CSIRO/UTS Solar Car Motors

The motors are brushless permanent magnet motors that feature two rotors, have no iron loss, and have an axial field construction. The motors are fully cased, use the highest quality magnet material, and have anti-corrosion coated magnets to ensure reliability. Having no iron loss and a fixed air gap gives optimum performance under all conditions.

	Surface	Halbach
Specifications [1]		
Number of poles	40	40
Number of phases	3	3
Weight of complete motor (kg)	16.2	13.2
Weight of frameless (kg)	10.7	7.7
Nominal speed (rad/s) [2]	111	111
Nominal torque (Nm) [3]	16.2	16.2
Maximum continuous torque at 111 rad/s (Nm) [4]	31	39
Magnetic gap – each side (mm)	2	2
Phase resistance (Ω)	0.0757	0.0997
EMF constant – L-N RMS EMF/speed (Vs/rad) [5]	0.39	0.56
Torque constant per phase (Nm/A) [6]	0.39	0.56
Performance at nominal rating [1]		
L-N RMS EMF (V) [5]	43	62
RMS phase current (A) [6]	13.9	9.6
Copper loss (W)	43.9	27.6
Eddy current loss (W)	2.6	2.7
Windage (W) [7]	2.1	2.1
Total loss (W)	48.6	32.4
Output power (W)	1800	1800
Efficiency (%)	97.4	98.2
Winding, temperature, rise (K)	22	14
Overload, winding, temperature, rise (K) [8]	64	40
Absolute maximum ratings [1]		
Maximum, winding, temperature (K)	383	383
Maximum speed (rad/s)	300	300
Maximum torque (Nm)	50.2	50.2

Notes

1. Specifications, performance, ratings, and price can change without notice, also see ‘Legal Notices and Disclaimers’. Specifications, ratings, and performance quoted for whole of motor at 293 k (20°C) except where noted.
2. 111 rad/s ≈ 1060 rpm.
3. 16.2 Nm ≈ 11.9 lb ft ≈ 2294 oz in.

4. Continuous torque is at maximum, winding, temperature.
5. EMF sinusoidal. Other EMF constants available, see ‘Motor Speed’.
6. Current sinusoidal and synchronised to rotor position. Other torque constants available, see ‘Motor Current’.
7. Excludes external windage etc., see ‘Motor Efficiency’ and ‘http://www.cip.csiro.au/Machines/papers/iwscem/’ for details.
8. Total temperature rise having already temperature stabilised at the nominal rating and then run for a further 72 s at 50.2 Nm and 111 rad/s, see ‘Thermal Modelling’.

Application Notes

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1. IMPORTANT SAFETY NOTICES

The earthing of the motor is achieved through the axle, see Figure 1 below. This earthing connection should be capable of carrying the maximum possible short circuit current. This maximum current is possibly the short circuit current capability of the batteries. The connection must be capable of carrying this short circuit current for the worst case time for protection devices (fuses, circuit breakers, etc.) to operate. If it is considered likely that the protection devices may fail then the earth connection should be rated continuously for the worst case short circuit current. Note power electronic devices normally fail short circuit, at least at first, therefore the motor controller cannot be relied upon to act as a fuse!

For the frameless motor it is necessary to handle magnetised rotors and there are a number of associated hazards. There is a large force of attraction between two rings or between a magnetic material and a ring. The force between two rings is the worst case and is approximately given by:

$$\frac{6.4}{\left(25\times10^{-3}+d\right)^2}$$

where d *is the distance in metres between the magnet rings.*

Note in the limit this force is 10 kN or 1 kkg or 1 tonne.

Other hazards include the demagnetisation/magnetisation of analogue watches, credit cards, and a like.

2. APPLICATION IDEAS

Below are a series of application ideas, it is *not* intended that these circuits are taken literally. All the circuits will require some experimentation before they can be used in a vehicle. The purpose of this section is to increase awareness of what is possible with the motors, *not* to provide complete solutions. The circuits are all suitable for either the Surface or Halbach motors.

- The motor can be interfaced to a wide range of controllers, a typical installation is shown below. Also see section 'Motor Controller'. Note, the diagram does not show user interface connections, soft start circuitry, or status information connections. The number and type of user interface and status connections will depend upon the controller. Whether a soft start is required will also depend upon the controller, note the CR20-75 requires a soft circuit (see controller manual).

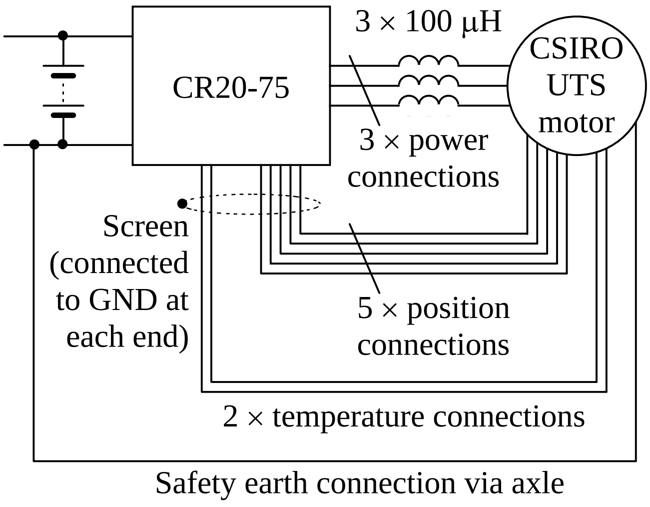


Figure 1. Power and control connections for Unique Mobility CR20-75 Motor Controller, note soft start circuity not shown

- Motor controllers typically apply a percentage of the battery voltage to the winding. This percentage is determined by their PWM ratio input. The PWM ratio input is sometimes, confusingly, called the speed input, but it does not hold constant speed if the battery voltage or load torque change. To provide true speed holding, a feedback loop is required, as shown below. The desired speed input shown below could come from a potentiometer or a cruise control unit, for example.

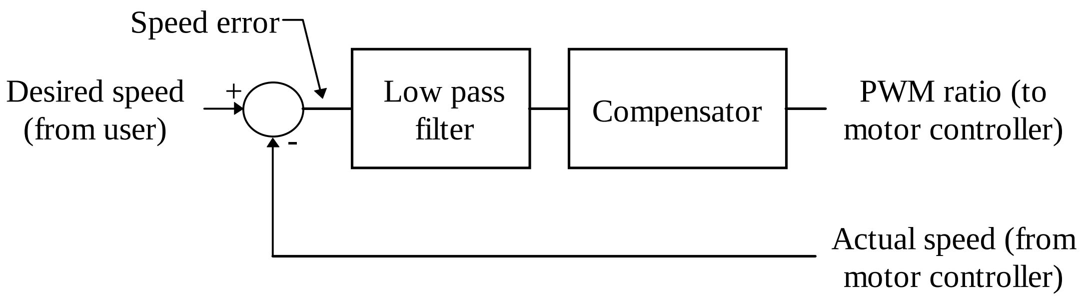


Figure 2. Block diagram of speed regulator for use with a motor controller that does not have speed regulation built in, but simply controls the PWM ratio

- Since the motor torque is approximately proportional to the RMS motor current it is possible to control the torque by controlling the current. Note, it is only practical to control the current on a per fundamental cycle basis using this technique, not on each PWM cycle.

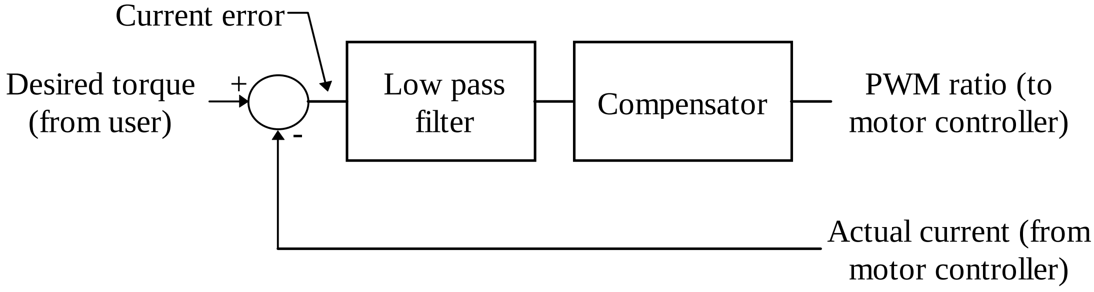


Figure 3. Block diagram of torque regulator for use with a motor controller that does not have torque regulation built in, but simply controls the PWM ratio

- Some motor controllers do not produce a signal proportional to RMS motor current; in these cases it is necessary to independently measure the current. The circuit shown below will require the filter in the torque regulator loop (see above) to be set so as to eliminate the fundamental phase ripple. About one fifth of the frequency of the fundamental for the lowest speed for normal running is a good starting point for finding the best setting for this cut-off frequency.

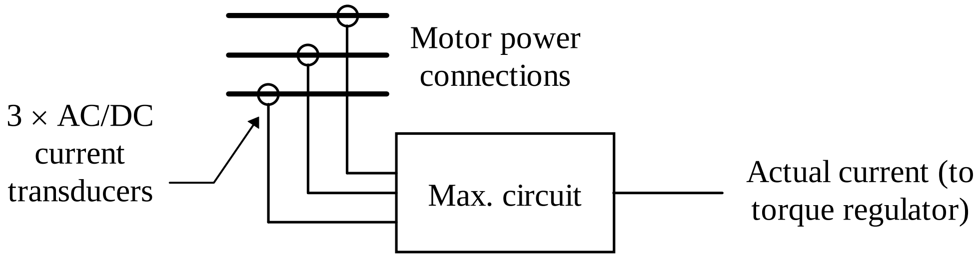


Figure 4. Measuring motor RMS current

- It is possible to parallel multiple motors under torque regulation, for example to drive individual wheels, to provide more power, and/or to provide redundancy. In general it is not possible to parallel motors under speed regulation, since the speed matching requirement is too great for most regulators in a typical application. It is possible to provide an overall speed regulator that uses the average motor speed. On vehicles with more than one driven wheel it is possible to provide traction control, ABS, and/or a limited slip differential by monitoring the different wheel speeds and adjusting the torque to each wheel accordingly.

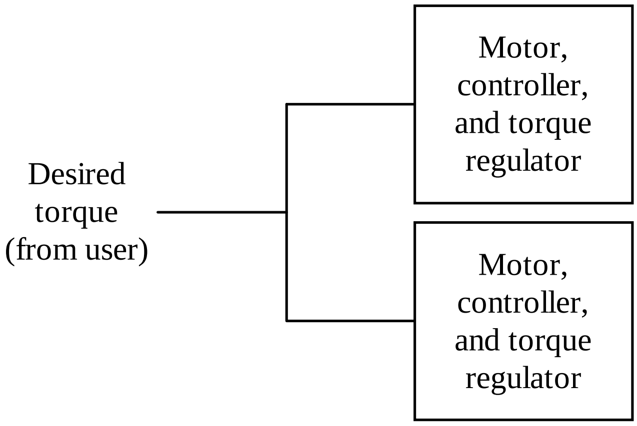


Figure 5. Paralleling multiple motors under torque regulation

- The main factor limiting the motor output is the torque; as the torque increases the motor gets hotter. As the speed increases relatively little heating occurs. Therefore it is possible to obtain more power from the motor, provided that the controller can deliver more power, by running the motor faster. For example using smaller wheels or a reduction belt drive. See section 'Thermal Modelling'.

3. FRAMELESS MOTOR

The frameless motor allows the designer to choose their own requirements in coupling the motor to a wheel.

The frameless form of either motor consists of a two rotor rings and an encapsulated stator (including the temperature sensor and position sensors). Drawings of the frameless motors can be found at:

- http://www.cip.csiro.au/Machines/success/sc.html

When designing your own frame (or case) and axle, consideration and due care must be exercised to achieve the desired running performance. The stator is held stationary against the reaction torque of the two outer rotating rotor rings, while maintaining a constant air gap and concentricity. See drawings for dimensions of parts and air gap. Note, different designs of magnet ring backing plate are possible at extra cost.

It should be noted that at the correct air gap there is a force of approximately 5 kN between the magnet rings. Therefore the motor frame must be strong enough under the influence of this force to maintain the air gap. Also it is necessary to design assembly tools to allow the motor to be pulled apart and to allow assembly in a controlled manner.

For ideas on how to mount the stator and rotor rings see drawings on web site, the paper describing the Aurora motor (also on web site), and the world solar challenge book (referenced in section 'Contact and Further Information' below).

When designing the motor frame it is necessary to consider the mounting of the rotor position sensing PCB and how adjustments can be made to the angle of this board with respect to the motor winding. The recommended method for providing adjustments is to provide an access hatch in the motor frame and to use the mounting slots provided in the board, see 'Rotor position sensor and adjustments' for more details concerning mounting and adjustment.

The frame of the motor needs to conduct the heat from inside the motor to the outside air. The thermal modelling of the motor given in 'Thermal Modelling' assumes a 2 mm thick aluminium frame.

Note also that it is necessary to terminate the motor leads inside the motor, since the type of wire used for motor windings has relatively fragile insulation. The external wire is typically a double insulated PVC construction, see 'Motor Controller'. The frameless motor winding is typically terminated in M5 rings. Other terminations are possible and the length of the wire to the termination is negotiable. The number of connections from the winding depends on the number of turns chosen for the motor, see 'Motor Speed'. For the standard (regular) winding the number of connections is six, three of these are bought out of the motor and the other three are joined inside the motor to form a star point. Therefore it is typically necessary to provide four termination points inside the motor, one for the neutral (or star) and three for external leads.

4. MOTOR CONTROLLER

The motors are tested with a Unique Mobility CR20-75 controller, but many other controllers will be suitable. The description of interfacing to a controller, as given in the text below, is biased towards connecting a CR20-75 to a complete motor (as opposed to frameless motor). Although, most of the information given would still apply to other motor controllers and to the frameless version of the motors and in some cases extra information pertinent to the frameless motor is given.

The maximum efficiency is obtained when the controller applies a sinusoidal voltage synchronised to rotor position, because the motor's EMF is sinusoidal. However controllers like the CR20-75 that apply a trapezoidal voltage can be used, see section 'Motor Current'. To maximise the efficiency of the controller it is generally wise to pick a controller of the correct voltage rating and with a generous current rating. Most controllers will require additional line inductors because the synchronous inductance of the motor is approximately 20 μH. A set of three 100 μH inductors designed for use with the CR20-75 can be supplied (see section 'Inductor Rating' and price list).

In general controllers run most efficiently with a minimal amount of PWM, i.e. flat out. Therefore it is best to pick the battery voltage close to the cruising speed, with a little in hand for overtaking (see 'Motor Speed').

The main issues in interfacing a given controller are:

- The motor has three phases
- The motor requires the applied voltage to be synchronised with rotor position
- The position information is provided by three sensors with open collector outputs, that are suitable for operation in the range 5 to 15 V, see below for more information
- A thermistor (or negative temperature coefficient resistor) senses temperature and the controller *must* shut down when 383 K (110°C) is reached, see below for more information
- The applied voltage needs to be sufficient for maximum speed (see 'Motor Speed')
- The applied current needs to be sufficient for maximum torque (see 'Motor Current')
- The fundamental frequency of the applied voltage needs to be sufficient for maximum speed (see 'Motor Frequency')
- The PWM frequency needs to be at least 8 kHz to use the 100 μH inductors if the controller modulates only one switch of the top and bottom pair at a time and at least 12 kHz if both switches are simultaneously modulated
- The controller must limit the maximum current supplied to the motor, see 'Motor Current'

4.1. Interfacing a controller

A block diagram of the required connections is given in Figure 6 and a typical list of parts in addition to the motor and motor controller is given in Table 1. In the figure terminations are given a 'T' number and cables a 'C' number. Terminations may be either a solder joint or a plug and socket arrangement. All the cables are multi-cored, i.e. they have multiple insulated conductors inside an outer insulation sleeve. The parts in the table are each given an item number. Note terminations T4 and T7-9 and cables C2 and C3-5 are inside the motor and are therefore not relevant to purchasers of the complete motors. The cables (C1-5) are separately described below with reference to the parts table.

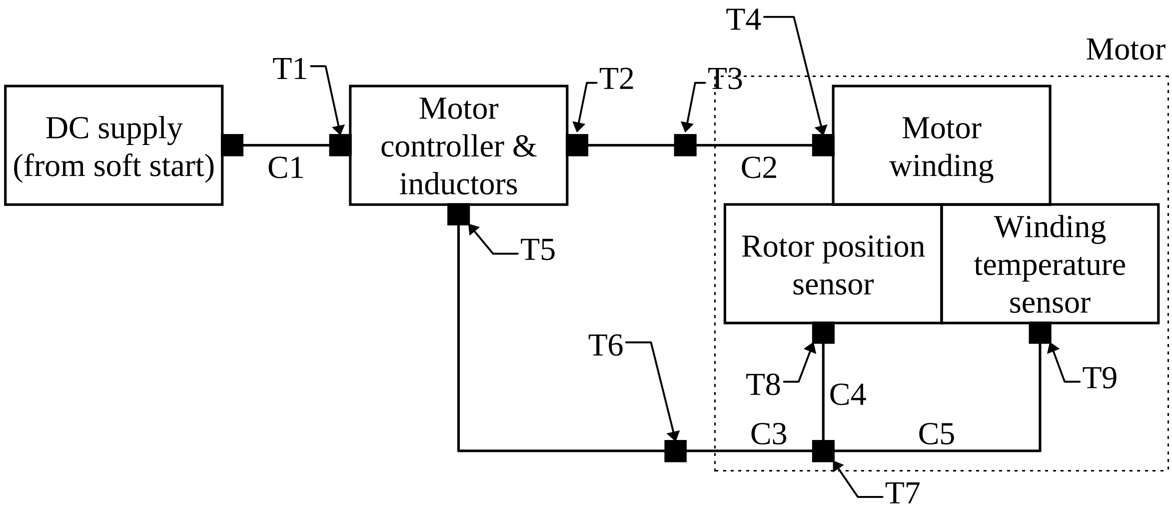


Figure 6. Block diagram of system connections (C = cable, T = termination)

Item	Supplier	Description	Quantity
1	Radio Spares	256-900, Hall effect IC, UGN3177	3
2	Farnell	967-208, 1 µF, 25 V electrolytic capacitor	1
3	Farnell	499-390, 0.1 µF, 50 V ceramic capacitor	1
4	CSIRO	Rotor position sensing printed circuit board	1
5	Farnell	148-315, ribbon cable 10 way, 1 A, 105°C	
6	Farnell	279-614, 10 KΩ, 1% Thermistor, see section 4.3	1
7	Farnell	715-463, Shielded cable 8 way, 1 A, 70°C	
8	Farnell	276-911, PTFE insulated wire 0.14 mm^2	
9A	Farnell	659-174, 7 way free plug	1
9B	Farnell	659-230, 7 way free socket	1
10A	Farnell	589-597, cable plug	1
10B	Farnell	589-640, free receptacle	1
10C	Farnell	593-291, cable clamp	1
10D	Farnell	592-912, pins	8
10E	Farnell	592-936, sockets	8
11	EMC (Tel. +61 7 3888 1277)	FAN-1-9601G1, crimp housing	6
12	EMC	FAN B00376P1, crimp	6
13	Source not known	3 core 4 mm^2 flexible cable, cannot have conductor coded as earth wire, see section 4.1.2	1
14	Farnell	587-187, Yellow M5 ring crimp terminals	

Table 1. Electrical parts list

4.1.1. Cable 1 (C1) - DC supply to the controller (2 power wires)

This cable should be sized to give an acceptable power loss for the length required. Typically this cable is made up from two single-insulated conductors that are inside an outer insulation layer. It is also important to follow the installation instructions given in the controller manual, e.g. the CR20-75 controller requires a soft start circuit. If a quick disconnecting system is desired then items 11 and 12 are a good choice. Several of these connectors can be paralleled to minimise the power loss across the connection. Similarly several cores can be paralleled inside the cable. Item 14 is suitable for termination T1 and again they can be connected in parallel.

4.1.2. Cable 2 (C2) - Three phase controller output to the motor winding (3 power wires)

Cable C2 is supplied with the complete motor, no connector (T2) is supplied. Item 14 is suitable for T2. To assist in the quick removal of the wheel an optional connector (T3) may be used to provide a break in cable C2, items 11 and 12 are suitable for T3. Adding T3 also allows a different, perhaps thicker, cable to be used from the controller to T3. Item 14 is suitable for T4.

The largest double-insulated cable that fits through the motor entry hole on the complete motors is item 13. Note the cable is be clamped within the complete motor and a similar arrangement is necessary in frameless designs.

For the frameless motor C2 is not supplied and is difficult to source because most three core flexible cable have one core colour coded as earth (and therefore may not be used for a power connection). One possibility is to make the double-insulated cable up from three separate single-insulated cables with heat shrink tubing used for the outer layer of insulation.

Another point to keep in mind for the frameless motor is that the insulation of standard mains flexible cable (item 13) is only rated to 70°C, so it should be kept away from the hotter parts of the motor (i.e. the winding). Two other alternatives are to find a cable with higher temperature rating or reduce the maximum temperature of the motor winding.

Additionally, the motor should be earthed to the battery negative through the axle, see ‘Important safety notice’.

4.1.3. Cables 3 (C3) - Motor controller to T7 (7 signal wires + shield)

C3 is supplied with the complete motor, no terminating plug is supplied. Like cable C2 it may be advantageous to beak C3 to allow for quick removal of the motor by using optional termination T6. Unlike cable C2, there is no advantage in using a different cable for the two parts of C3. C3 is typically item 7 in the table, note this cable has one more core than needed.

Items 9 and 10 are two different, quick connect, screw locking, alternatives for optional termination T6. Item 9 is small and has a good shield connection, whereas item 10 has better quality pins and sockets. The pin out for T5 on a CR20-75 controller is given in Figure 7. The cable shield and one conductor are both connected to GND at both the controller and motor ends of C3. Note: the shield pin on the CR20-75, center pin, and the tab are left unconnected.

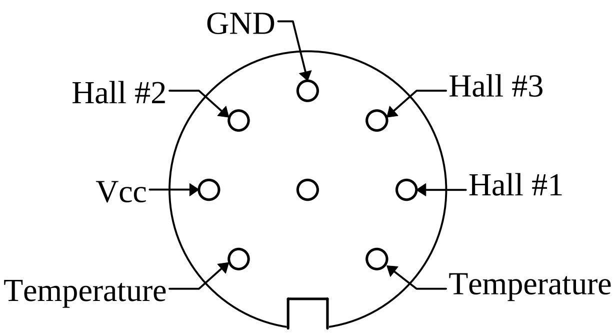


Figure 7. CR20-75 motor control connections looking into back (solder side) of plug that goes into the CR20-75

For the frameless motor, the same temperature considerations apply as to cable C2. The cable should again be clamped within the motor. If a higher temperature cable is used then it is possible to eliminate T7 (see ‘Cable 5 (C5) - Temperature sensor signal to T7 (2 signal wires)’). Even if a higher temperature cable is used T7 may still be present to ease wiring up the motor. T7 is typically a solder joint.

4.1.4. Cable 4 (C4) - Rotor position sensor signals to T7 (5 signal wires)

These notes are only relevant to the frameless motor. The pin out for T8 is given in a drawing that can be found at:

- http://www.cip.csiro.au/Machines/success/sc.html

note T8 is a solder join between a cable and solder pads on a PCB. In the figure from the web the Hall sensor outputs are labelled A, B, and C, whereas in Figure 7 the Hall outputs are labelled #1, #2, and #3. This different labelling is deliberate, it is to emphasise that their is not necessarily a one to one connection between these points (see ‘Rotor position sensor and adjustments’).

The ribbon cable (Item 5) should be clamped to the PCB to ensure that the solder pads are not stressed. Additionally, the ribbon cable should have enough free play for the 9° rotation adjustment and the cable should also be kept clear of the moving motor parts.

4.1.5. Cable 5 (C5) - Temperature sensor signal to T7 (2 signal wires)

These notes are only relevant to the frameless motor. The cable C5 (supplied) that is connected to the thermistor (Item 8) is embedded in the winding epoxy and must be rated for the maximum winding temperature. The termination T7 is typically a solder joint. Also see ‘Winding temperature sensing’.

4.2. Rotor position sensor and adjustments

The complete motor comes with a tested and aligned position sensor, for the frameless motor a tested PCB is supplied. The rest of this section is only directly relevant to the frameless motor.

The rotor position sensor contains three hall effect devices (Item 1 in Table 1) used to sense the fringing magnetic field on the inside of one of the motor magnet rings. The top of the hall sensors should be located no more than 1 mm from the inside edge of the magnets and around about the centre of the magnet (preferably slightly closer to the backing iron). Please Email Paul Gwan (paul.gwan@csiro.au) for further details of the sensor board mounting.

The position sensor board should not be in contact with the motor winding. The winding can reach 110°C (383 K) and the board is only rated to 70°C (343 K). An air gap of 1 mm is found sufficient to insulate the board from the winding in the complete motor. Depending on the air flow around the board, this 1 mm spacing may or may not be sufficient in other motor designs.

The CR20-75 controller provides a logic supply of 15 V. The controller also has internal pull up resistors to a 5 V supply for each of the hall sensor outputs. The hall sensor output is digital; when the magnetic field passes through the sensor in one direction the output is 0V and if the field reverses the output becomes 5 V. The motor has 40 poles per magnet ring (20 North and 20 South), so for every revolution of the motor shaft each rotor sensor signal should have 20 corresponding High’s (5 V) and Low’s (0 V). The electrical signals repeat every 360/20 = 18°, this is often stated as “360° electrical is equivalent to 18° mechanical”. Figure 8 shows the idealised hall sensor output with the motor turning at a constant speed.

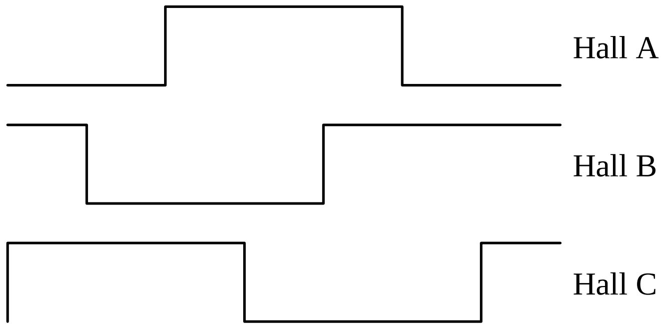


Figure 8. Rotor position sensor digital signals

The safest way to test the position sensing system once it is installed in the motor is by building a test circuit that simulates the signals normally provided by the motor controller, a suitable circuit is shown in Figure 9. The motor can then be rotated at constant speed and the signals observed on an oscilloscope and compared with Figure 8. Note the test circuit given contains no filtering and would therefore be unsuitable for use as the input to a real controller.

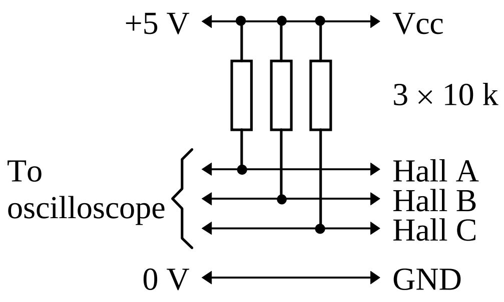


Figure 9. Test circuit for position sensors

The sensing system can also be tested by plugging the motor control lead into the CR20-75 controller and monitoring the hall signals on the back of the plug. *But, care should be taken not to inadvertently short any of the CR20-75 control pins as this can cause, extensive, controller failure.*

The next step is to align the position sensor board with the winding. This is a two stage process: first a coarse alignment and then a fine tuning alignment over a 9° arc.

1st the CR20-75 controller should be connected to the motor as shown in Figure 1 and a 50 V, DC, current limited, power supply instead of the battery (shown in the figure) and instead of the soft start circuit. The wiring order between the motor and controller is arbitrary, as explained below, but a good starting point is to wire Hall #1 to Hall A, etc., similarly for the power connections.

The current limit should be set on the power supply to around 5 A. Set up an oscilloscope to display the current in motor winding A and the voltage between motor winding A and the DC power supply negative. A Hall type current probe is recommended because it will give a DC reading and it is isolated. An isolated voltage probe is recommended. *Be careful not to introduce a short circuit or earth fault via the common, earthed, ground connections on oscilloscope inputs.*

- Set the speed and regeneration on the user interface board supplied with the CR20-75 to zero, i.e. fully anticlockwise.
- Turn on the enable and logic switches on the user interface board.
- Turn the direction of rotation to be forwards on the user interface.
- Increase the voltage on the DC power supply slowly (no more than 10 V per second) to 50 V, you should hear the fan come on inside the CR20-75.

- The speed setting should be gradually increased (no more than $^{1}/_{10}$ of a turn per second) whilst monitoring the motor current (there is no need to exceed 5 A).

As the speed setting is increased the motor will do one of four things:

- turn clockwise,
- turn anticlockwise,
- become locked,
- or oscillate.

If the desired result is not achieved: turn everything off, swap two of the power wires that go to the motor over, and start again. *Do not swap the power wires that go from the DC supply to the controller over.* There are six distinct combinations of wiring and only one will probably produce the desired result. Depending on where the board has been located with respect to the rotation of the winding it may also be necessary to swap two Hall sensor outputs over, although this is less likely.

If it is not possible to obtain rotation then check all the current and voltage waveforms, you may have a fault in one phase.

Once the motor is turning the voltage and current waveforms should be observed on an oscilloscope to fine tune the alignment angle of the position sensor board over the 9° arc. This is achieved by stopping the motor and adjusting the angle of the sensor board through the access hatch in the motor frame, see 'Frameless Motor'.

Once the angle has been set correctly the current and voltage waveforms should look similar to those shown below. Some load applied by hand may be required to determine the true shape of the current waveform. The correct angle will also consume the minimum power to run the motor at a given operating point. Optimise the running of the motor for forwards running of the vehicle. The motor will run in reverse, but with slightly higher losses.

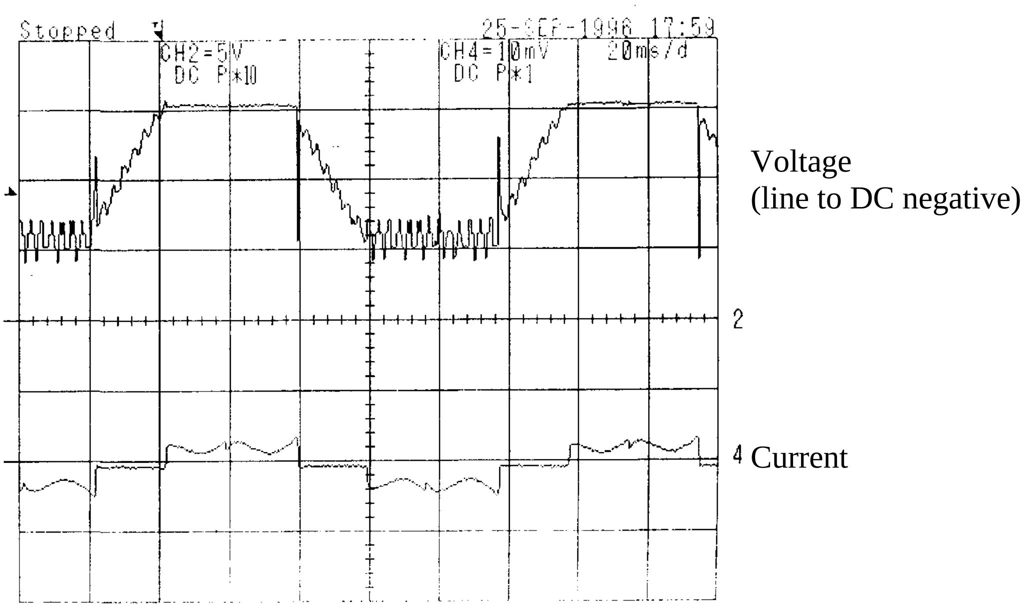


Figure 10. Typical motor voltage and current waveforms when the sensor board has been adjusted to the correct position

4.3. Winding temperature sensing

The combination of the thermistor fitted to both the frameless and complete motors and the CR20-75 controller will result in a temperature cut out of 110°C (383 K). The CR20-75 starts to fold the current back before this temperature, however. If a lower temperature cut out than the standard 110°C (383 K) is required, then a resistor may be placed in parallel across the thermistor to reduce its resistance.

The sensor fitted (item 6 in Table 1) is a Phillips type 2322-640-55103, which has the following properties:

- Their resistance is approximately $0.016 \times E^{\frac{3977}{T}}$ where T is in kelvin.
- At the maximum motor temperature their resistance is 508 Ω.
- At room temperature their resistance is 10 kΩ.

The devices have a tendency to self heat, so it is necessary to limit the maximum current through them to 1 mA. More data is available in Phillips data handbook PA02, April 95. On page 46 a more accurate formula for the resistance is given (formula 1). The constants for this formula are from row 3977 of table 2, also on page 46. The last column of table 3 on page 47 tabulates the resistance verses temperature. The data book also gives some application notes at the start. The time constant of the sensor is in the second range and therefore the sensed temperature can be heavily filter to reduce noise.

5. MOTOR SPEED

The motor EMF constant (induced voltage/speed) and winding impedance determines the motor speed at a given load torque for a given voltage applied by the motor controller. The controller adjusts the applied voltage up to a maximum determined by the battery voltage, or more precisely up to a maximum determined by the mean voltage at the controller input terminals.

The maximum speed for a given battery voltage is also dependent on the controller and the inductors fitted. For example, the maximum speed depends upon the internal impedance of the controller, the losses in the controller, and whether it applies a trapezoidal or sinusoidal waveform. Therefore it is only possible to give a rough guide. A typical controller, e.g. Unique Mobility CR20-75, with:

- a mean voltage of 150 V DC on the controller input terminals,
- a trapezoidal waveform,
- full output voltage (speed set to max.),
- the recommended inductors fitted in series with each motor phase,
- the total impedance, per phase, of the wiring between the controller and the inductors and including the wiring between the inductors and the motor should be less than 20 mΩ of resistance and less than 10 μH of inductance, and with
- an external load torque of 16 Nm,

will give a maximum speed of approximately:

- 179 rad/s (1710 rpm) for the Surface motor and
- 125 rad/s (1190 rpm) for the Halbach motor.

The maximum speed will be roughly proportional to the mean DC voltage on the controller input. If these speeds are not suitable then other EMF constants are possible by changing the number of turns, please contact CSIRO/UTS electrical machines for more information. Note that changing the number of turns and hence the EMF constant also changes the torque constant (torque/ampere), see ‘Motor Current’.

6. MOTOR FREQUENCY

The fundamental frequency applied to each motor phase is proportional to speed. The fundamental frequency is

- 3.183 Hz per rad/s or 0.3333 Hz per rpm.

7. MOTOR CURRENT

The motors are fitted with a thermistor and the motor should be shut down if it reaches 383 K or 110°C (see 'Thermal Modelling' below). Since there is a response time associated with the thermistor it is also necessary to limit the rate of rise of temperature by limiting the maximum current. The *absolute* maximum recommended RMS current is 3.1 times the nominal current (or 30 A RMS for the Halbach motor and 42 A RMS for the Surface motor). These values correspond to a peak torque of 50.2 Nm, 3.1 times nominal torque, if a sinusoidal voltage synchronised to the rotor position is applied (since torque is proportional to the fundamental component of the current).

If the controller applies a trapezoidal voltage as opposed to a sinusoidal voltage, then an extra 5% RMS current is required for a given torque to account for the non-ideal waveform shape. Therefore the peak torque available from this type of controller is 48 Nm.

Most controllers do not limit the RMS current, instead they limit the peak current. Neglecting peaks due to the action of the PWM, the ratio of RMS current to peak current is:

- 1:1.4 for a sinusoidal applied voltage and
- 1:1.8 for a trapezoidal applied voltage.

Except when at maximum speed (PWM ratio = 1) there is also some extra RMS current required due to the PWM action of the controller. This is difficult to quantify as it is torque, speed, inductor, and controller dependent. For a typical controller, e.g. Unique Mobility CR20-75, with a PWM duty ratio of 0.86, a PWM frequency of 10 kHz, and the recommended inductors, at nominal torque and speed, a rough guide is to allow an extra:

- 0.1 A RMS and 1 A peak current.

It is worth noting that only the fundamental frequency component of the current produces torque and the other frequency components only contribute to the losses in the motor, inductors, and controller. Therefore running with minimal PWM, i.e. speeds close to maximum speed, are advantageous in terms of losses. The controller also has switching losses when the PWM is enabled.

Note that the limiting factor for peak current may not be the motor, but may be the controller or the batteries.

Other torque constants (and hence the relationship between RMS current and torque) can be accommodated at cost, please contact CSIRO/UTS electrical machines. Note that changing the torque constant also changes the EMF constant (induced voltage/speed).

8. THERMAL MODELLING

There are three temperatures of interest when modelling the motor: the ambient (T_a) or outside temperature, the magnet temperature (T_m), and the winding temperature (T_w). The winding temperature is the limiting factor and the maximum permissible is 383 K (110°C). The thermistor fitted to the winding should be monitored and the motor shut down when this temperature is reached. However it is still useful to estimate the winding temperature in advance to see if the motor is suitable for a given application. The following procedure should be used as a guide *only*, and to prevent motor burn out, the motor *must* be shut down when the temperature reaches the limit as indicated by the thermistor.

There are two types of thermal modelling: steady-state and transient. As their names imply, steady-state modelling is when the motor speed and torque are constant, and transient modelling is when either of these quantities is varying. It is easier to work out the steady-state temperature than the transient temperature, hence the calculation of steady-state temperature is presented first.

8.1. Steady-State Modelling

The procedure for calculating the steady-state winding temperature is iterative. To begin with you need the motor torque (τ) in Nm, the motor speed (ω) in rad/s, and an estimate of the initial winding temperature (say 353 K) in K. The following set of equations is repeatedly solved until the winding temperature calculated does not change significantly, say less than 1 K.

1. The magnet temperature is approximately half way between the winding and the ambient temperature, i.e.:

$$T_m = \frac{1}{2}(T_a + T_w) \tag{1}$$

2. The magnet remanence (B) is given by:

$$B = 1.29 - 1.2 \times 10^{-3}(T_m - 293) \tag{2}$$

3. The RMS per phase motor current (i) assuming a sinusoidal current aligned with the rotor position is given by:

$$i = 0.6626 B\tau \text{, Surface} \tag{3s}$$

$$i = 0.4614 B\tau \text{, Halbach} \tag{3h}$$

4. The per phase motor winding resistance (R) is given by:

$$R = 0.0757(1 + 0.0039(T_w - 293)) \text{, Surface} \tag{4s}$$

$$R = 0.0997(1 + 0.0039(T_w - 293)) \text{, Halbach} \tag{4h}$$

5. The total motor winding i^2R (copper) loss (P_c) is given by:

$$P_c = 3i^2R \tag{5}$$

6. The total motor eddy current loss (P_e) is given by:

$$P_e = \frac{9.602 \times 10^{-6}(B\omega)^2}{R} \text{, Surface} \tag{6s}$$

$$P_e = \frac{13.13 \times 10^{-6}(B\omega)^2}{R} \text{, Halbach} \tag{6h}$$

7. The steady-state motor winding temperature depends on the thermal resistance, which is 0.452 K/W for the surface motor and 0.4448 K/W for the Halbach. Therefore the winding temperature is given by:

$$T_w = 0.452(P_c + P_e) + T_a \text{, Surface} \tag{7s}$$

$$T_w = 0.4448(P_c + P_e) + T_a \text{, Halbach} \tag{7h}$$

For example, at nominal torque (16.2 Nm) and nominal speed (111 rad/s) in a 293 K ambient, the steady-state winding temperature is 316 K for the surface motor and 307 K for the Halbach motor (see ‘Worked Example’ below). Another example is the steady state, thermally limited, torque (maximum continuous torque), i.e. the maximum torque for a winding temperature of 383 K in a 293 K ambient at 111 rad/s, which is 31 Nm for the Surface motor and 39 Nm for the Halbach.

8.2. Transient Modelling

An easy, but approximate, technique for finding the winding temperature under transient conditions is to approximate the transient load at an equivalent steady-state value (to allow the losses to be calculated) and then to approximately calculate the transient temperature rise above ambient. The validity of this transient calculation can be assessed by calculating the difference in the steady-state and extremes of transient temperatures. If this difference is less than 50 K then the calculated absolute temperatures, in K, are probably within 5%.

The calculation assumes that the transient condition can be broken into a sequence of steps or intervals and that the sequence repeats for ever, i.e. the calculated temperature rise at the end of the last interval is the temperature rise at the start of the first interval.

1. There are essentially two techniques to work out an equivalent steady-state temperature for the winding.
   - If the transient event is a one off occurrence in an otherwise steady operation, then the equivalent steady-state temperature is simply the temperature given by equations (1) to (7) with the speed and torque as for the steady operation.
   - If the transient event is cyclic, then the equivalent steady-state temperature is given by finding the RMS values of speed and torque and using these values in the steady-state calculation. If in doubt, use the RMS values.
2. Use the value of T_w calculated in step 1 to calculate B and R (equations (2) and (4) respectively).
3. Divide the transient cycle of speed and torque into n intervals. For each interval, j, the time the interval lasts for, t_j, the speed, ω_j, and the torque, τ_j, are required. Calculate P_{cj} and P_{ej} (equations (5) and (6) respectively) for each interval.
4. The thermal time constant is the product of the thermal resistance and thermal capacitance and is 273.5 s for the Surface motor and 269.1 s for the Halbach. Using the thermal time constant, calculate the exponential coefficient, α_j, for each interval:

$$\alpha_j = e^{\frac{-t_j}{273.5}} \text{, Surface} \tag{8s}$$

$$\alpha_j = e^{\frac{-t_j}{269.1}} \text{, Halbach} \tag{8h}$$

5. Calculate the steady-state temperature rise, β_j, over ambient, for each interval:

$$\beta_j = 0.452(P_{cj} + P_{ej}) \text{, Surface} \tag{9s}$$

$$\beta_j = 0.4448(P_{cj} + P_{ej}) \text{, Halbach} \tag{9h}$$

6. Formulate the α matrix $\mathbf{m}$:

$$\mathbf{m} = \begin{bmatrix} 1 & 0 & 0 & \cdots & -\alpha_1 \\ -\alpha_2 & 1 & 0 & \cdots & 0 \\ 0 & -\alpha_3 & 1 & \cdots & 0 \\ & & \ddots & \ddots & \\ 0 & 0 & \cdots & -\alpha_n & 1 \end{bmatrix} \tag{10}$$

7. Formulate the β row vector $\mathbf{v}$:

$$\mathbf{v} = \left[\beta_1(1-\alpha_1) \quad \cdots \quad \beta_n(1-\alpha_n)\right] \tag{11}$$

8. Find the winding temperature rise above ambient (row vector θ) at the end of each interval, assuming the sequence of intervals repeats ad infinitum by solving the matrix equation $\mathbf{m}\theta^{\mathbf{T}} = \mathbf{v}^{\mathbf{T}}$.

For example if the motor is run at its nominal rating until temperature equilibrium is reached and then it is run at 50.2 Nm for 72 s, the final temperature rise over ambient will be 64 K for the Surface motor and 40 K for the Halbach motor (see ‘Worked Example’ below).

8.3. Worked Example

The motor thermal calculations are available as a Zipped Microsoft Excel (Office 95 version) file at ‘http://www.cip.csiro.au/Machines/success/sc.html’. However, it is still useful to run through the calculations.

First a steady-state calculation for both the Surface and Halbach motors running at their nominal rating of 16.2 Nm and 111 rad/s in an ambient of 293 K. The results from iterating equations (1) to (7) and showing the results for the Halbach motor between parenthesis are given below.

T_m = 304 (300) K

B = 1.2768 (1.2816) T

i = 13.7045 (9.5801) A

R = 0.0822 (0.1051) Ω

P_c = 46.3240 (28.9495) W

P_e = 2.3458 (2.5270) W

T_w = 315 (307) K

These numbers are easily verified using equations (1) to (7) to show that the values do not significantly change with another iteration.

If the motor having first temperature stabilised under nominal load, as above, is run for 72 s at 3.1 times nominal torque (i.e. maximum torque of 50.2 Nm) at nominal speed (111 rad/s) in an ambient of 293 K, then this overload and the subsequent cooling of the motor may be modelled by dividing this load sequence into 4 intervals for example.

In the example below, the first interval is the overload and the next three intervals are at nominal torque to show how quickly the motor cools. Note, the sequence (of overload followed by cooling) and number of intervals (provided that the total time at a given torque is the same) are not important. However, it should be noted that the sequence is cyclic and therefore the whole of the overload and cooling down times must be completely modelled. In summary the example sequence of intervals is:

1. The overload at 50.2 Nm for 72 s
2. Cooling at 16.2 Nm for 720 s
3. Cooling at 16.2 Nm for 720 s
4. Cooling at 16.2 Nm for 720 s

The values of B and R found above in the steady-state example are used in the transient calculation, since this transient sequence is predominantly the nominal torque of 16.2 Nm. Using parenthesis to indicate values for the Halbach motor:

i_1 = 42.4669 (29.6864), i_2, i_3, i_4 = 13.7045 (9.5801) A

P_{c1} = 444.8194 (277.9833), P_{c2}, P_{c3}, P_{c4} = 46.3240 (28.9495) W

P_{e1}, P_{e2}, P_{e3}, P_{e4} = 2.3458 (2.5270) W

α_1 = 0.7685 (0.7652), α_2, α_3, α_4 = 0.0719 (0.0689)

β_1 = 202.1301 (124.7643), β_2, β_3, β_4 = 22.0000 (14.0000) K

θ_1 = 63.6553 (40.0098), θ_2 = 24.9941 (15.7910), θ_3 = 22.2152 (14.1233), θ_4 = 21.9484 (14.0085) K

From these temperature rise above ambient results it is seen that the maximum winding temperature for the Surface motor is $293 + 64 = 357$ K and for the Halbach it is

$293 + 40 = 333$ K and that both motors quickly return to their normal temperature for nominal load, i.e. $293 + 22 = 315$ K and $293 + 14 = 307$ K respectively.

9. MOTOR EFFICIENCY

Most of the information needed to calculate motor efficiency is given in the 'Thermal Modelling' section, i.e. the copper loss, P_c, and the eddy current loss, P_e. The missing calculations are the motor's internal and external windage and the bearing losses. The external windage depends on how the motor is attached to the wheel, the wheel and tyre it is attached to, and the geometry of the wheel spats. The bearing loss depends on the loads applied to the bearings. The external windage and bearings, may be approximately measured by running a wheel without the motor attached under load.

Because it is difficult to theoretically determine the external windage and the bearing losses and because it is a debatable point as to whether these losses should be counted as motor or wheel losses (the wheel requires sides and bearings!), both these losses are neglected in the following calculation of motor efficiency.

The internal windage, P_w, for both motor types is given by:

$$P_w = 170.4 \times 10^{-6} \omega^2 \tag{12}$$

The motor efficiency, η, in % is:

$$\eta = \frac{\tau\omega}{\tau\omega + P_c + P_e + P_w} \times 100 \tag{13}$$

For all parts of the motor at 273 K with a load, τ, of 16.2 Nm at a speed, ω, of 111 rad/s the efficiency is 97.4% for the surface motor and 98.2% for the Halbach.

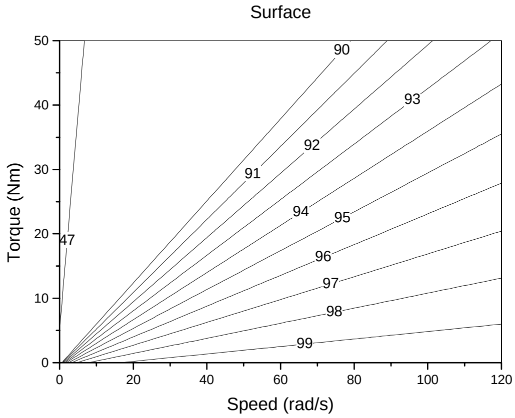
Since the copper loss is typically much bigger than the eddy current loss and the windage loss and the efficiency changes little with temperature, the loss may be approximated as:

$$\eta \approx \frac{\tau\omega}{\tau\omega + 0.1765\tau^2} \times 100 = \frac{\omega}{\omega + 0.1765\tau} \times 100 \text{, Surface} \tag{14s}$$

$$\eta \approx \frac{\tau\omega}{\tau\omega + 0.1103\tau^2} \times 100 = \frac{\omega}{\omega + 0.1103\tau} \times 100 \text{, Halbach} \tag{14h}$$

Note, the above equations are based on the copper losses calculated for steady-state operation at nominal load in Section 8.3 and the copper loss is therefore a little higher than the losses given in the Specifications. This is because the Specifications are given for the whole motor at 293 K, not the raised winding temperatures of 315 K for the Surface and 347 K for the Halbach that result from continuous nominal load running (see 'Thermal Modelling'.

Therefore the efficiency can be approximately calculated as a function of speed and torque and the result is shown in Figure 11.



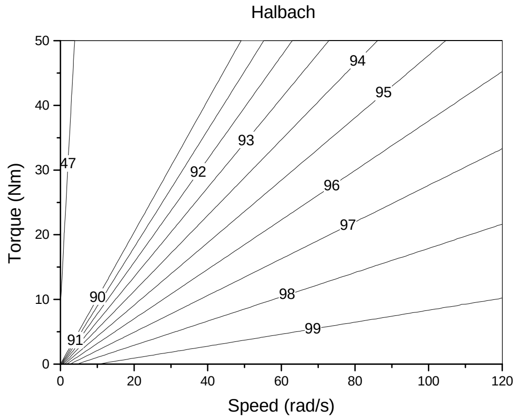


Figure 11. Approximate efficiency contours

From the figure it can be seen that efficiency tends to increase with increasing speed and decrease with increasing torque and the Halbach motor is always more efficient than the Surface motor.

In the steady-state, the power delivered to the road approximately determines the car's speed. A simple model of a car is to assume that speed cubed (v^3) is proportional to the power delivered to the road (P_d). If the car takes 1798.2 W to propel it at 27.8 m/s (100 km/h or 61.2 miles/h) then the velocity is given by:

$$v = \sqrt[3]{\frac{P_d}{0.08386}} \tag{15}$$

Assuming that 27.8 m/s corresponds to a motor speed of 111 rad/s and that the tyres are 100% efficient, then the motor speed and torque are given by:

$$\omega = 3.993v \tag{16}$$

$$\tau = \frac{P_d}{\omega} \tag{17}$$

Combining equations (14) to (17) gives the efficiency as a function of the power delivered to the road for the example vehicle.

$$\eta \approx \frac{912.25}{9.1225 + 0.01935(P_d)^{1/3}}\text{, Surface} \tag{18s}$$

$$\eta \approx \frac{912.25}{9.1225 + 0.01209(P_d)^{1/3}}\text{, Halbach} \tag{18h}$$

The resulting efficiency as a function of power for the example vehicle is shown in Figure 12. From the figure it is obvious that at all steady-state operating points the efficiency of both motors is excellent. This is because the losses are proportional to torque squared and are independent of speed, but the torque required is proportional to power to the two thirds and the speed required is proportional to the cubed root of power. Motor designs that *have* iron loss *do not have* the feature of loss independent of speed and therefore they *do not hold* their efficiency over a wide operating range.

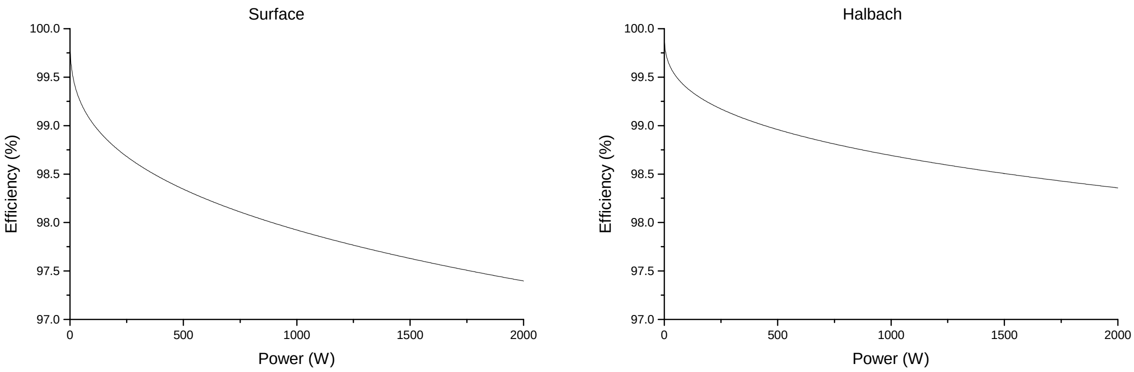


Figure 12. Approximate steady-state efficiency as a function of power for an example vehicle

10. INDUCTOR RATING

Most motor controllers require some additional series inductance, typically at least 100 μH per phase is required (see Figure 1 and section 'Motor Controller'). Specially designed low loss inductors are available, which are suitable for use with both motors. The nominal ratings of each inductor are:

- Inductance 110 μH
- Resistance 12 mΩ
- Weight 1.1 kg
- Temperature limit 393 K (120°C)
- Maximum peak current before saturation 55 A

The thermal rating of the inductors is designed to be better than the thermal rating of the motor. Therefore provided that the motor and the inductors are in a similar ambient temperature, there is no need to measure the temperature of the inductors.

There are two loss components in each inductor: copper loss (P_{ci}) and yoke loss (P_{yi}). These losses are given by:

$$P_{ci} = 12 \times 10^{-3} i^2 \qquad (19)$$

$$P_{yi} \approx 2.7 \times 10^{-6} i^3 f \qquad (20)$$

where f is the fundamental frequency of excitation, see 'Motor Frequency'. Note, the yoke loss is given only approximately since a more accurate calculation requires a Fourier analysis of the current waveform.

At the nominal rating of 16.2 Nm and 111 rad/s in an ambient of 293 K for the Surface motor the total loss in each inductor is 4.88 W and for the Halbach motor 1.95 W. Since these losses are so low, it is normally reasonable to neglect inductor losses.

11. CONTACT AND FURTHER INFORMATION

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Web information concerning:

CSIRO/UTS Electrical Machines	http://www.cip.csiro.au/Machines
Surface and Halbach (index)	http://www.cip.csiro.au/Machines/success/sc.html
Halbach motor in the Aurora 101	http://www.cip.csiro.au/Machines/success/sc.html
Paper on the Halbach motor	http://www.cip.csiro.au/Machines/papers/iwscem

General solar car reference material and the Halbach motor used by Aurora in their 101 car in the 1996 World Solar Challenge.

DM Roach, AET Schinckel, JWV Storey, CP Humphris, and MR Guelden, *Speed of Light: The 1996 World Solar Challenge*, Photovoltaics Special Research Centre, University of New South Wales, Sydney, Australia, ISBN 0 7334 1527 X

12. LEGAL NOTICES AND DISCLAIMERS

- Australian Patent Application PO8917, 1st Sept. 1997
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- Specifications, performance, and price can change without notice
- The term ‘vehicle’ is used below to encompass any use of the motors, for example in a solar and/or battery powered car, boat, or bicycle.
- The motors are supplied as research prototypes as part of a research contract between CSIRO, Insearch Ltd. (the Commercial arm of UTS), and a licensee. It is expected that the licensee ensure that the complete vehicle meets any race rules and laws for the relevant countries that may be applicable. The motors are not intended for stand-alone use.
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