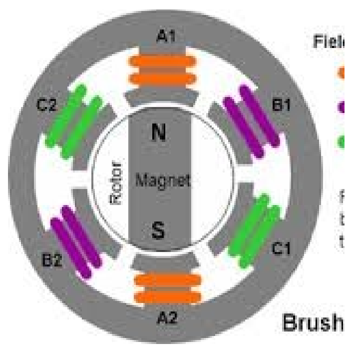
Introduction

The first application of the saturable transformer project will be in improving efficiency for brushless DC motor output as a means of proof-of-concept toward improvements in renewable energy efficiency.

Challenge

Brushless DC (BLDC) motors offer greater efficiency, more torque per weight, reduced noise, and lower mechanical wear than their predecessors, brushed motors. BLDC motors are increasingly being used in a wide variety of applications including electric/hybrid cars, heating, ventilation and cooling (HVAC), robotics, aircraft, and medical technologies. While BLDC motors are currently the model of efficiency, we believe there are ways to improve their output without further energy expenditure.



BLDC motors rely on using a rotating magnetic field to create torque. In the diagram shown to the right, internal coils are energized and de-energized at specific angular positions of the shaft (i.e.: energize A1 & A2, then energize B1 & B2 to turn the shaft 60 degrees, and so on.) to create torque. The time spent between energizing a winding and developing the current required to generate torque, however, can represent a significant inefficiency. Since motor output torque is roughly proportional to winding current, any delay between the coil energization and torque-producing current represents a limit on performance.

The result of continuous, accumulated delays is a limit on maximum speed achievable with a given input voltage which then constrains the constant-power speed range (CPSR) of the motor. Vehicles, for example, will demand at least a 10:1 CPSR, which is beyond what most motors can provide. The limited CPSR is a mismatch with many other desired applications (addressed later in the document) that then mandates a variable coupling module to reach the CPSR required by the system to which the motor is delivering power. The most obvious example is the transmission required in almost all automobiles to match limited CPSR of an engine or motor to the CPSR required by the vehicle. While transmissions are not inherently bad or tremendously inefficient, they do represent a high percentage of the full drivetrain mass and therefore serve as a major source of energy consumption.

The source of delays in changing the current flowing through a motor coil is the electrical inductance (or self-inductance) of the coil itself. Delay in any circuit with inductance (as is the case with almost all motors) is directly proportional to the inductance (L) divided by the full electrical resistance (R) in series with that inductance. Although this fixed L/R delay is usually insignificant at low rotational speeds, it imposes a limit to both the CPSR and the terminal speed achievable by most motors.

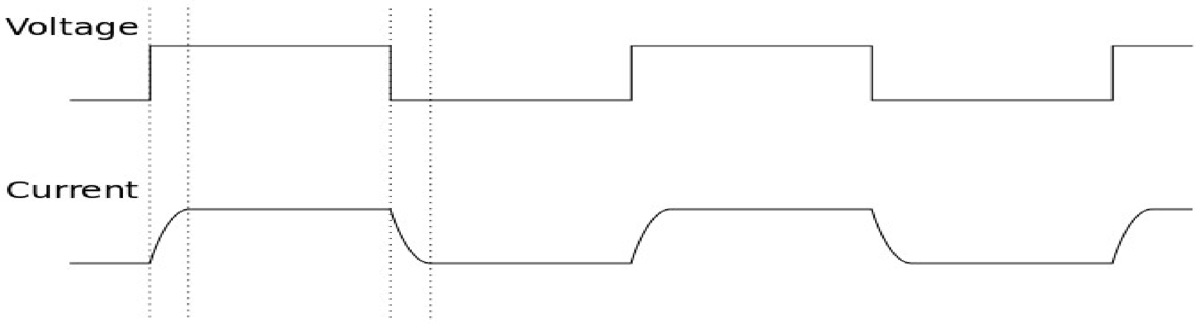


Fig 1

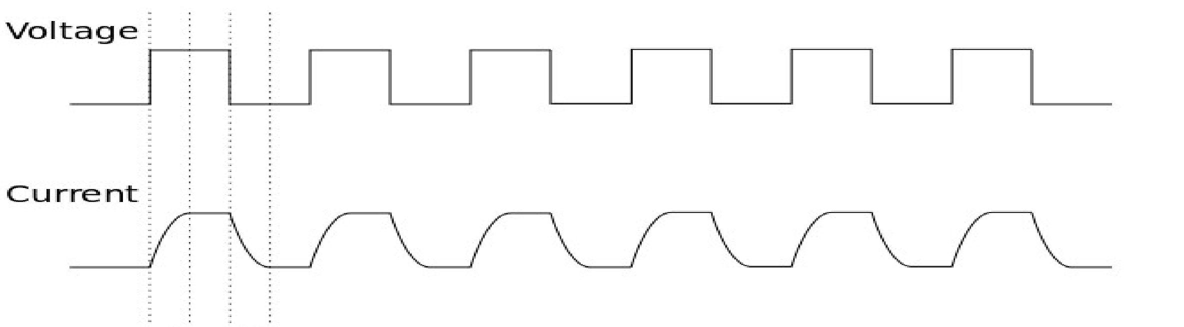


Fig 2

Figure 1 shows a changing voltage as applied to an inductive coil and the resultant current in that coil. At the low rotational speed shown, the fixed L/R delay does not yet represent a severe impact on motor performance. Figure 2 shows the excitation of the same coil at a much higher rotational speed. It can be seen that the fixed L/R delay now significantly impacts the ability of the coil to develop torque by limiting the time during which full current flows. As rotational speed is increased, the motor eventually encounters enough delay in current changes that no additional torque may be developed, imposing a terminal speed for a given input voltage. Although high-speed torque can also be improved by increasing the voltage driving the motor, this approach quickly impacts efficiency at lower speeds.

Constrained CPSR primarily impacts the efficiency of systems with motors that contend with highly reactive loads and/or variable loads. These loads sometimes require voltages or currents for transient behavior – brief periods requiring high power – which are inconsistent with those required for subsequent static operation. The complexity resultant from multiple energy sources with entirely disparate characteristics is however justified only in extremely high-performance situations.

The direction of most efficiency improvements to date has been toward reducing winding inductance, usually through reducing the number of turns in each motor coil. Not only does this measure reduce inductance, it as well reduces the electrical resistance, which initially appears helpful in developing higher current. Decreasing the resistance, however, can be seen by the time constant above to actually increase the time required to develop current in the coil. In this scenario, t = L / R, where t = time, L = coil inductance, and R = resistance through the entire coil circuit path. When starting from a high inductance, reducing the turns proportionally reduces the inductance faster than it reduces the resistance of the circuit, improving performance through reducing delays to torque development. As the number of turns is further reduced, however, the relative reduction in inductance occurs at a slower rate than the reduction in resistance. This more rapid decrease in resistance then imposes a limit to performance benefits through coil turns reduction.

Furthermore, higher currents resultant of lower coil resistance can dramatically impact system efficiency through exponential losses in drive electronics. Per Ohm's law, current in the coil is indirectly proportional to its resistance. Power dissipation in motor drive devices (which also exhibit resistance as series elements to the motor coils) are proportional to the *square* of the motor current. If resistance is constant while doubling current, the power loss in the semiconductor is quadrupled. This exponential power loss then makes high current less attractive when high efficiency is a system goal.

Improvements in even BLDC motors are now at an impasse and have achieved the best possible compromise between L and R – the point of diminishing returns. Further turn reductions will result in longer time constants and/or degraded system efficiency.

Although reducing motor coil inductance itself may be impractical, mitigating the deleterious *effect* of inductance may be accomplished by selective increases in instantaneous voltage – delay time to development of full current is indirectly proportional to the applied voltage. The very nature of the delay problem is in this case also advantageous – current is low during the points in time where high voltage would be the most helpful in hastening development of current in a coil. In that high voltage is never required with high current, high system efficiency may be maintained. Use of a high-voltage source (at low current) at current transitions can then reduce the time to current development. After full current is developed in the coil, high voltage is no longer either needed or advantageous. Dynamic control of voltages applied to individual motor coils can therefore provide an alternative drive method whereby even high-inductance motors may provide performance unattainable with conventional fixed voltage drive techniques.

Opportunity

We believe we have a relatively simple improvement that will greatly improve system efficiency when employing electrical motors, such as BLDC motors. The technique involves use of a transformer that can function as a switch when "saturated" with current. Selective control of transformer saturation is then used to provide either a high-voltage, low-current source or a low-voltage, high-current source to the load. Use of a passive transformer to aid switching facilitates high output voltages otherwise unattainable with inexpensive low-voltage drive transistors.

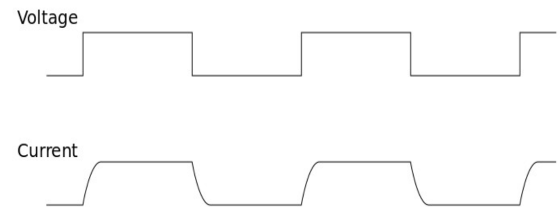


Fig 1

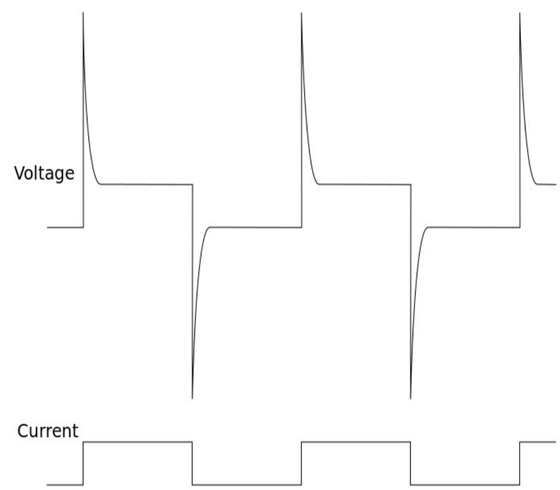


Fig 2

Electrical characteristics of a typical BLDC motor coil can be seen in Figure 1. A significant delay in achievement of full current can be seen at each voltage transition. This delay represents the efficiency loss noted above. The same characteristics for a motor coil driven by the current invention are shown in Figure 2. In this scenario, the large voltage spikes created by the transformer before saturation can be seen to speed the achievement of full current, both minimizing the efficiency loss and making the motor load appear to be purely resistive.

The root of this development is in exploiting a variable in the equation for the time constant imposed by cell inductance. Specifically, the time required for current development in a coil is indirectly proportional to the voltage applied across the coil. While this variable is considered moot for motors which are conventionally driven by fixed voltage sources, it does provide a possible alternative means to reduce the lag time in developing coil current.

If, for example, the voltage initially supplied to a coil is 100 times the voltage normally supplied to create torque from the coil, current in that coil will develop approximately 100 times more quickly than if a constant voltage were used. Changing this initial voltage does not necessarily impact any characteristic mentioned above other than mitigating the effect of coil inductance on lag time to torque development. This technique of driving a motor winding requires either high voltage or high current at any given time, but never both simultaneously.

The inductance presented by motor coils affects not only the motor coils but the power source driving the motor. Specifically, the inductance causes the current demanded by the power source to lag the voltage. This reactive load presents a difficult problem for the power source or upstream power grid. Resultantly, PFCs are routinely implemented on reactive loads like higher-powered motors to align the load current with the driving voltage, making the load appear resistive. By mitigating the effects of motor inductance with the technique afforded by the saturable transformer, the motor can be made to appear resistive to its power sources, hence obviating costly and bulky PFCs.

Benefits

High Efficiency: By reducing the effective electrical time constant through mitigation of the effects of inductance, the CPSR and/or terminal velocity of the motor may be increased, opening multiple venues through which efficiency may be improved.

Low Cost of Goods: Semiconductors are not used in the high-voltage path, as the combination of high breakdown voltage and high current capability either increase cost dramatically (high-voltage MOSFETs) or degrade performance and efficiency (IGBTs). Cost associated with the high voltages produced involves only wire varnish capable of withstanding higher voltages. Additionally, a transformer required for this use must have a small, light core for ease of saturation, further reducing mass and expense. Complexity required is less than that of a PFC.

Load Stabilization: A resistive load, such as that enforced by this technique, mandates that power supply current is in phase with voltage, allowing an easier-to-manage source of power that does not require additional energy to mitigate power factor. Additionally, the fact that voltage is in phase with current leads to diminished incidence of waveform distortion that may lead to unexpected voltages in other areas of the grid.

Improved Reliability: A saturable transformer is a robust, passive component interposed between the motor and drive electronics. Voltage spikes at the motor are reduced by the transformer turns ratio before transference to switching semiconductors. The circuit topology used effectively decouples much of the motor reactive behavior from sensitive drive circuitry.