Introduction

Electrical motors are reversible machines; they can function as motors or as generators. A motor receives electrical power from a battery and transforms it in torque developing a Counter Electromotive Force CEMF, which opposes the battery. A generator receives mechanical power from a mechanical actuator and transforms it in electrical power developing a Counter Torque, which opposes the actuator.

A motor behaves as motor and as generator at the same time. In fact while a motor is 'motoring', that is doing mechanical work, it generates CEMF acting as generator, although the CEMF is lower than the battery voltage so the motor acts as a load and absorbs current.

In certain situations the CEMF may overcome the battery, in which case the generator component becomes dominant; the motor acts as a generator inverting the direction of its current and forcing it into the battery.

The typical situation is the one of a heavy vehicle rolling on a sharp downhill slope and forcing the motor to turn fast enough that the CEMF becomes larger than the battery voltage. As soon as the motor overcomes the battery it inverts the current direction and starts feeding current into the battery, while developing a counter torque that acts as a brake. This phase is called regeneration (recharging of the battery).

The Voltage / Current plane

Two wire DC electrical devices have one of the two poles marked as positive. By convention this is the pole where the positive voltage applied or generated is located.

These devices are divided into two categories:

- Generators: Batteries, dynamos, fuel cells etc.
- Users: Resistors, ovens, motors etc.

The current is defined as positive if it enters the positive pole of a user, or exits the positive pole of a generator. See figure 1.
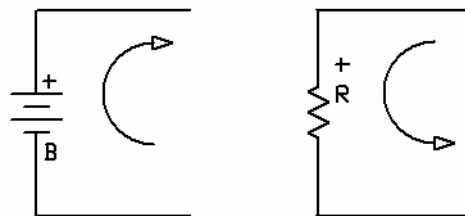

FIGURE 1.

Obviously it is possible to force a negative current on the positive pole.

As an example, a common car battery (generator) sources a positive current (exiting the positive pole) when starting the car and sinks a negative current (entering the positive pole) while being recharged.

Similarly current can be made to exit from the positive pole of a resistor (user) inverting the voltage across it. By representing positive and negative voltage / current in a plane as VI axis, we distinguish four quadrants.

As an example let's look at a car battery (figure 2); Q1 and Q 3 are the quadrants where the battery acts as a generator, since the current exits the positive pole. In Q1 the generator maintains a positive power rail while in Q3 the battery maintains a negative power rail.
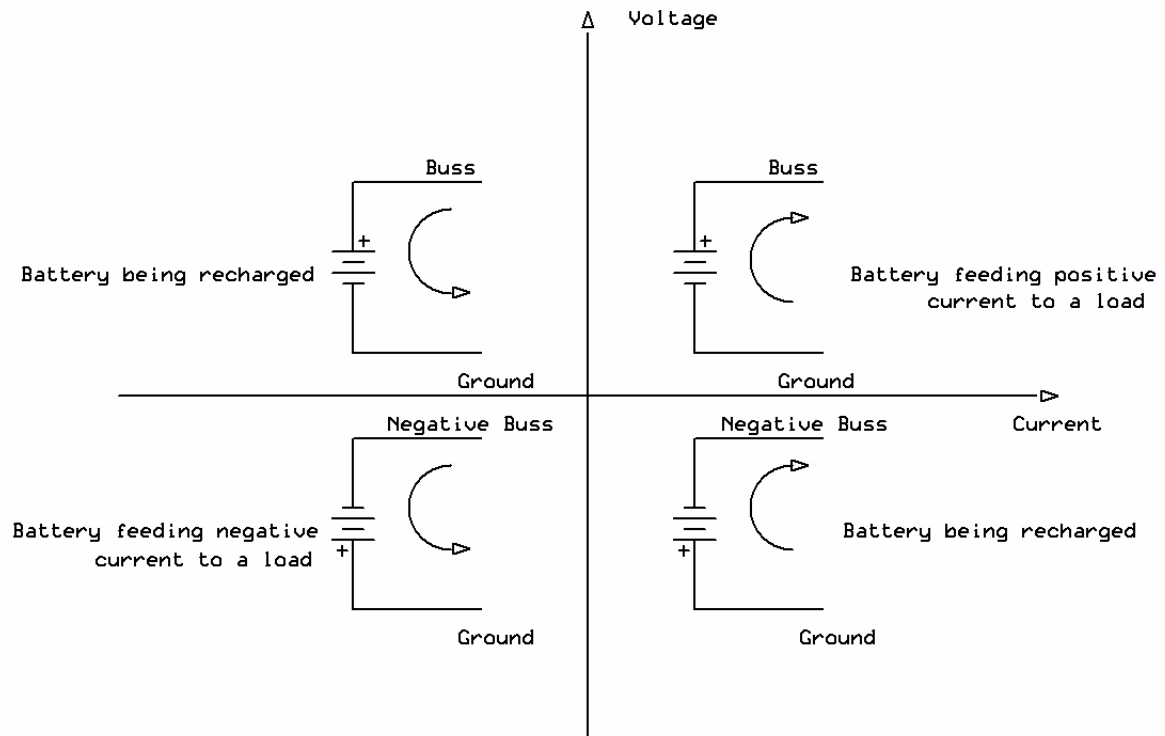

FIGURE 2.

Q2 and Q4 are the user quadrants, where the battery acts as a load to a battery charger that pushes current into the battery recharging it. In Q2 the battery charger output maintains a positive power rail, where in Q4 the charger maintains a negative power rail.

We will see shortly that a permanent magnet DC motor is also a four-quadrant device, acting as a user in Q1 and Q3, and as a generator in Q2 and Q4.

The motor as a four quadrant device

Most electrical motion operated by a battery use permanent magnet PM motors, since in this case no battery current needs to be spent to generate the magnetic field. Reversing the armature current reverses the direction of rotation.

The only exception is for very large vehicles, where high power motors are needed, beyond the capability of permanent magnets, In this case a 'separately excited' motor is used, mostly the shunt version which, as long as the field winding is feed at constant voltage, behaves like a PM motor (constant flux).

In practice, since the shunt motor may malfunction should the field current accidentally become zero, what is used is a variation of the shunt motor called 'compound'. A small series field winding is added, to guarantee a minimum amount of field as long as there is armature current. An advantage of the shunt motor is that direction is reversed by reversing the field current, rather than the much larger armature current.

The interesting characteristics of the permanent magnet motor are:

- Predictable behavior.
- Ability to develop maximum torque at startup, when speed is zero
- Absence of run away condition, this being the situation where the motor indefinitely increases its speed, until it destroys itself (something that can happen with separately excited motors).
- Ideal in battery operation, since they do need to consume current to create the field flux.
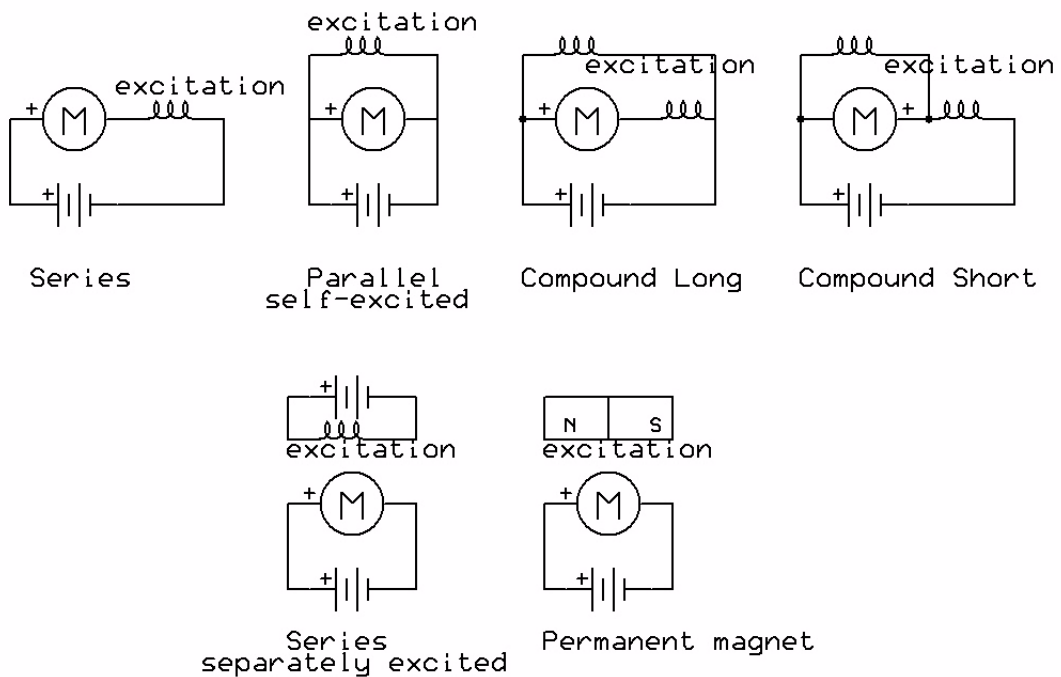
FIGURE 3.

From now on we refer exclusively to PM motors; they are widely used in many applications up to several HP.

As previously shown, a motor is a reversible machine; it acts in four quadrants of the Voltage / Current plane.

The motor can be assigned a positive pole, which corresponds to one of the two senses of rotation, for example the one moving a vehicle forward. Let's assume this is the clock-wise CW direction (Q1). Inverting the armature current inverts the direction, which becomes counter-clock-wise CW (Q3).

Q1 and Q3 are the quadrants where the motor is motoring, that is absorbing electrical energy and making mechanical work. Q2 and Q4 are the quadrants where the motor is generating, that are it is mechanically pulled, like for example by an electrical golf cart going downhill, and it acts as a DC generator.
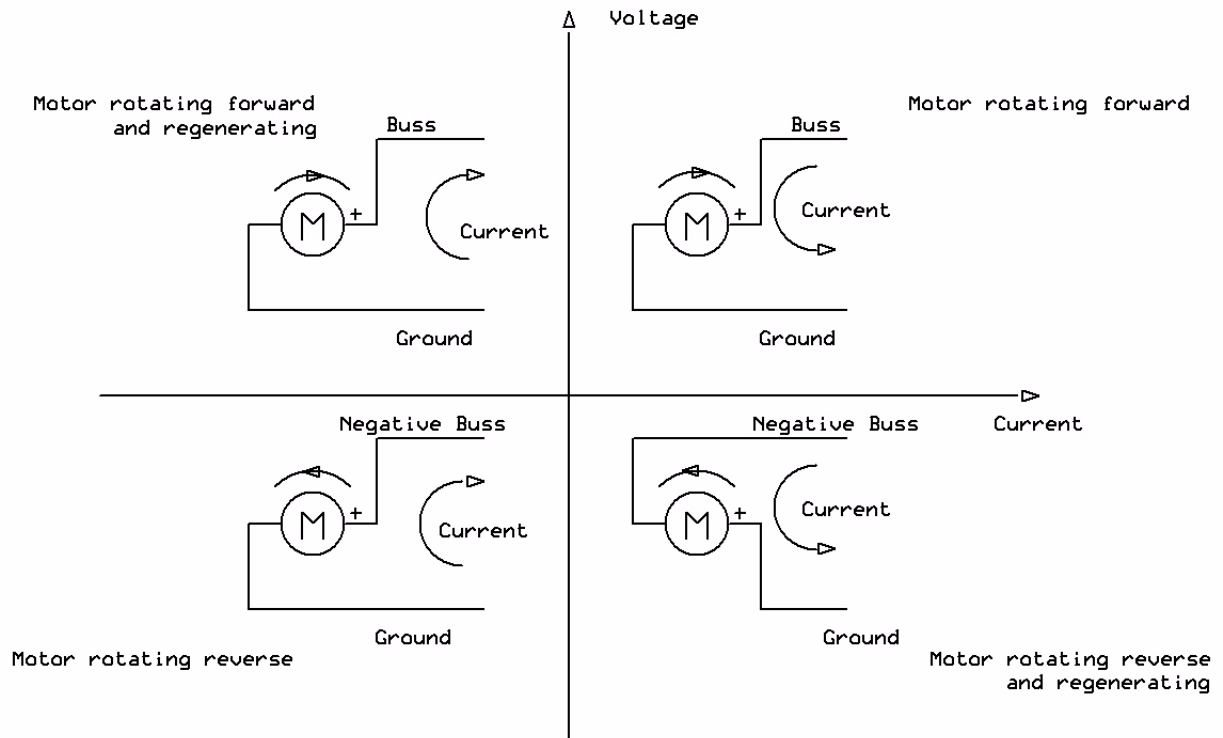
FIGURE 4.

It is useful to understand the equivalent circuit of a permanent motor. It is composed of a voltage generator equivalent to the Counter Electromotive Force CEMF, a series resistor equivalent to the resistance of the copper of the armature winding, a series inductance.

```
                            +
                                        Va armature voltage
Armature resistance  <Ra

                                     ↑

Armature inductance  ≷La

                +
              ═══
              │CEMF                    ▽     Ia armature current


                _

        CEMF = K1 x Speed
        Ra from 0.1 to 1 Ohm
        La few milli-Henry
        Torque = K2 x Ia
```
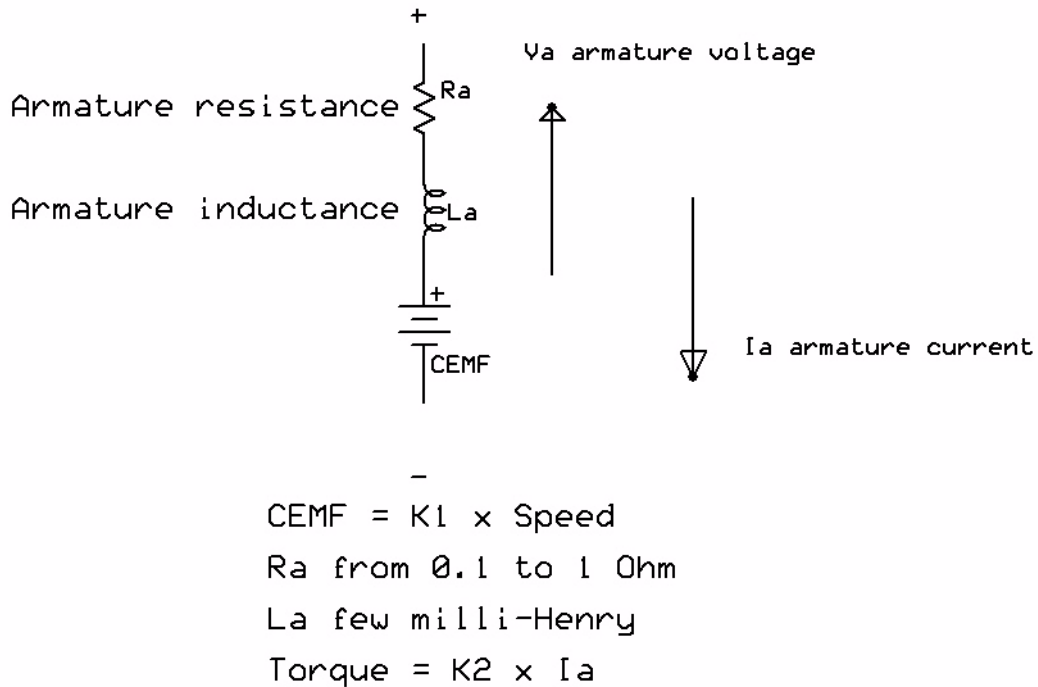
FIGURE 5.

The figure above shows the electrical equivalent circuit. The flux of the motor is constant so it is incorporated in the constant.

Note that torque is proportional to armature current and CEMF is proportional to the speed; the faster the motor turns, the higher is the CEMF. If the motor is turned by an external agent (gravity on a steep downhill) the CEMF can exceed the voltage of the battery and recharge it.

Energy balance in a vehicle

A moving vehicle has three energy components associated with its motion:

- Kinetic energy E_K
- Potential energy E_P
- Rotation energy E_R

$$E_K = \tfrac{1}{2} M V2 \text{ where M is the mass and V is the speed} \qquad \textbf{(EQ 1)}$$

$$E_P = M g H \text{ where } g = 9.8 \text{ m/sec}^2 \text{ is the gravity acceleration and H is the height} \qquad \textbf{(EQ 2)}$$

$$E_R = \tfrac{1}{2} I W^2 \text{ where I is the moment of inertia and W the angular velocity} \qquad \textbf{(EQ 3)}$$

E_R is normally very small and can be ignored (unless the vehicle is build on purpose with a heavy spinning wheel, such as boats using gyroscopic rotating masses for stabilization).

The total energy of the vehicle is:

$$E_{tot} = E_K + E_P = M (½ V2 + 10 H) \hspace{2cm} \textbf{(EQ 4)}$$

We have approximated gravity to 10 meter/second^2.

A vehicle beginning an uphill slope will slow down losing kinetic energy (speed diminishes) while gaining potential energy (height increases). A vehicle beginning a downhill slope will lose potential energy (height decreases) and gain kinetic energy (speed increases).

A vehicle going over a summit with its motor disengaged will start moving downhill at constant acceleration until it will reach constant speed. This will happen when attrition and air resistance become sufficiently high to balance gravity. This is similar to a man parachuting who will initially fall at constant acceleration, until wind resistance will balance his speed and keep it constant.

A vehicle going over a summit with its motor engaged will behave in the same way, except that the motor will turn into a generator, effectively adding a braking effect to attrition and wind resistance so the vehicle will reach constant speed sooner and the speed will be lower.

Once the speed becomes constant, the kinetic energy remains constant; only the height decreases by a constant quantity over time. The delta Energy DE_P is equal to:

$$DE_P = 10 M (H2 - H1) \hspace{2cm} \textbf{(EQ 5)}$$

H2 is the initial and H1 is the final height.

Let's assume in the last case for simplicity that attrition and wind resistance are negligible, then all the lost potential energy goes into the motor.

If we make the loss of altitude H2 - H12 equal to the loss in one second, then assuming the motor is connected to the battery, then the motor will transform in electrical power the lost Potential Energy per second.

$$\text{Electrical Power} = DE_P = 10 M (H2 - H1) \hspace{2cm} \textbf{(EQ 6)}$$

Let's make an example.

A 300 kilograms electrical cart rolls downhill at a constant speed of 15 km/hour (about 10 mile/hour) on a 15% incline. Each second the cart covers four meters.

The loss of height per second is:

$$H2 - H1 = 4 \times 0.15 = 0.6 \text{ meters.} \hspace{2cm} \textbf{(EQ 7)}$$

The loss of potential energy per second is:

$$DEp = 10 \times 300 \times 0.6 = 1,800 \text{ Joule per second} \hspace{2cm} \textbf{(EQ 8)}$$

In electrical terms this equates to 1.8 kilo Watt of electrical power.

The motor will generate an equivalent current (minus the generator efficiency), which will recharge the battery.

Coasting, Dynamic, Regenerative Braking

Let's assume we have an electric cart reaching a summit and then rolling downhill. As the cart passes the summit, the current in the motor drops to zero as no more torque is requested of the motor. The cart starts rolling downhill at constant acceleration, speeding up and forcing the motor to turn faster and faster so the CEMF increases until the motor turns fast enough that the CEMF exceeds the battery. At that moment the motor becomes a generator and the current will invert its direction and flow into the battery recharging it.

The motor, as generator, will develop a Counter Torque, (equivalent to the motor developing a CEMF) which will act as a brake. Eventually Counter Torque and gravity will balance each other, at which point the cart will stop accelerating and will roll downhill at constant speed.

There are three ways a cart can be designed to handle a downhill:

- Coasting.
  The motor is disconnected and left floating. There is no braking effect from the motor and the cart will accelerate so to accumulate the maximum kinetic energy to help with the next uphill climb.
- Dynamic braking
  The motor is detached from the battery and connected to a resistor. The potential energy lost downhill is dissipated as heat. The motor acts as a brake but the energy is lost as heat.
- Regenerative braking
  The motor stays connected to the battery and the CEMF (once exceeding the battery) will recharge the battery. The motor acts as a brake and the lost potential energy is stored in the battery.

Using a Power Supply

In some stationary application a power supply may be used instead of a battery; in this case regenerative braking may become dangerous.

A battery is a two-quadrant generator, capable of issuing (discharge) or receiving (recharge) current at constant voltage.

A power supply in general is designed as a one-quadrant generator, designed for issuing current at constant voltage, but not for receiving it.

If a power supply has to be used, then the best choice is a conventional power supply with large filtering output electrolytic capacitors; a regenerating motor will charge the capacitors and as long as the voltage does not exceed their maximum rating, the power supply will operate in two quadrants. A switching power supply may is in general not suitable.

The variable speed electronic motor controller

A Roboteq Variable Speed Electronic Motor Controller is a device capable of regulating direction and speed of a motor. This is achieved by using a Power MOS bridge. The controller controls the direction of a motor by conducting on one side or the other side, which effectively inverts the current in the motor.

Speed is controlled by pulsating the Top MOS on one side of the bridge, while the Bottom MOS on the other side is always ON (PWM regulation); the speed will be proportional to the Duty Cycle of the PWM.

The Bottom MOS on the same side of the bridge of the Pulsating MOS is pulsated too in opposition to the Top MOS (the two must never be ON at the same time, or they will short the power supply with consequent damage to the controller).

The reason for pulsating the Bottom MOS is to provide a low resistance path to the inductive current of the motor, which is made safely re-circulate avoiding the typical high voltage spikes generated by an inductive load.

The Figure below illustrates the concept. At the top the Power Bridge is shown when the battery feeds the motor, and at the bottom when the motor re-circulates.

Top Mos pulsed ON; Bottom Mos pulsed OFF
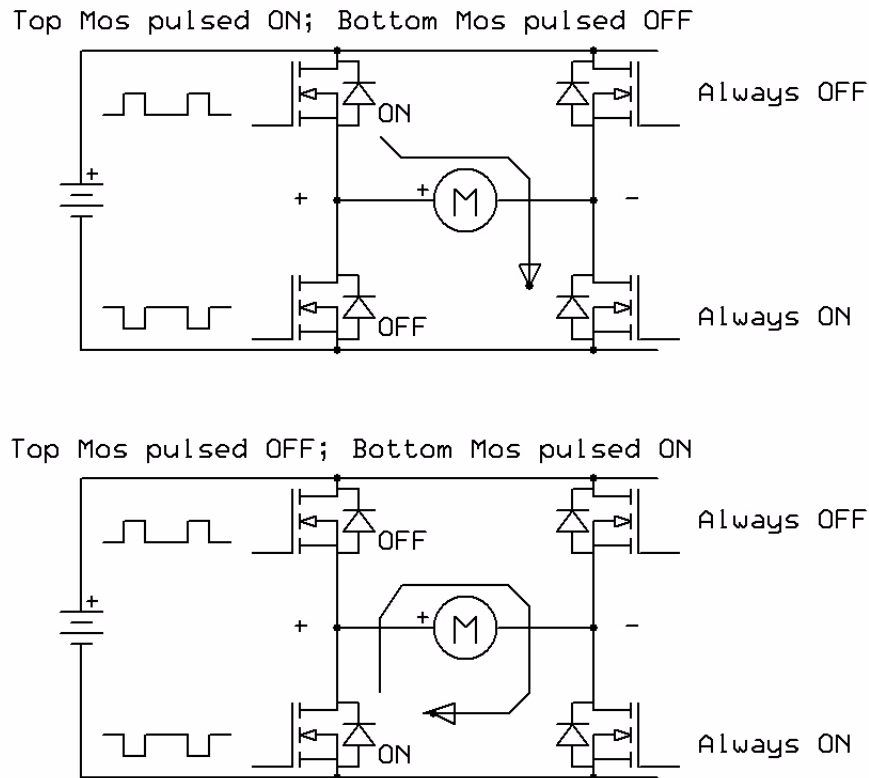
Top Mos pulsed OFF; Bottom Mos pulsed ON

FIGURE 6.

In the figure above both the controller and the motor have been conventionally assigned a positive pole, which for the controller corresponds to a positive current being generated and for the motor corresponds to the forward sense of rotation. Clearly this is a convention, as neither the controller nor the motors are in reality sold with a positive pole clearly marked.

Reversing the power bridge would reverse the sense of rotation of the motor, which would rotate backwards.

Less intuitive is the operation in the second and fourth quadrant, where the motor would generate current. To better understand this let's refer to the practical situation of a vehicle in motion.

A consequence of the motor current re-circulation is that the motor current is almost constant (effectively filtered by the inductance of the motor). Typically the inductance of a motor is few milli-Henry while the internal resistance is at least 100 milli-Ohm, so the time constant $T = L/R$ is in at least 10 millisecond, much lager than the PWM frequency, hence the smoothing of the current into an almost DC current.

The figure below shows how the Power Bridge chops the battery current, while allowing the motor current to be DC. In essence the controller maintains the battery voltage constant and chops the battery current, while in turn chopping the motor voltage and maintaining constant the motor current.

Obviously the power generated by the battery must be equal to the power given to the motor (the controller has very high efficiency). Indicating the duty cycle as DC:

Power generated by the battery:

$$V_{bb} \times I_{average} = V_{bb} \times I_{peak} \times DC \qquad \text{(EQ 9)}$$

Power received by the motor:

$$I_{mot} \times V_{mot} = I_{mot} \times V_{bb} \times DC \qquad \text{(EQ 10)}$$

Therefore:

$$V_{bb} \times I_{peak} \times DC = I_{mot} \times V_{bb} \times DC \qquad \text{(EQ 11)}$$

$$I_{peak} = I_{mot} / DC \qquad \text{(EQ 12)}$$

As an example, measuring 5 Amp continuous current in the motor when the duty cycle is 10% means that the peak of current in the battery is 50 Amp, something to take into account in designing the mechanical and electrical power connections.
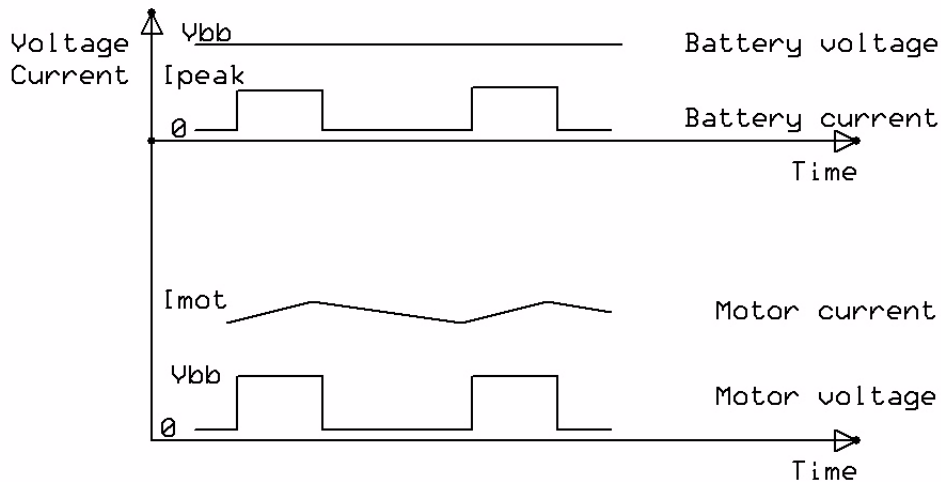

FIGURE 7.

In reality what described above is not what is observed, since the current at the battery I_{bb} is close to a DC current, due to the smoothing effect of the of large electrolytic capacitors mounted in the controller.

Consequently the battery delivers a constant amount of power (constant voltage/constant current):

$$P_{bb} = V_{bb} \times I_{bb} \qquad \text{(EQ 13)}$$

The motor conversely has its voltage V_{bb} chopped by the duty cycle DC and a constant current I_{mot}; the two powers need to be the same, therefore:

$$V_{bb} \times I_{bb} = (V_{bb} \times DC) \times I_{mot} \qquad\qquad I_{mot} = I_{bb} / DC \qquad \text{(EQ 14)}$$

In conclusion the current flowing in the motor is larger than the current measured at the battery except than when the duty cycle becomes 100%.

The example above refers to the controller and the motor in the first quadrant,

The motor as a generator

Figure 7 depicts an electrical vehicle climbing an incline moving forward (top) or in reverse (bottom). When the vehicle rolls downhill it will turn the motor pressed by the force of gravity so the motor will actually turn into a generator.

Motor pushes vehicle
motor rotates forward

Vehicle pushes motor
generator rotates forward

motor rotation CW

vehicle drives forward
going uphill

vehicle rolls forward
going downhill

(A) First Quadrant   (B) Second Quadrant

Vehicle pushes motor
generator rotates reverse

Motor pushes vehicle
motor rotates reverse

motor rotation CCW

vehicle rolls backwards
going downhill

vehicle drives backwards
going uphill

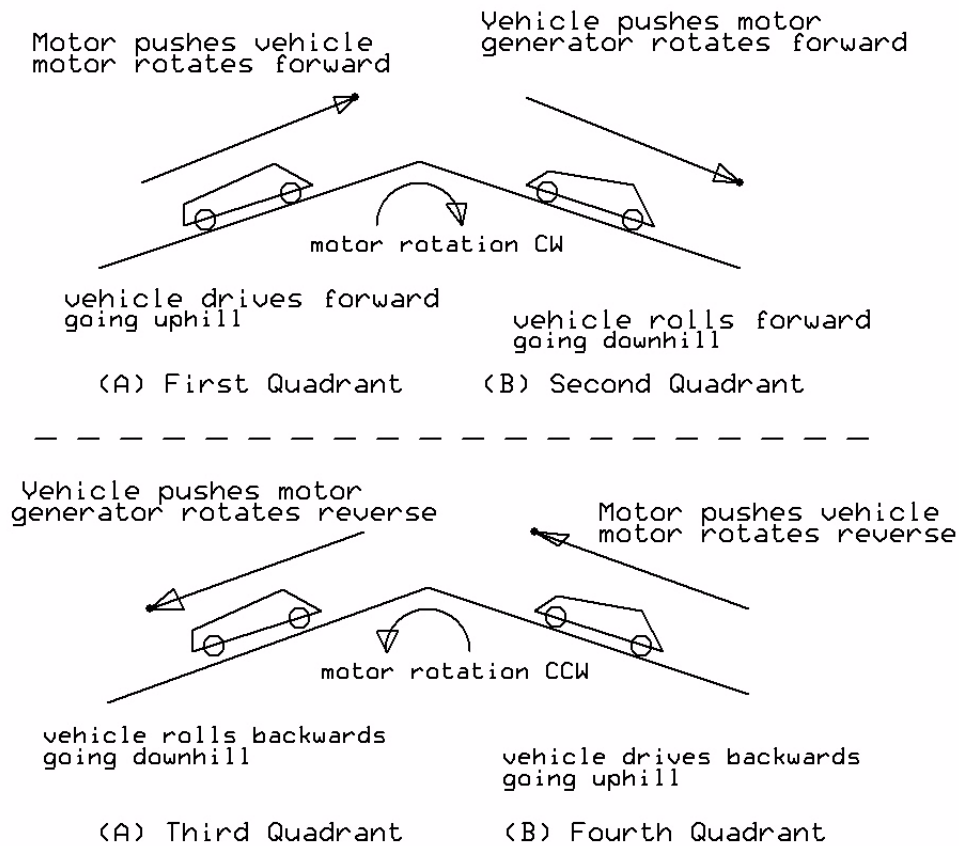(A) Third Quadrant   (B) Fourth Quadrant

FIGURE 8.

When the vehicle is climbing the motor will absorb current; when the vehicle reaches the summit the torque required will drop significantly and the motor current will drop practically to zero. When the vehicle rolls down the downhill slope the current will actually invert direction and flow into the controller.

The four quadrants

The figure below illustrates the four quadrants corresponding to the above situation of a vehicle moving forward and reverse either climbing up or rolling down.

For simplicity we have indicated only the current flow when the Power Bridge is in conduction, so the Top MOS ON and the corresponding Bottom MOS is OFF.

(A) First Quadrant

(B) Third Quadrant

(C) Second Quadrant
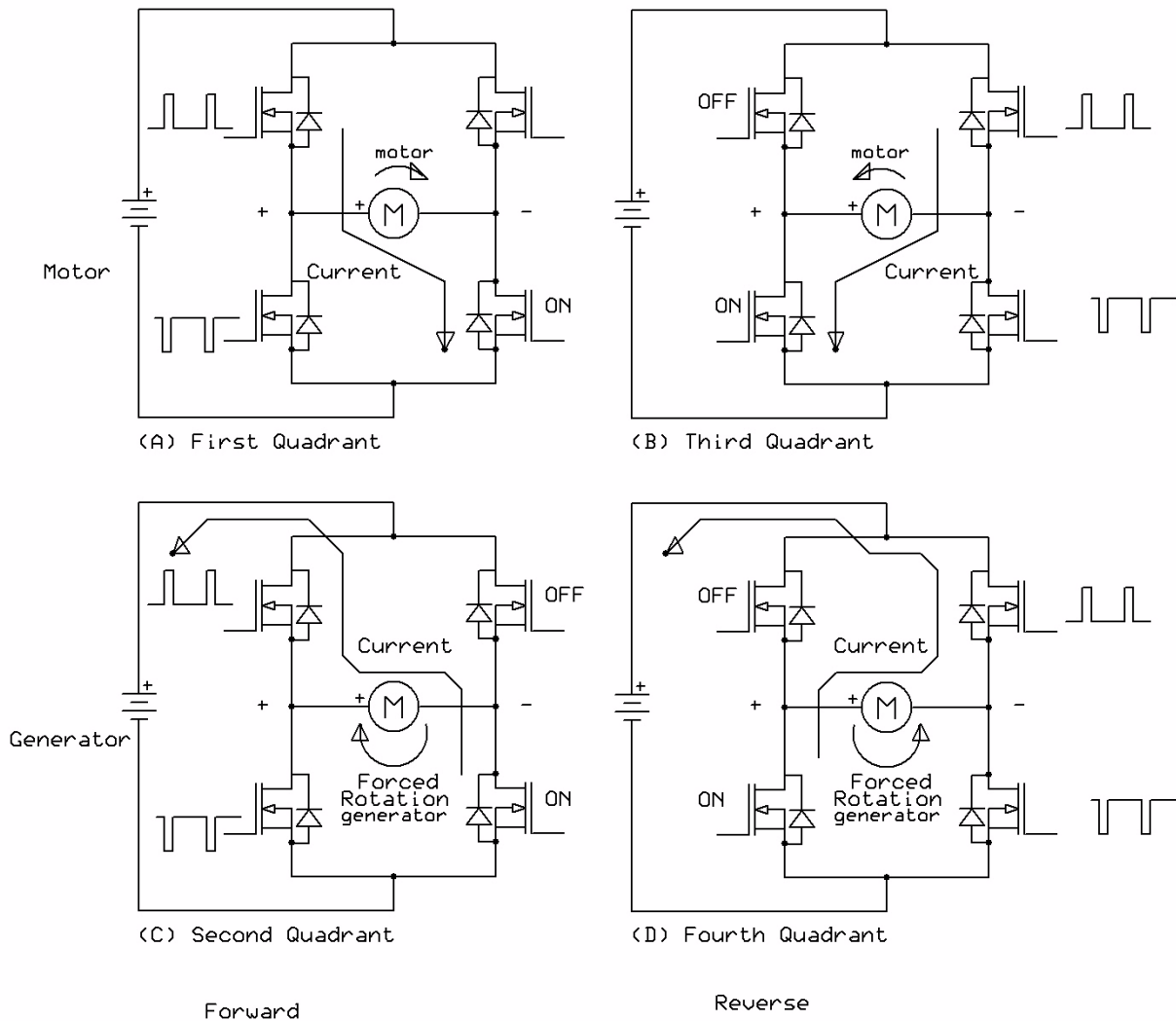
(D) Fourth Quadrant

Forward

Reverse

FIGURE 9.

The currents are indicated only for the phase of the Duty Cycle corresponding to the pulse (ON); when the Duty Cycle is OFF the current flow is not indicated, but in this case both Top MOS are OFF and both Bottom MOS are ON, so the motor is shorted and the current flows through the two Bottom MOS.

The Forward/Reverse gear switch controls the Power Bridge, which in turn controls which side of the Bridge conducts so inverting the current in the motor by exchanging the polarity of the voltage across the motor.

The accelerator pedal controls the duty cycle, which can be zero (both Bottom MOS ON), 100% (DC current) or in the between (pulsating).

While the vehicle rolls downhill the operator could keep gear and pedal in any position.

This means we have different situations where the motor regenerates.

Specifically:

- If the operator releases the accelerator pedal then the duty cycle becomes zero, both Bottom MOS are ON, both Top MOS are OFF and the generator is permanently shorted. The gear position makes no difference. This corresponds to dynamic braking, where the generator dissipates energy on its own internal resistance developing a Counter Torque that has a braking effect on the vehicle. No regeneration takes place.

- If the operator keeps the pedal pressed half way and the gear Forward, there will be a duty cycle and during the pulse of the duty cycle (ON) the Power Bridge will conduct and the generator will discharge its current into the battery. The regeneration lasts only the time of the pulse in the duty cycle (ON). During the OFF time of the duty cycle the motor is still shorted being both Bottom MOS turned ON so dynamic braking takes place.

- If the operator keeps the pedal pressed half way and the gear in Reverse, the above situation still applies, except that the other half of the Power Bridge will conduct. Consequently the current will enter the battery from the negative pole, so there will be no regeneration

From the above discussion results that the maximum regeneration is achieved with the pedal pressed fully forward so the duty cycle is 100% forward.

In this case the top left MOS and the bottom right MOS are permanently ON, and we have un-interrupted regeneration.
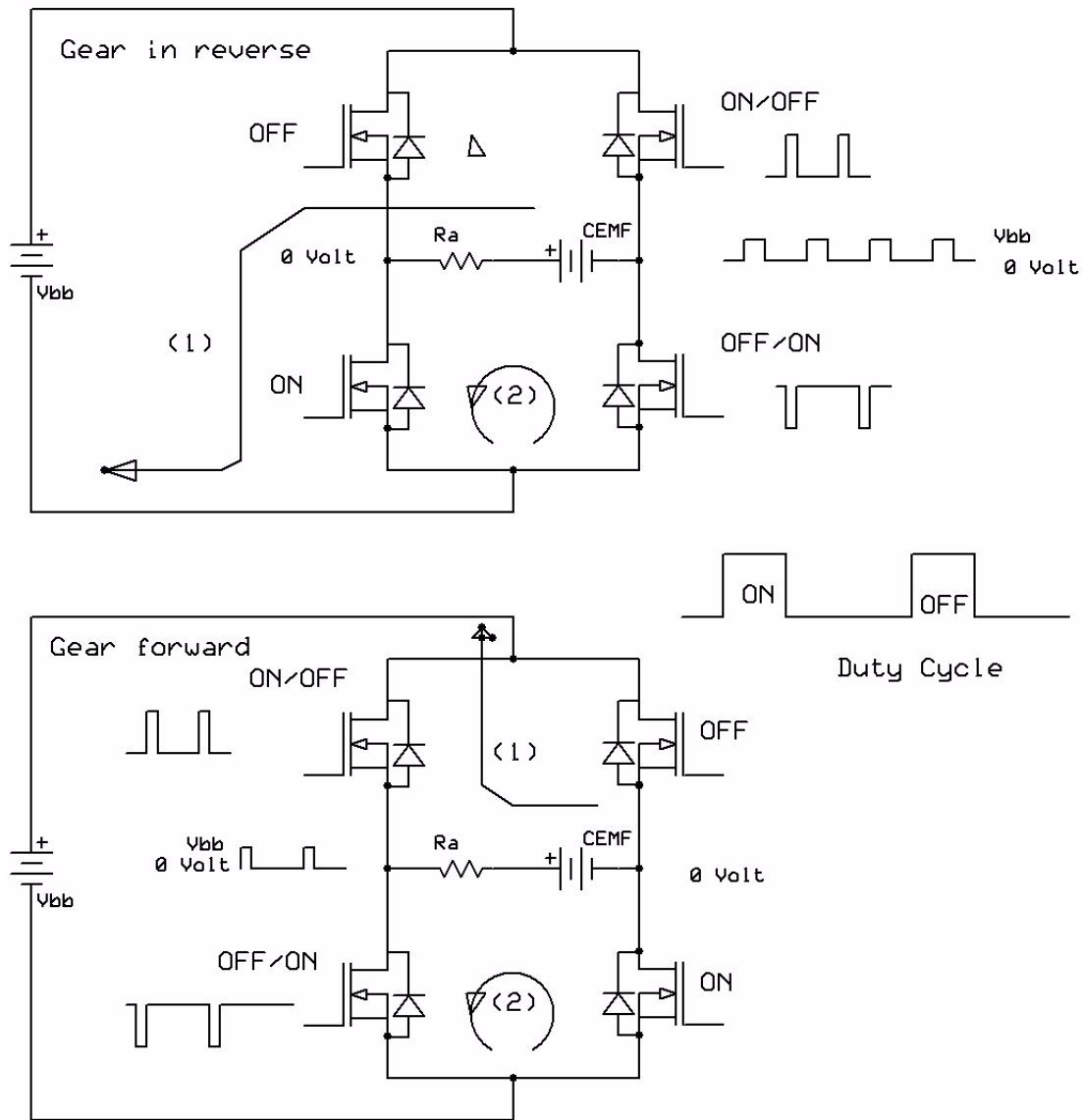
FIGURE 10.

Proofing the installation against regeneration

Few simple rules can help in achieving an installation which is secure against regeneration.

- Use two separate batteries, one (Vbb) for the motors and one (Vcc) for the controller logic. This ensures that the control logic is always correctly working even if the Vbb battery is semi-discharged and becomes subject to ample voltage swings which may cause unpredictable transients while the motors turn. Vcc can be any voltage and does not need to be tightly regulated, as long as its value does not fall below 12 Volt. Vbb needs no regulation at all and large changes in its value are tolerable as long as its peak value does not exceed 40 Volt. This means that in applications where a power sup-

ply is used, it is possible to use a simple supply consisting of a center tapped transformer, a four diode rectifier bridge and a small electrolytic capacitor to provide a moderate amount of filtering.

- Avoid turning ON/FF the voltage to the motors by a switch in series with the battery. Ground the Vcon wire instead.
- Should an emergency switch be needed, use:
  - a Double Pole Double Throw switch for small / medium motors.
  - a high current contactor which actuates a relay shorting Vcon to ground.
  In both cases ground the Vcon terminal when operating the emergency switch.

Following the above precautions will considerably reduce the chance of damage because of transients or regeneration.

Please note that grounding the terminal Vcon will float the power bridge; this will bring to zero the motor current except that if the motor is driven, it could create a regeneration current through the battery Vbb. Grounding Vcon does not automatically always ensure zero motor current

The figure below illustrates the above concepts in schematic form.

(A) SMALL MEDIUM MOTOR CIRCUIT WITH MANUAL EMERGENCY SWITCH
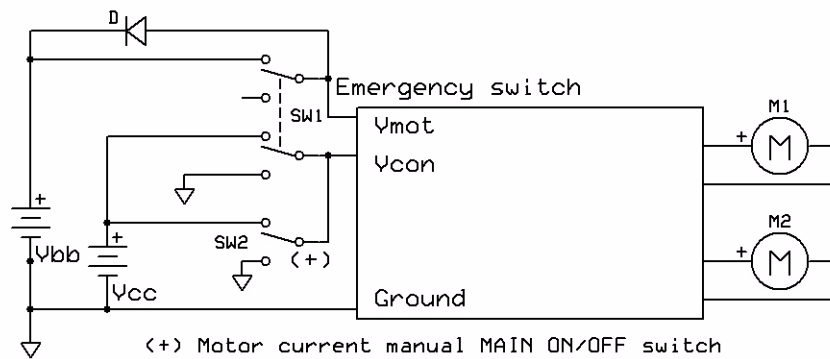
(B) LARGE MOTOR CIRCUIT WITH CONTACTOR EMERGENCY SWITCH
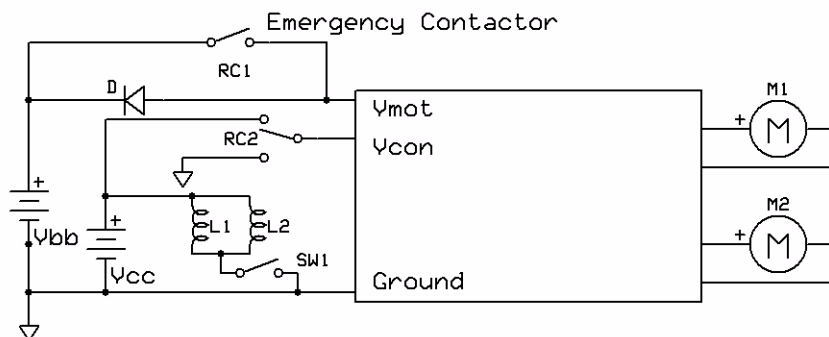
RC1 Contactor switch

RC2 ON/OFF relay contact

SW1 ON/OFF switch

L1 L2 Contactor and relay coils

With reference to the figure above, the schematic (A) is applicable to motors for a total current up to 30 Amp; above such value (B) a specialized high current switch, the contactor is used, a DC current switch operated through a coil, similarly to a relay. In both cases, operating the emergency switch automatically grounds the terminal Vcon. This fact not only helps against regeneration transients, but has the additional advantage that forces the current to zero, extending the life of the emergency switch by reducing the sparking across the emergency switch contacts.

A few words about the role of the diode D; such diode is normally reverse biased and conducts only if the regeneration voltage across the motors exceeds the voltage value. In this case the diode will conduct and will clamp Vmot to the voltage Vbb avoiding regeneration over-voltages and dangerous over-voltage spikes.

Essentially Vbb acts as a giant zener diode in parallel to the motor generator and limits the voltage across the motor and therefore across the controller.

For Robotic applications where a light vehicle moves on an almost flat terrain, then the diode D can be a plastic 50 volt, 10 Amp continuous current for motors having an armature resistance larger than 200 milli-Ohm.

In fact the diode D does not normally conduct, as it is shorted by the emergency switch, and conducts only if (1) the emergency switch is opened and (2) there is a regeneration voltage above the voltage Vbb, a situation which will happen rarely and will last a few seconds.

Obviously in cases where prolonged regeneration is expected from very powerful motors, like a fully loaded vehicle in a long downhill ride, then a diode D with adequate current capability needs to be used.

Battery disconnect during regeneration

From the above discussion it is clear that when the battery Vbb is disconnected it is essential to (1) short to ground the terminal Vcon and (2) have a recirculation path through the battery via the diode D to discharge the regeneration energy.

Unfortunately the battery Vbb may become disconnected in an unpredictable way when a protection fuse is blown open; in this case it a method needs to be adopted where the open fuse is detected and Vcon is consequently grounded.

The figure below shows a circuit which detects either an open fuse or an open emergency switch and shorts Vcon to ground. It is more complex then the preceding examples and its use is suggested in applications where high power motors are used (armature resistance below 200 milli-Ohm) and substantial regeneration is expected (large vehicle or heavy rotating mechanical mass).

It should be noted that the moment the fuse blows, the battery current from Vbb instantaneously goes from the tens of Amperes (the fuse current rating) to zero; the voltage drop across the battery internal resistance will disappear and the voltage across Vbb will increase instantly by several volts.This reinforces the turn on of the transistor Q1, creating a sort of histheresys effect turning on Q1even if the Vmot voltage before the fuse blows is close to Vbb.

If heavy regeneration is expected, then the regeneration voltage may exceed Vbb for an extended period of time (clamped at Vbb plus the forward diode drop), during which Q1 will remain OFF. In this case a second transistor Q2 will turn on. It should be that either Q1 or Q2 is ON, but not both at the same time. Q2 will conduct in case of extended regeneration.

If the fuse or the emergency switch becomes open,
    either Q1 or Q2 grounds Vcon avoiding regeneration damag

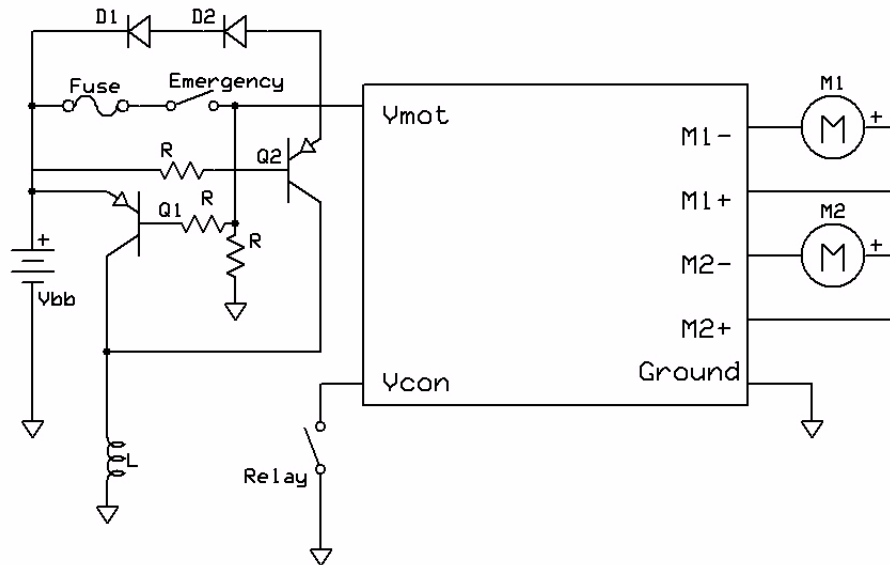D1/D2 clamps regeneration overvoltage to Vbb max

FIGURE 11.

Appendix A - Sizing the motor

There are many power train calculators on the Web, so rather than repeating one here, we take the opportunity to show on which formulas are they based.

Let's assume we want to determine the size of the motor needed to accelerate a 300-kilo mass M golf cart from zero to 15 kilometer/hour speed S up a 20% incline I reaching final speed in 10 seconds.

The speed V in meter / second is:

$$V = 15,000 / 3,600 = 4.2 \text{ meter / second}$$ **(EQ 15)**

The constant acceleration A required will be:

$$A = V / Time = 4.2 / 10 = 0.42 \text{ meter / sec2}$$ **(EQ 16)**

The space S covered by the cart is equal to:

$$S = ½ A T2 \qquad S = 0.5 \times 0.42 \times 10 \times 10 = 21 \text{ meter}$$ **(EQ 17)**

The cart will climb according to the slope I gaining H elevation:

$$H = I \times S = 0.2 \times 21 = 4.2 \text{ meter}$$ **(EQ 18)**

The cart energy will go from zero to E_{tot}, where

$$E_{tot} = E_K + E_P = M (\tfrac{1}{2}V2 + 10\ H) = 300 \times (0.5 \times 4.22 + 10 \times 4.2) = 15,246\ \text{Joules} \qquad \textbf{(EQ 19)}$$

The power P will be:

$$P = E_{tot} / \text{Time} = 15,246 / 10 = 1,525\ \text{Joule/sec} = 1,525\ \text{Joule / sec} \qquad \textbf{(EQ 20)}$$

Since 1 HP is equal to approximately 750 Joule / sec, the HP rating of the motor is:

$$HP = 1,525 / 750 = 2\ HP \qquad \textbf{(EQ 21)}$$

Assuming a 24 Volt battery system, considering the average efficiency of a motor is 75%, the electrical power required by the motor will be:

$$\text{Electrical Power} = 1,525\ \text{Watt} / 0.75 = 2,033\ \text{Watt} \qquad \textbf{(EQ 22)}$$

$$\text{Motor Current} = \text{Electrical Power} / \text{Battery Voltage} = 2,033 / 24 = 85\ \text{Amp} \qquad \textbf{(EQ 23)}$$