To achieve higher efficiencies with aluminum conductors, more conductor must be employed. This can be done by making the motor either larger in diameter or longer in length. This increase in size does add extra permeable material, but the cost tradeoff is still positive. The extra hysteresis and eddy losses from the larger stator are minimal when the stator is constructed from amorphous iron material.

2.3 Design Process

Besides picking the optimum materials and motor topology to achieve very high efficiency at low cost, a high level of design optimization is also required. Since the stator uses amorphous iron, the iron losses are extremely low. This results in the conduction losses being the dominant losses in the FluxDynamics motor. This allows the use of the motor constant, Km, to be used to optimize efficiency per unit cost over a wide range of motor design parameters. To accomplish this, a selection of variable parameters is chosen and computer optimization algorithms are employed to determine the optimum value for each parameter to achieve the best results. A paper presenting some of the approaches used was presented at EEMODS 2022 [8].

2.4 Drive Integration

Many manufacturers are starting to release motors with integrated drives. Historically, the main impediment to doing this was a thermal issue. This is still a major problem, as electronic equipment does not function as well at higher temperatures. The electronics have losses and produce their own heat that needs to be dissipated, so mounting the drive on a hot motor clearly can create a real problem.

The focus on super-high motor efficiency greatly simplifies this issue. A 7.5 kW motor running at 91 percent efficiency generates over 700 watts of heat, while a 95 percent efficient motor has less than 400 watts of heat to dissipate. The more efficient motor can run cooler. This can make a large difference in the ability to mount a VFD onto the motor.

Integration of the motor drive onto the motor has numerous benefits with respect to cost and ease of use. First, the external drive case, connectors, and cabling are all eliminated. The drive can be closely matched to the motor characteristics, which can improve performance. The mounting of the external drive and switching noise from drive to motor cabling is also eliminated. Since most commercial external drives need to be universal, they often are loaded with setup switches, multiple interface connectors, and other associated components that are not always necessary with an integrated drive.

The use of a drive also has benefits in limiting in-rush currents, improved motor startup characteristics, and insensitivity to voltage variations and line unbalance. Drive integration with a specific known motor provides benefits such as major cost savings and preset motor tuning that cannot be achieved with separate components.

2.5 Real-Time Cost Savings Data

Providing real-time cost savings data from motor replacement could accelerate the transition to higher efficiency motors. This can be accomplished in an integrated motor and controller system with the addition of a simple rotor position sensor and appropriate software. Current motor controllers can estimate motor torque from phase currents, but they are limited by not knowing the motor's real torque constant and not accurately knowing its operating position on the torque versus current curve.

By knowing the actual rotor position, the phase current angles and current magnitudes, as well as the motor's actual torque constant with respect to current, output torque of the motor can be accurately calculated. Speed is easily obtained, and therefore output power can be accurately calculated. By monitoring input current and voltage, input power can be obtained and overall motor efficiency calculated.

This motor efficiency information is valuable to the user. However, it would be even better to provide the monetary savings achieved when a new highly efficient motor replaces an older motor. This can be relatively easily accomplished for the replacement of induction motors. The efficiency vs. torque curve of an induction motor is usually available on the motor's data sheet. Therefore, by knowing the actual running torque of the new operating motor, a prediction can be made of the older replaced motor's operating efficiency. From this, power can be computed for both the replaced motor and the newly installed motor and the difference computed and provided to the user. Given an input of electricity costs, real-time cost savings can be computed and provided to the user. The additional cost of this capability is estimated to be minimal when part of an integrated motor/drive system.

2.6 Induction Motor Emulation

In some applications, such as operating a fan, the replacement of an induction motor with a characteristic torque versus speed curve with a fixed-speed PM motor can lead to increased power consumption due to the speed mismatch. With an integrated motor and controller system, a programming provision can be made to alleviate this issue. With an accurate measurement of motor operating torque, a PM motor can be programmed to emulate the performance of an induction motor with respect to speed. With no load it can be programmed to run at a speed that matches the no load speed of the induction motor, and then as the torque load increases, the motor speed can be lowered in the same manner that occurs in the induction motor being replaced.

The motor can be programmed to start when AC power is supplied and detected by the controller, so the only wiring needed is the standard AC power connection. It can also be set to do a smooth, controlled start which greatly reduces the line inrush current. This is a significant advantage in that it allows the replacement of older induction motors with higher efficiency PM motors in existing applications. There is no additional manufacturing cost for adding this capability to an integrated motor and controller system.

2.7 Disadvantages and Limitations

No motor design is without tradeoffs and the FluxDynamics design is not an exception to this. The most significant tradeoff in this design is power density. While the FluxDynamics motor design can compete well with standard induction motors on power density, it is nowhere close to being a highly power dense motor.

Also, this motor design cannot compete with other PM motors on peak torque. Typically, a good PM motor can reach three times the rated torque for short periods of time. This motor design can only achieve a ratio of about 1.5 without excess loss of efficiency and associated heating.

This design, due to its larger diameter axial rotors, is also limited on maximum permissible speed. It is not suited for turbo fans and other high-speed applications.

Frankly, it is also not as efficient as it could be. Using aluminum for the conductor material is a great choice for getting the best efficiency per unit cost, but clearly if copper conductors were used, the efficiency would be higher. However, the goal at FluxDynamics was not the highest possible efficiency, but the best efficiency per unit cost because motor cost limits market penetration.

3 Details and Performance of the FluxDynamics Motor

The FluxDynamics axial motor uses a flat rotor constructed from a flat disc of steel which has flat wedge-shaped magnets attached to it. A molded magnet spacer helps with magnet location and alignment. This simple construction leads to low rotor manufacturing cost. A picture of a typical rotor is shown in Figure 5.

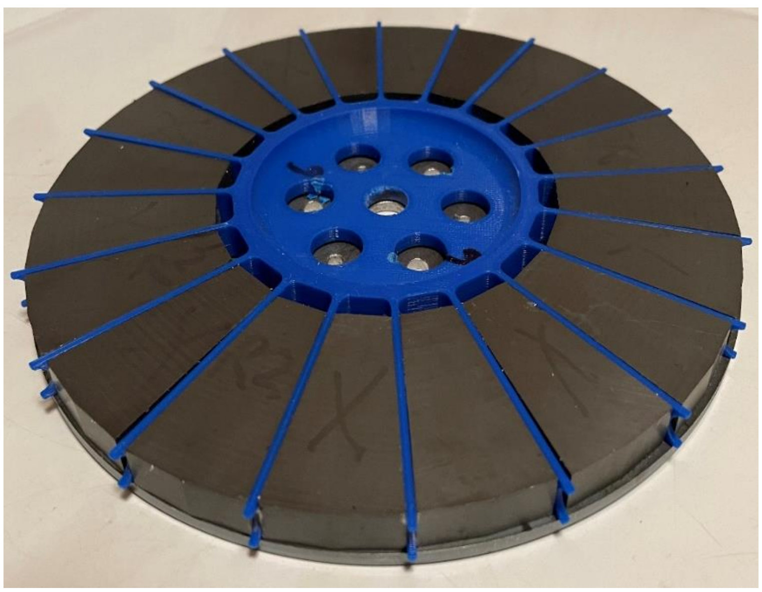

Fig. 5. FluxDynamics rotor with flat ferrite magnets attached.

The coil assembly is constructed of bobbin-wound individual coils which are then assembled into a completed winding assembly. This winding assembly is then fully tested to confirm performance and placed over the stator poles during final assembly of the stator. The bobbins provide excellent insulation between each of the coils and the stator assembly. Thermal transfer between the outer diameter of the coils and the case is enhanced with ribs from the casing. A typical winding assembly is shown in Figure 6.

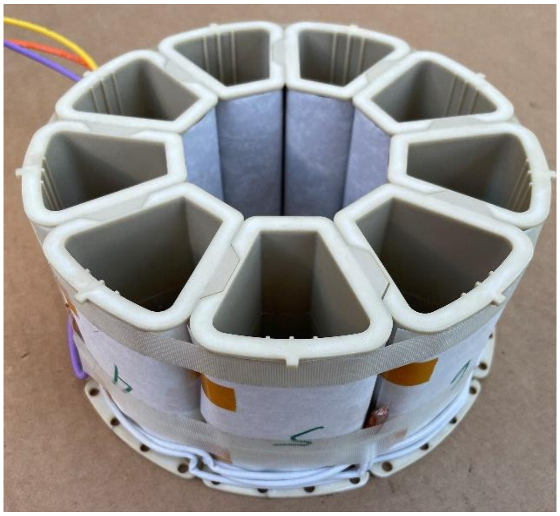
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Fig. 6. Winding assembly from a FluxDynamics motor.

Final assembly of the motor involves bearing insertion, shaft insertion, and assembly of the end bells. The motor was designed to allow easy conversion between IEC and NEMA frame conventions. The motor can be foot-mounted or mounted via tapped holes on the face plate. The case shown in Figure 7 below can be configured for either IEC 90 or NEMA 56 or NEMA 143 applications. As shown, it does not include the axial integrated drive.

Figure 7. Case of a FluxDynamics motor.

Prototypes of this motor technology have demonstrated the effectiveness of using amorphous iron for the stator permeable material. We have also proven that good performance can be obtained with low-cost ferrite magnets. The conductors can be easily changed between aluminum and copper, depending on how price sensitive the application is to efficiency improvements.

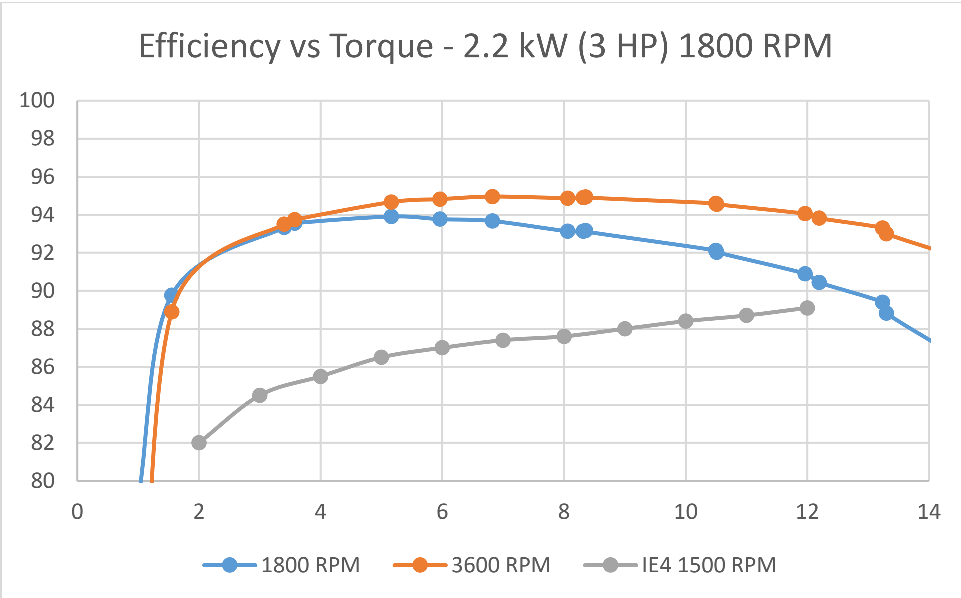

Fig. 8. Efficiency vs. Torque at 1800 RPM and 3600 RPM in a 2.2 kW FluxDynamics motor.

The graph in Figure 8 shows the efficiency of a FluxDynamics 12 Nm, IEC 90 frame (NEMA 56) 2.2 kW (3 HP) motor at 1800 and 3600 RPM. It also shows the IE4 percent efficiencies at various rated motor torques for 1500 RPM operation. This figure shows only motor efficiency, which is what the IE efficiency levels are based on. It does not include the drive losses, which reduce the total system efficiency by 2 to 3 percent. At 1800 rpm the motor is above the IE4 level and is close to IE5 levels at the rated point and is above that level of efficiency down to about 2 Nm or about 20 percent of full load. At 3600 RPM the efficiencies are significantly higher, unlike the result from a 3600 RPM, 2-pole induction motor which has lower efficiency than a 4-pole 1800 RPM motor. This is due to the very low iron losses of the amorphous iron material in the stator. Higher speeds will increase efficiency even more.

One of the results of nearly zero iron losses is that the shape of the efficiency curve is different. Efficiency rises rapidly at low loads, reaches a peak early, and then slowly falls off to the rated load. As can be seen from the graph, efficiency continues to fall off with increasing higher than rated loads. This is where the integrated drive helps prevent continuous operation at higher than rated loads. Of course, very brief periods at higher loads can be tolerated, but by limiting this loading in the drive the motor manufacturer has the ability to prevent users from overloading a motor.

4 Conclusions

So how well does the FluxDynamics motor technology address the issues presented at the beginning of this paper which limit motor efficiency in real-world applications? First, the use of low-cost materials and efficient manufacturing processes allows the motor to be manufactured at attractive costs. The low production cost will greatly increase the likelihood that the motor will be adopted by OEM manufacturers in applications where it is appropriate.

With respect to motor oversizing, the FluxDynamics motor's part load efficiency is higher than its rated efficiency down to 30 percent. Therefore, oversizing a motor by even a factor of three actually increases the operating efficiency of the motor. The integrated drive prevents the continuous use of the motor at higher-than-rated loads, while still allowing for some limited peak loads to be handled.

The integrated drive allows for variable speed operation, takes care of line voltage variations, and greatly reduces inrush current during motor startup. It also simplifies installation. For users who just want to replace an induction motor, the emulation mode allows simple, drop-in replacement. This is also made easier with IEC and NEMA standard packaging.

Finally, the ability to provide cost savings information compared to the replaced induction motor, can encourage users to upgrade a test system and then use the acquired data to justify the upgrade of other systems.

In conclusion, the FluxDynamics motor design was not designed to achieve the maximum efficiency possible and was certainly not designed for power density, but was designed with real-world cost constraints in mind in order to achieve the highest efficiency per unit cost. The reason that this approach was taken was to achieve the maximum possible impact on global motor energy consumption.

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