Electric Drives for Small Homebuilt Vehicles

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For the uninitiated the implementation of an electrical drive in a small vehicle may seem a complicated business; it is in fact fairly straight forward but it is a job made easier by understanding a few of the design issues. Although there are variations in drive types for higher power road going vehicles that can include sophisticated electrically commutated "brushless" drive motors and their matched multi-phase controllers most small power output drives use simpler brushed DC motors and battery powered DC motor controllers. These DC systems control motor, and hence vehicle speed by varying the supplied voltage to the motor; and reverse the motor direction of rotation by reversing the polarity. This kind of simple drive can be found in a huge range of small DIY EV applications from fighting robots, electric go-karts, electric locomotives, home-built scooters, kiddie cars etc, as well as in many commercial EV applications.

First off - a reminder of the main electrical elements. Clearly one or more motors is needed with an overall power capacity matching that required to drive the vehicle. These can be connected to the drive wheels in various ways which can affect the way your vehicle operates – more later. A power source is needed – usually a pack of rechargeable batteries. It is worth pointing out here that the total volume of batteries used affects the vehicle range – the underlying engineering parameter here is the amount of energy stored. Whereas the batteries must be wired up to give the correct nominal voltage it is the energy storage requirement that determines just how many batteries are needed. It's usual for the battery pack, motor and controller nominal voltages to be the same. Finally a motor controller is needed – or is, at the very least, preferable. The rest is wiring – well almost!

We'll start with the controller.

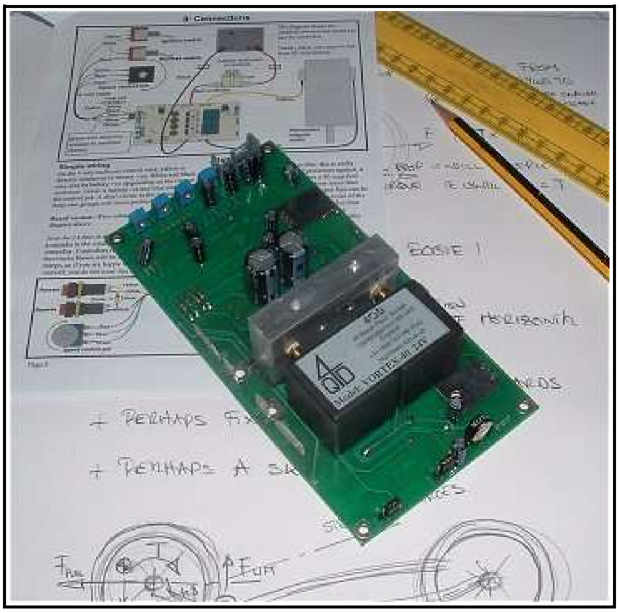
Why use a controller, what does it do? The DC motor controller takes the nominally fixed voltage from the power source, usually your battery pack, and outputs a variable voltage supply needed to control the motor. It does this in response to control signals supplied by the user – from a foot or thumb accelerator or a joystick control say. In modern controllers this voltage conversion is done very efficiently, with much much less wasted energy than a variable resistor arrangement and, given a good quality controller, with very smooth speed control results. Controllers also bring other valuable control functions – easily reversed drive, top speed limiting, control over acceleration and deceleration ramps, over-discharge protection for the batteries and in "4 quadrant" units dynamic regenerative braking capabilities in which the power generated by the motors as they slow a vehicle is fed back into the battery pack. In many ways electric drives perform much more like hydrostatic drives than clutch & gearbox mechanical transmissions. It is possible to make an electric vehicle work without a modern controller but using one provides many advantages in terms of performance, controllability and efficiency. The latter issue is important because the Achilles Heel of most EV's is the amount of energy that can be stored in a reasonably sized battery pack – loosing a significant proportion of this through inefficient speed control circuitry is just plain daft.

24/36V 150Amp Controller
Note the aluminium heat sinking and the gauge of the power cabling.

DC battery motor controllers are rated by voltage and current. If you think back to your high school physics you might remember that electrical power (in watts) in a DC circuit can be calculated from P= I x V where I is current in Amps and V is voltage. A typical smallish 24V 75 Amp controller therefore has an electrical power output capacity of 24 x 75 = 1800 W or 1.8 kW, about 2.5 Hp. Similar controllers are available right up to 48V x 300 Amp units with nominal power outputs of 48 x 300 = 14400 Watts, about 20 Hp. Note that these electrical powers are not what's finally available as mechanical work output at the drive wheels. Inexpensive DC motors may have efficiencies around the 75% to 80% mark and some energy will be lost in the mechanical transmission also. Perhaps our 2.5 Hp electrical output will end up as about 1.75 Hp at the drive wheels. When selecting a controller try to download the full spec sheet or manual from the manufacturer and read the conditions that apply to the current ratings – they are usually time limited and, because in the end it's controller heating that's usually the concern, effective heat sinking can make quite a difference. In our experience however it's much easier to keep a properly rated controller cool than the motors it supplies!

Controller – 150Amp
24/36V 150Amp controller with cover removed.

One of the best places to see the range of controllers available to you is to check out web sites of suppliers to the home-built robot community. Some of these fighting robots are heavy and require good acceleration and pushing power and they can demand a lot from their controllers. Two examples are given at the end of the article.



Controller – 40Amp
Smaller 40Amp controller without its box – note the wiring diagram in background from its user manual.

Motors

In our small vehicle projects we've generally found the use of DC permanent magnet motors to be least expensive and most satisfactory option – these are not the only type of DC motor that can be used but generally they are easy for the DIYer to get a hold of, are relatively efficient, physically compact and many can be used for reversing and dynamic braking applications. They also have the considerable advantage of being, at times, astonishingly inexpensive to buy – especially when Far Eastern built motors imported for electric scooter spares are considered. If you are keen on obtaining good levels of performance and controlled

Motor – 250W
Low cost Chinese built 250W electric scooter motor.

behaviour from your electric vehicle it is worth trying to obtain DC PM motors intended for variable speed duty such as electric scooter, bike or wheelchair motors. Power tool motors, auto-starter motors etc might work but not well compared to those actually built for the job.

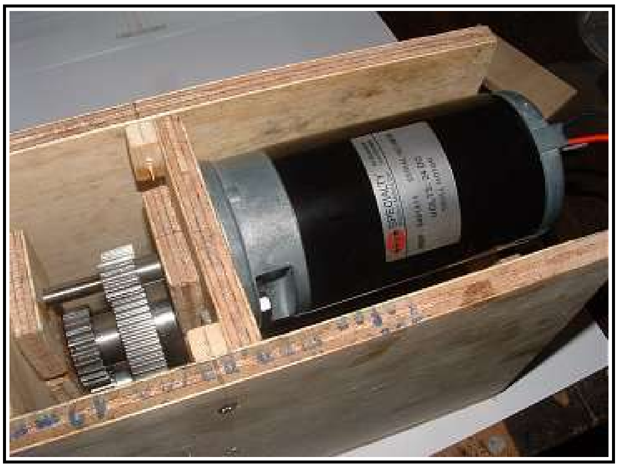
In what arrangement?

Perhaps the obvious first choice is a single drive motor and thinking just about motor cost a single motor is usually cheaper than two or more with the same overall power rating. However there are advantages to using two or even four motors rather than one that are worth thinking about. The main benefit is in achieving acceptable differential wheel action in the turns. To drive two rear wheels, say, with a single motor and to give variable wheel speed on cornering you will need either a differential gearbox or wheels fitted with bicycle style over-running clutches. The first is expensive and can be difficult to source for small projects, and the second removes both the ability of the vehicle to reverse under its own power and the ability of the drive system to contribute to braking the vehicle.

Alternatively driving each wheel with its own electric motor will allow the drive wheels to adjust their speeds on the turn under most cornering conditions whilst eliminating need for a differential box and keeping the wheels engaged to the drive for both forward and reverse drive - remember that there is no need to disengage an electrical drive just because the vehicle stops – if the vehicle stops so do the electric motors.

Gearing

In most small EV applications, unless there is a very large speed range, the motors can be connected to their individual drive wheels through a fixed ratio transmission – by either gear, chain or belt. If you choose to use a single motor driving a single common axle with no differential clearly this transmission is to the axle, for drives with differential gearboxes the detail depends on the diff and its input and output provisions. For whichever arrangement an important mechanical design parameter is the reduction ratio ie the ratio of the motor shaft output speed to the road wheel speed – this must be built into the transmission. To get an initial estimate of this work out the rpm of the road wheel when the vehicle is traveling at its full powered speed (see Issue #12) and find out the rated shaft speed of the motor (the shaft speed at full rated load and voltage). Divide the shaft speed by the wheel speed and that's your required reduction ratio. If you do not build in enough of a reduction ratio the motor will try to drive the road wheel faster than intended and will experience shaft torque demand higher than its rated capability. For DC PM motors the current draw is roughly proportional to the shaft torque - high shaft torques lead to high currents and then to high rates of heat generation which in the end cause the motor to overheat.



Motor – 250W – Wheelchair
250W wheelchair motor mounted in timber cased drive box – note the double stage gearing to reduce the drive speed to the main drive axle.

Many moderately paced small EVs can be found which have permanently engaged dual motor drives. The motors are usually connected in parallel to a single speed controller. This arrangement although theoretically less ideal for differential behaviour than series wired motors places less current load on each motor. It's worth reiterating here that the main limiting parameter for motors (and many other electrical components) is current throughput, excess current causes excess heating which if not controlled can fry the component from the inside out!

Motor Powers

Whether you choose 1, 2, 4 or more motors the key engineering design parameters are power output closely followed by correct gearing ratios. The motors must be capable of producing the required torque at the required speed to drive your vehicle (the product of torque and speed is power – back to high school again!) and this output torque and speed must be matched through the gearing to that required at the vehicle's road wheels. In the end using under-powered motors or failing to build-in enough of a reduction ratio simply results in motors overheating in their attempt to sustain the torque outputs asked of them.

Whereas the desired motor power can be determined analytically (an engineering degree helps here!) perhaps the quickest way to estimate power is by comparison with other similar sized and performing vehicles for which drive powers are known. 250 W to 500 W are fine for small kids buggies, a kart with a 1000 W drive will fairly shift with lighter riders. Our 1000 W mini garden tractor can easily haul combined loads of me, its own weight plus trailer loads of compost that I can barely lift to hook up to the drawbar – an all up mass of about a quarter of a ton. Look also at the specs for small commercial EVs - mobility scooters, golf carts, electric sports karts etc to see what they're capable of. But beware, the performance quoted by suppliers for such EV's is often right on the envelope for the motors used and is often conditional on load, drive conditions, short term duty etc.

For heavier vehicles comparison with existing IC engines will help, however IC engine and electric motor ratings are not made on the same basis and the performance characteristics of the two are quite different. An IC engine rating will be given at its max power output point and in a vehicle it will spend a great deal of time running at lower power output conditions. At the bottom of its speed range its output is likely to be considerably less than maximum, whereas a DC PM electric motor will produce large torque output at zero speed – a short term output several times its continuous rated torque output and just when you need it – accelerating the vehicle from rest. As a rough guide only, one manufacturer of larger AC electric drive systems suggests that to replace an IC engine in a road going vehicle use an electric motor with a continuous power rating of about one quarter that of the IC engine's rated output!

Batteries

As we've already hinted these are the weak points for many EV's – the general problem faced by the designer is the volume or mass of battery needed to store the amount of energy the vehicle will need to keep it going between charges. Some battery technologies are better at this than others ie some have higher “energy densities” than others, and, yes you guessed it, the cheaper battery types are generally the least capable. Lead acid batteries are the norm for most DIY builds – they are easy to get, easy to charge and are the least expensive to buy - as are their chargers. Other battery types that might be considered are Ni-Cad or Ni-MH although you will need to do your homework before constructing powerful enough packs and make sure you use compatible chargers. You can also expect to dig deeper into those pockets. Again, check out the robot builders, these types are used by some to save weight in their designs.

For those going down the lead-acid route they will find a large range available from shops supplying mobility scooters, golf carts etc and plenty on-line. Be sure however to use “cyclic” duty or “deep draw” types. These are specifically made for vehicle applications and are designed to be discharged deeply and then re-charged over several hundred cycles. Their internal construction is a bit different from standby or float type batteries which generally do no see this cyclic duty. Conventional automobile starter batteries are <u>not</u> cyclic duty batteries.

How many? Good question!

The quickest way for you to answer this may be the “empirical” approach – check out the batteries used in comparably powered EVs. You can always work up or down from there. If you don't have information on comparable vehicles or are interested in understanding what's going on in more detail then read on. Many engineers will want to be able to reach their own view before splashing out on a set of batteries.

In short you have to compare the current drawn by your electric motors to the discharge current capacity of your batteries. The discharge current is simply the current the battery can sustain for a given time before exhausting its charge. The motor's drawn current can be complicated to determine accurately because most vehicles have a variable duty – uphill, downhill, fast, slow etc and the drawn current varies with the varying load on the drive system. You may still be able to get some useful initial estimates though.

Motor drawn current.

First check the name plate on your electric motor(s). If it gives a rated current this is helpful and is usually the current drawn by one motor at its rated load. If you don't know this but do know their rated power output you can work out the drawn current from our equation $P = I \times V$, or rearranged, I (in Amps) = P / V, remember P must be given in watts and V is voltage for this to work. Multiply your answer by 1.25, this will make an approximate adjustment for motor inefficiencies (here 80%) - the electrical power input is always more than the mechanical power output from a motor. Do the motors run at full torque output all the time and therefore draw this full current all the time? Probably not, and it depends on the vehicle and how well the motors are matched to the vehicle's duty. However small, low power leisure EVs, especially those driven by kids may well be driven quite hard most of the time. It can be worth working out approximate battery life for two conditions – one in which the motors are driven at full capacity all the time (severe) and one in which they are only driven at, say, 2/3rds all the time – an estimate of average duty. Remember to add the currents from each motor if you have more than one connected in parallel.

Battery discharge current

If you then look at the name plate on most rechargeable cyclic lead-acid batteries you will see an “amp-hour” figure quoted. This, taken with the battery voltage, is a measure of the amount of energy stored in the battery, by convention it's a 20 hour (or C/20) rating, ie it reflects the amount of energy recoverable from the battery if you discharge it at a constant rate over a twenty hour period. The trouble is most DIY EV's end up with discharge times much shorter than this – 2 or 3 hours of continuous use would be a more realistic, even optimistic target, and the amount of energy recoverable from a lead acid battery is dependent upon the rate of discharge – the faster it has to discharge the lower the total energy it gives out. As a rough guide these batteries discharged in 1 hour will yield only about 60% of their 20 hour rating. At 2 hours it is about 75%. It might be tempting to assume that a 38 AmpH 12 V battery will give us a current of 38 amps at 12 V to be discharged in 1 hour – but it won't, it'll give us about 65% of 38 amps ie about 24 amps for 1 hour. Similarly for 2 hour discharge, we might think that 38/2 or 19 Amps for 2 hours will discharge our battery but in truth we'll only get about 75% of this – about 14 amps for 2 hours. There's really no substitute here for getting the full spec. sheets for your batteries from the manufacturer if you want to look into this further. These will usually list, or show in graphs, the currents that can be drawn over different time periods to discharge the battery.

Compare motor and battery currents.

If you have a single battery you can then simply compare the full, or if you choose average, motor current from your motor calculations with these current capacities for the battery to gauge roughly how long the battery will last before going flat. However the picture is a bit more complicated when you have more than one battery. For batteries connected in parallel, eg if you are running 12 V motors with several 12 V batteries, simply add up the discharge current figures for each battery and compare this total to the motor currents. If you have batteries connected in series you can't do this. Two 12 V 38 AmpH batteries in series still have a combined rating of 38 AmpH, but now it's at 24 V rather than 12 V – the controller draws the current at 24 V. You might think we are not acknowledging the added battery capacity here but we are – current at 24 V is capable of doing twice as much work as the same current at 12 V. Another way to see this is to look at the rated current of a 24 V motor and a 12 V motor both with the same nominal power output. The 24 V motor draws half the current of the 12 V motor.

So for batteries connected in parallel – add the discharge currents up, for batteries in series use the discharge current figure for one battery only. For battery packs made up of both parallel and series connected batteries identify the discharge current figure for each series block and then add them up over the parallel connections.

An example might help. Let's say you have 6 of 17 AmpH 12 V batteries arranged in three parallel connected 24 V series pairs to power a 24 V controller and motors. The 2 hour discharge current for one battery will be about 75% of 17/2 = 6.4 Amps. The discharge current capacity of the battery pack will then be roughly 6.4 Amps (the capacity of each 24 V series pair at 24 V) times 3 (the number of parallel connected 24 V pairs) = 19 Amps. This would be sufficient to drive a single 24 V 350 W motor at full load for about two hours - longer if the average power draw was less than 350 W.

There are a number of provisos here – we are talking about "balanced" packs ie using the same sized batteries in symmetrical connection arrangements, the batteries are new (their capacity will be affected by age) and the motors are running at full speed all the time. This later condition offers some hope of longer life. If the controller doesn't output 24 V all the time it effectively reduces the time it draws current from the pack. If it is a 24 V controller delivering 12 V to the motors it will, effectively, only draw current from the batteries for 50% of the time – the battery life will roughly double. You will need to read up on PWM battery motor controllers to understand why this is, suffice to say here they can be thought of as high speed switching devices in which the current flow from the batteries is being constantly switched on and off. The lower the controller's voltage output the longer these battery current "switches" spend in the off position.

With your motors, batteries and controller sorted all you need to do is figure out where and how to mount the motors, design the mechanical transmission to the wheels, find space for the batteries, find a space for the controller, figure out how to wire it all up and how to charge it when discharged – and you're off, simple! Well, maybe there's a wee bit of scope for another article there.

Joking aside, a few final notes. I haven't said much on building your mechanical transmission or on other build issues such as braking. So much depends upon the motor's shaft details, wheel details, vehicle space available and, not least, the tools you have available. However a few reminders might be appropriate. Try and get the gearing ratios right, this makes life a lot better for your motors. On brakes it really is bets to provide independent mechanical brakes – even if you have a dynamic braking electrical drive system. Note also that electric motors produce heat. Internal working temperatures well in excess of 100 C are not uncommon and much of this internal temperature will be transferred to the motor's external surfaces – how else can the motor loose heat. So watch what you touch and, if you are concerned about motor life consider parking up your vehicle if its motors are getting to hot to touch – this will usually still be well within their operating range and will keep things safe. For details of hand/foot speed control devices, battery charge monitors, "ignition" switches (yes many controllers allow you to build in a key operated on/off switch), fuses and wiring details check out the controller manufacturers' web sites. Finally, don't forget you will need a decent battery charger – one that looks after your batteries properly, get an automatic multi-mode charger.

Two web sites worth visiting to get a feel for the range of motors (especially larger output) and DC motor controllers available are; www.robotmarketplace.com/ in the US and www.technobots.co.uk/ in the UK. Lower cost motors can be seen at many on-line electric scooter spares retailers.

Ian develops and sells plans for small EV's at www.buggies.builtforfun.co.uk