DC MOTOR POWER REGENERATION

This paper will focus on the subject of retrieving electrical power from a spinning permanent magnet DC motor or generator. Hopefully this paper will give readers a more practical understanding of the DC motors/generators and power regeneration.

The power may want to be tapped from the spinning generator for the following reasons:

- Stopping
- Controlled deceleration
- Generating electricity

Introduction

Permanent magnet generators differ from inductors since inductors store energy in their magnetic fields where Permanent magnet generators or motors store the majority of their energy in the rotational kinetic energy.

The energy stored in an inductor is equivalent to:

E= ½ L* I^2

E= energy in joules

L= inductance in Henries

I = Current in amperes.

The kinetic energy of a rotating object:

E=1/2 *I* w^2

E= energy in joules

I=moment of inertia of the mass about the center of rotation in (kilograms * meters^2)

W=angular velocity in radians per second or (revolutions per second * 2PI)

The moment of inertia for a solid-cylinder is

I=1/2 * Mass * radius^2

I=moment of inertia of the mass about the center of rotation in (kilograms * meters^2)

Mass= Mass in (kilograms)

Radius=Radius of cylinder in (meters)

Rotor Spinning Example:

For a typical ½ Horsepower DC motor with a rotor weighing 2kilogram and a radius of 6cm(.06 meters) the moment of inertia is:

I= ½* 2 * (.o6)^2 = .0036 kg*m^2

For the rotor spinning at 3600 rpm (60 revolutions/sec) the kinetic energy is:

E=1/2*(.0036 kg*m^2)*(60*3.14*2 rad/sec)^2= ½*.0036*142000= 255 joules

255 joules is equivalent to charging a 12 volts battery at 20amps for 1sec or 1amp for 20seconds.

Train wheel Spinning Example:

For a typical 1000kilogram train wheel with a radius of 1/2 meter the moment of inertia is:

I= ½* 1000 * (.5)^2 = 125 kg*m^2

For the rotor spinning at 300 rpm (5 revolutions/sec) with no load, the kinetic energy is:

E=1/2*(125 kg*m^2)*(5*3.14*2 rad/sec)^2= ½*125*986= 61622 joules

61622 joules is equivalent to charging a 12 volts battery at 20amps for 256sec(4+ minutes)

Inductor Example:

For a large 15mh inductor with 10 amps circulating.

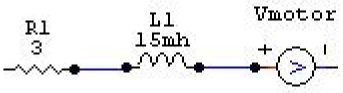
E= ½ * 15mh * 10^2 = .75 joules

Notice that the energy increases with the square of the rotational speed. If a train wheel or flywheel weighing 1000kg was spinning at 10000 rpm the kinetic energy stored would be about 70 Mega Joules. 70 Mega Joules is enough to supply a home with 1kilowatt of power for a whole day. Clearly it would be nice to be able to tap into this power source rather than waste the power as heat.

Models

The following figures are indicative of a simple inductor and permanent magnet motor/generator.

INDUCTOR MODEL



PERMANENT MAGNET
MOTOR MODEL

As can be seen from the models the permanent magnet generator is modeled with a voltage source. The voltage source is normally proportional to the speed. The voltage source adds a very important aspect with large implications.

Vmotor= K * (Revolutions per second)

Note if the current being feed to the motor is from the right the polarity of the voltage source in the model will be positive from the source. If the motor reverses direction the polarity of the voltage source in the model will change.

The models do not indicate the size of the flywheel or if the motor/generator is continuously supplied with power from a vehicle gliding down a hill, wind continuously blowing, or water wheel driving the shaft. The only why to sense the load is to start drawing power from the motor/generator and sense if the voltage drops. Clearly with a large moment of inertia the motor/generator will behave more like a battery.

The resistance and inductance vary greatly, depending on the construction. In general the longer and thinner the wire applied the higher the resistance. The only advantage the wind resistance gives is the current will be limited to the applied voltage divided by the winding resistance.

The inductance will also vary greatly depending of the size of the motor, number or windings, and core material. The inductance cannot typically be obtained from measuring the dc resistance. Permanent magnet motors/Generators are normally specifically design for a specified load, drive voltage, and drive current. The models do not indicate the size of the flywheel or if the motor/generator is continuously supplied with power from a vehicle gliding down a hill, wind continuously blowing, or water wheel driving the shaft. The only why to sense the load is to start drawing power from the motor/generator and sense if the voltage drops.

The first implication is the speed of the motor can be found by measuring the open circuit voltage. Second, the voltage source can provide a large current draw. Third the inductor in series with the voltage source may be of use. Fourth, the resistor is still in the way and will burn power as we try to tap power from the spinning rotor.

Motor Example

Max voltage: 40 Vdc

Series resistance: 3ohms

Max RPM: 3000 (50 revolutions/ second)

K= 40v / 50rev/sec = 0.8 v*sec

Therefore at 1200RPM (20 rev/sec) the voltage supplied with no load would be:

Vmotor= .8v*sec * 20per sec = 16 volts

Short circuit current= 16v/3ohms= 5amps

The power delivered to the load is:

Pdel= Vmotor*Imotor – Rmotor* Imotor^2

Notice the last squared term. Drawing too much current will result in no power delivered from the motor. Matching the motor coil resistance will deliver the most power from the motor but, with an expense of a 50% loss in power. Clearly shorting the coil will result in the fastest way to stop or braking the motor. Our goal here is to tap the most amount of available power over a finite period of time. For reasonable 10% power loss across the windings the current draw will equate to:

I= (Vmotor * .1) / (Rmotor *1.1)

Notice the optimal 10% loss current draw varies with the motor voltage, which varies proportionally to the speed of the motor. Therefore knowing the speed of rotation of the generator is a useful variable for figuring out how much power to draw. Tapping too much power may result in slowing the motor down too rapidly. For example the designer may want an optimal rotation speed for a given wind speed, water height, or down hill coasting speed.

Tapping Power

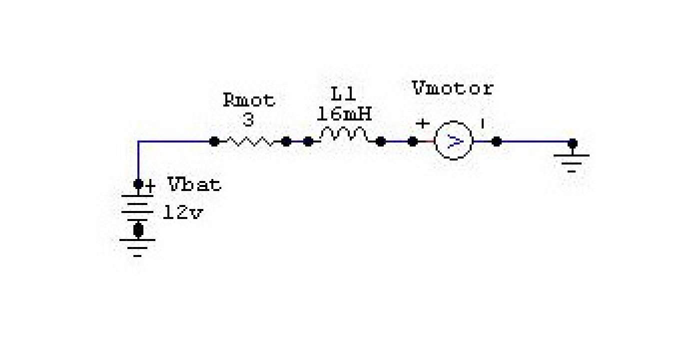
There are few popular methods for tapping power from the spinning generator. The best method depends on the variables such:

1) Desired battery voltage

2) Simplicity

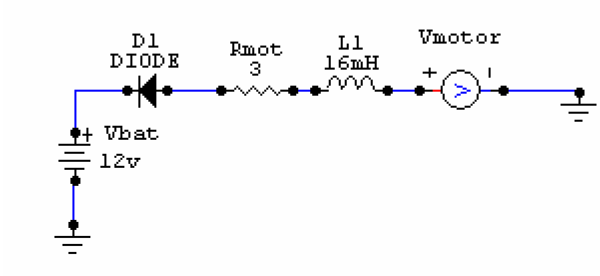
3) Hardware requirements.

The easiest method is to tie the motor directly to a battery.

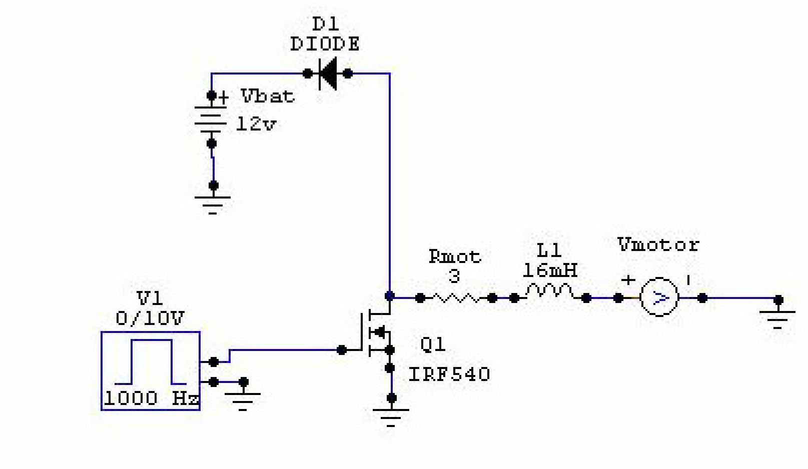


There are a few problems with this configuration. One is the battery will draw current, turning the motor, when the motor voltage is below the battery voltage. The second problem occurs when the motor voltage is above the battery voltage drawing from the motor what could be a large current braking and possible over heating of the motor and battery.

The solution to one problem is to add a diode in series with the motor. The diode will prevent the battery from driving the motor. When the motor voltage, which is proportional to the speed, increases above the battery voltage the motor will start charging the battery. At lower speeds when the open circuit motor voltage does not reach the battery voltage the battery will not charge this may not be desirable. At low speeds no load will be presented to the motor and no battery charging will occur. Once the motor voltage is reach the load on the motor will increase rapidly. The increase in load will be sudden. At high speeds the current drawn from the motor limited by the internal winding resistance. The simple series diode technique may be useful for some applications.

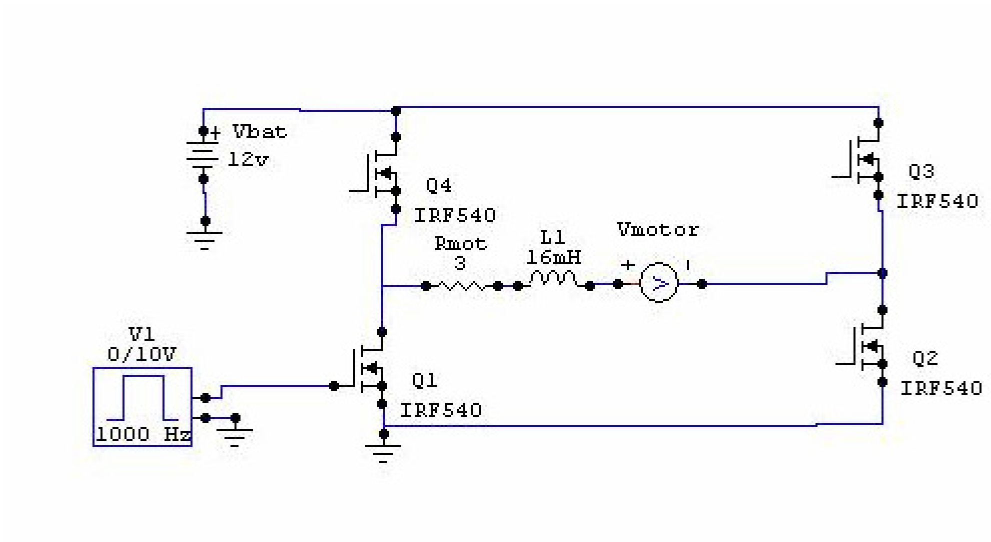


The third solution is more complicated. The nice part, a chopping H-Bridge configuration inherently includes all the necessary components. The simple explanation, the motor’s internal inductance and voltage is used as a DC-DC converter. If you examine the schematic below, the N-Channel MOSFET is added along with a MOSFET gate driver. If the Q1 MOSFET is turned on for an extended period the motor will short, drawing a large current, braking the motor. If the MOSFET is pulsed for milliseconds or micro seconds the current will build up in the inductor L1. With the field built up in the inductor the MOSFET will be quickly turned off. The voltage across the inductor will rise till the voltage reaches the battery voltage plus a diode drop. The battery will then be charged till the field in the inductor drops.



Most of the principles of DC-DC converters apply to chopping technique. The main differences are the variable motor voltage and the motor inductance. In the design of a typical DC-DC the designer chooses the optimal inductance. Inductances in DC-DC converters are typically in the micro Henry range not the tens or hundreds of milli Henry range for motors. The switching frequency will then need to be lower and possibly variable to match the motor inductance.

The typical H-bridge configuration is indicated below. Note the extra MOSFETS and the removal of the diode. The MOSFETS have internal diodes from the source to the drain. MOSFET Q1 is still pulsed to build up the current in the motor's internal inductance. Once Q1 is turn off the current will pass through the internal diode of Q2 and Q4 to the battery. MOSFETS Q4 and Q3 remain off but Q2 can be left on will no impact.



The H-bridge chopping technique has many advantages. When the motor open circuit voltage is lower than the battery voltage regeneration can still be achieved. A higher voltage battery can also be used since the inductor voltage will increase till the battery voltage is met. The motor will no longer see an abrupt load and the loading current can be controlled with the PWM pulse width and cycle rate. Note if the motor voltage is larger than the battery voltage the chopping technique will not work, the motor will continuously charge the battery though the Q4 MOSFET diode.

The formulas below indicate the behavior of the inductor, not including the series resistance. As can be seen during the PWM cycle the current will increase linearly with time. The power in the inductor’s magnetic field increases with the square of the current. For the large inductance in a motor the PWM on duty cycle will need to be longer than for a typical DCtoDC converter. The other possibility is to not let the current in the inductor not drop back to zero when charging the battery so the inductor will not need to start at zero current each time.

$Vmot = L\ d(i)/d(t)$

$Vmot * deltaT = L * deltaI$

$(Vmot * deltaT)/L = deltaI$

Energy Inductor = $\frac{1}{2} * L * I^2$