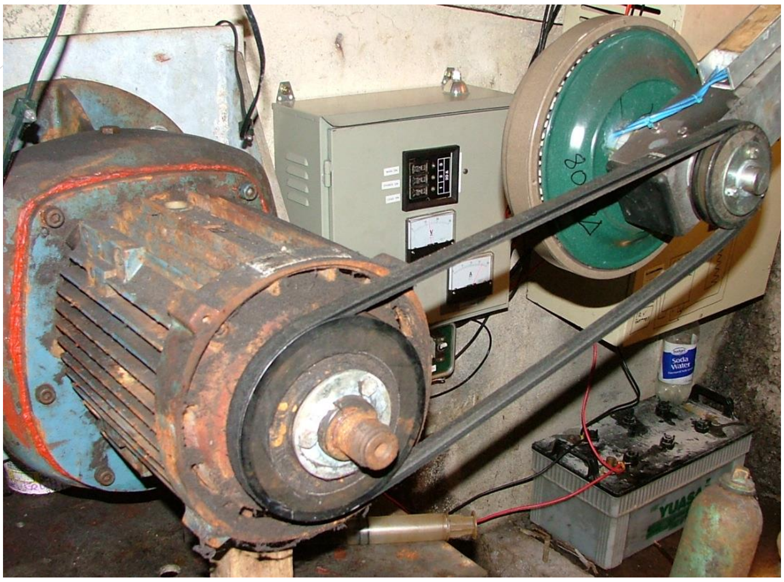
EcoInnovation Smart Drive Applications for DIY projects



Please read this manual carefully before beginning installation.

CONTENTS

Disclaimer

UNLESS SPECIFICALLY AGREED TO IN WRITING, ECOINNOVATION LIMITED:

(a) MAKES NO WARRANTY AS TO THE ACCURACY, SUFFICIENCY OR SUITABILITY OF ANY TECHNICAL OR OTHER INFORMATION PROVIDED IN ITS MANUAL OR OTHER DOCUMENTATION.

(b) ASSUMES NO RESPONSIBILITY OR LIABILITY FOR LOSS OR DAMAGE, WHETHER DIRECT, INDIRECT, CONSEQUENTIAL OR INCIDENTAL, WHICH MIGHT ARISE OUT OF THE USE OF SUCH INFORMATION. THE USE OF ANY SUCH INFORMATION WILL BE ENTIRELY AT THE USER'S RISK.

Revisions history

1.1. New release. March 2016. Edited by H.P.

EcoInnovation Contact details

EcoInnovation Ltd
671 Kent Road
New Plymouth R.D.1
New Zealand 4371

Web: www.ecoinnovation.co.nz

If you need to contact EcoInnovation by phone then email first via our web site (for our phone number) and check the local time in NZ if calling from overseas. Business hours are 9:00am to 5:00pm weekdays only. EcoInnovation is closed for up to 3 weeks over the Christmas break from 24th December.

1. Scope of Application, and Safety

This document and linked reference material is part of the product. This document is intended to guide readers who may wish to use Smart Drives for both generation and motor applications of their own making. Motors applications are fully covered in another more comprehensive document, please refer to our INDEX and locate “BLDC applications of Smart Drives”.

This document is not a step by step design guide, but rather an overview of what is possible using Smart Drives. The reader will need good practical skills, access to a well-equipped workshop and have a good understanding of electricity and electrical safety.

This section addresses safety concerns. If you are not technically competent, experienced and qualified you should not experiment with Smart Drive equipment alone and should engage the services of a suitably trained professional.

Electrical equipment can be installed or operated in such a manner that hazardous conditions can occur. It is your responsibility to ensure that you are competent and understand the risks, and how to avoid danger when working on electrical machines. If unsure ask a trained professional for assistance.

The following safety warning signs are used throughout this manual.

Caution
Risk of electric shock that could result in personal injury or loss of life

Caution
Cautions identify condition or practices that could result in damage to equipment, fire and personal injury other than by electric shock.

2. Introduction - Generating power with the Smart Drive

The Smart Drive is an ideal generator for small scale electricity generation projects. It will not however produce any free lunch. It must be driven by a prime mover that converts some available form of energy into mechanical power. There are many readily available sources of energy such as wind and water turbines, engines of various sorts and even human power. The energy must be coming from somewhere, even if it's coming from your lunch as you crank a human power generator.

We have helped many DIY'ers over the last 20 years, and have observed a common question. "What Smart Drive do I need to get 1000W?" Our reply is to ask for calculations that show that they have > 1000W available, and the RPM of the proposed machine. In most cases the DIY'er is unable to answer as they have done no calculations but require 1000W as this can power their home - this being the sole basis of the question. The point that has been missed is that you need to put in 1000W/0.8 = 1250W to get 1000W out. (The Smart drive is typically 80% efficient as a generator.)

2.1. Can I hook up to a Smart Drive and power my house?

Your house probably runs on utility-style AC power at a fixed frequency and it needs variable power at different times of day. You can use a Smart Drive as a Permanent Magnet Alternator or "PMA" to power an off-grid house via a battery and a battery inverter, or on-grid you can use a grid-tied inverter to reduce your electricity bills. In both cases the 3-phase variable-frequency "wild AC" output of the PMA is converted to DC and back to single-phase AC at grid voltage and frequency, on demand. It is not practical to run the PMA at a constant speed (around 200 rpm) to supply fixed frequency output for your needs. In reality your demand will rarely match the supply exactly.

The Smart Drive is built as a motor but can function as a very efficient, affordable and versatile PMA, whose output is readily converted to DC *at any voltage you want*, depending on your choice of Smart Drive parts.

2.2. The basics of electrical power generation

The prime mover drives the shaft of the PMA. We can call this the input mechanical power, which the PMA converts to electrical power. Mechanical power can be measured in Watts, just like electricity. One kilowatt of mechanical power is a bit more than a horsepower. A horsepower is 746 Watts.

The output electrical power of any generator will always be less than the input mechanical power, due to losses. For example we would need about 1250 Watts mechanical to generate 1000 Watts electrical using a Smart Drive as PMA.

> Mechanical power has two elements: speed and torque
> Electrical power has two elements: voltage and current.

2.2.1. Speed affects the voltage

When there is no electrical load connected, the "open circuit" output voltage of the PMA will vary in direct proportion to the input RPM at which it is being driven. However there will be no power generated because there is no current. If you spin it by hand and measure the voltage you can witness this fact. It is easy to spin because the only power you need to provide is to overcome internal losses (friction etc) which are very small. You don't need to input much torque at all. This is the open circuit voltage which we will call Voc and it depends on the RPM.

2.2.2. Current affects the torque

If however you connect the PMA to a load (lamp, battery, etc) and spin it until it produces output power then you will notice that turning it is much harder work. You have to put some muscle into the turning action and this is called torque. The more current you draw on the output, the more torque needed on the input and the more power you convert from your lunch into electricity.

An interesting feature of the SD PMA is that the torque (and current) has an upper limit. You do not have to worry about overloading the PMA with too much mechanical power (which might burn out the windings in other alternators). Beyond a certain point, the SD PMA will simply overspeed if you push it too hard. Even if the output is short circuited (which makes it much harder to start due to the high current) there are situations where you can provide enough torque to break through this barrier and spin it quite fast without damage.

2.2.3. Designing a PMA application

To be successful with using the SD PMA for your application, you will need to measure, calculate or successfully guess various facts that determine the choice of PMA parts that best fit your needs. Below we will be describing the characteristics of the various PMA models and windings. You must try to select the best PMA magnetic rotor and stator to match the characteristics of your prime mover and your load. We will also describe how to adjust the PMA in case you are slightly off with your predictions.

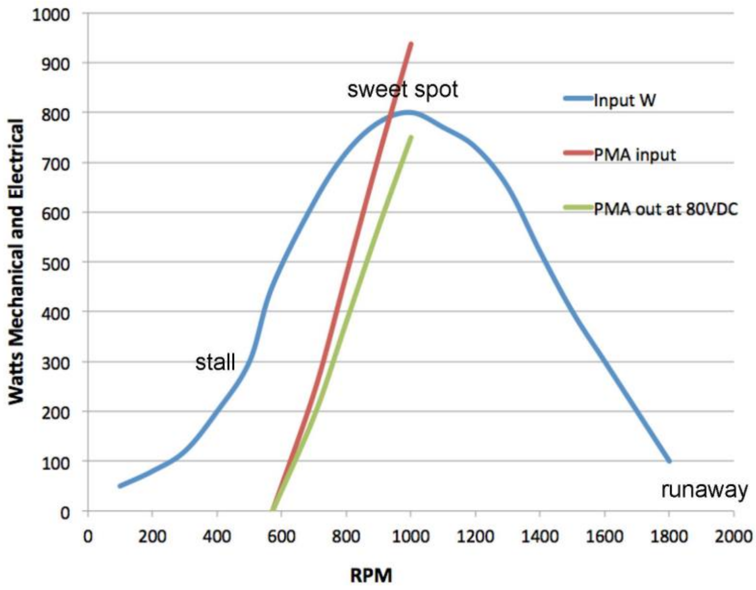
Most prime movers have a range of useful operating speeds that reach a "sweet spot" in the middle where you get the best results. When you change gear in your car you are seeking the sweet spot for your engine rpm and avoiding the edges of the operating range where it either overspeeds or stalls. A turbine is the same, and even a human on a bike has a best pedalling speed and a choice of gears.

Figure out where this sweet spot is and note the expected power (Watts) and speed (rpm). You may need to work over a range of conditions, so you may have to look at how these figures will vary, but one spot is enough to begin with. Bear in mind that the PMA is typically about 80% efficient and therefore your output electrical power will be roughly 0.8 times your input power from the prime mover.

The chart below shows the notional power of the prime mover in blue. The input (mechanical drive) power absorbed by the PMA is in red. The PMA output electrical power is shown in green.

The PMA achieves 80V Voc at 570 rpm but as the load comes on it needs 1000 rpm to maintain the same 80V.

So long as the blue line is above the red line, the device will accelerate, but when the lines intersect then we have the operating point. We try to arrange that this lands close to the sweet spot where we get the most input power.



An important characteristic of the PMA is the "W/rpm". Due to the limited output current described above, there is a corresponding limit to the output power in Watts your PMA will be able to handle at low rpm. Start your design process by making sure your prime mover is within this operating envelope. Speed must be high enough and power low enough that the PMA can handle your application or the prime mover must be redesigned or geared up. Or you would need multiple PMAs to handle the load power.

The other design variable you need to consider is voltage. If you are charging a battery directly then this might be the battery voltage. Often nowadays the DC output of the PMA will be fed to a "maximum power point tracking" (MPPT) device such as a grid-tied inverter or a solar controller for battery charging. These devices can find the sweet spot automatically whilst working over a range of voltages but they all have limits to their operating range above which damage can occur.

As we shall see below, the "V/rpm" of the PMA can be chosen from a huge range of possible values. This makes it possible to design for almost any possible combination of input and output conditions within the power handling envelope. The factors we take into account in the PMA construction when we predict V/rpm for you are as follows:

- Density of the magnetic flux in Tesla
- number of turns per coil on each finger pole
- number of finger poles in series per phase
- connection of the phases (Star connection yields higher voltage than Delta.)

"Why would you want *less* voltage instead of *more*?" you might ask? The answer is that it's like a gear box. You need the ***right*** voltage. A high gear will not make you go faster. You must choose a gear to suit the engine and the speed of the vehicle. If you want to charge a 12V battery then you need one stator. If you want to operate a grid-tied inverter at 300 V then you need a very different stator - but they both look the same. In each case we choose the stator that helps us hit the sweet spot of the prime mover whilst delivering the voltage that we need.

Be aware that the V/rpm relates to the open circuit voltage of the PMA (which we will call Voc) and not the operating voltage on load, which will be lower at the same rpm. Later we will describe how to match the best operating voltage of the PMA to the desired output voltage at the operating sweet spot of your prime mover.

2.3. The history of the Smart Drive

The Smart Drive was designed over 25 years ago and was the 1st direct drive motor for mass produced washing machines. It was also injection moulded from plastic, never before done on a motor this large subject to high torque reversals.

Since its inception it has undergone four design changes for higher voltage applications, but remains little changed in appearance. It is still in manufacture today and installed on many leading brand washing machines such as:

- Fisher & Paykel
- Whirlpool
- Maytag
- Haier

Other companies such as LG have also copied this design, but as they run with large clearances and do not use laminated steel rotors or high strength ferrites these units have a much lower power density and efficiency. In other words they are inferior products.

For a more comprehensive introduction to the Smart Drives, refer also to these links:

- Article Smart Drive History
- History of the Smart Drive PMA/Motor
- Smart Drive Open Heart Surgery
- Choosing the right parts
- Bearings and shafts
- 2004 Smart Drive Manual - reference only

2.4. Smart Drive Features

Smart Drive is a trade mark of Fisher and Paykel and also the name of the motor it makes using a fully automated production line. They make many other similar motors, but in our experience the original design is still the best option as all the main components can be easily separated - which is what makes it so versatile. This is not the case for their other motor designs which are often integrated into the appliance.

There are 2 production lines in the world (Thailand and the USA) and each line can make a Smart Drive every 30-45 seconds. The Smart Drives (and machines that manufacture them) are designed and made in New Zealand, hence our connection with this company.

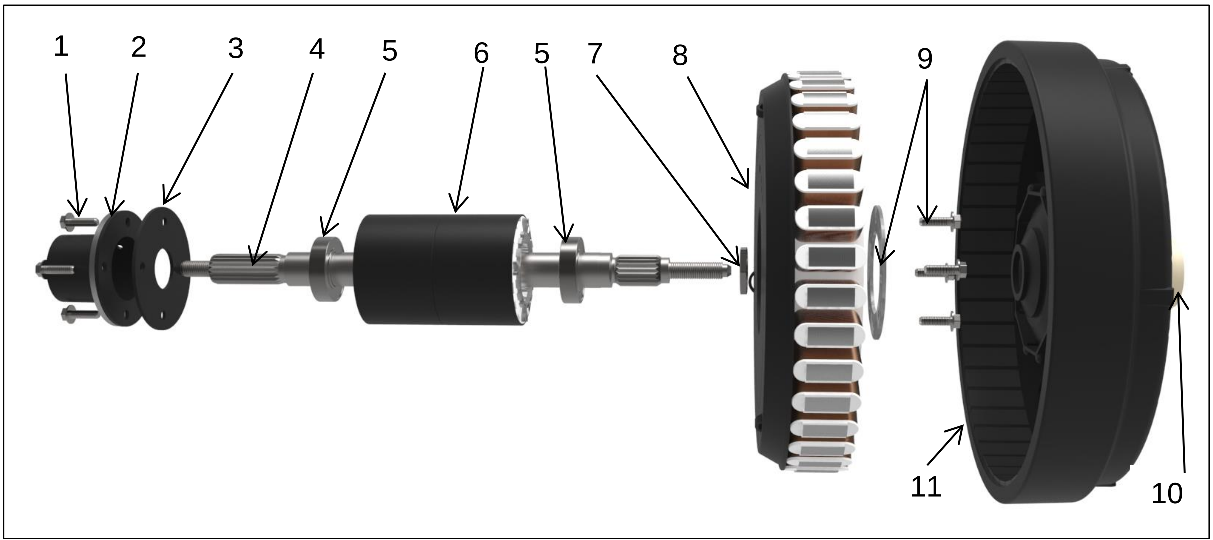
A Smart Drive is a 3-phase BLDC (Brushless DC) electrical machine that works equally well as a PMA (Permanent Magnet Alternator) or as a BLDC motor.

To operate as an electrical motor advanced electronics are required (similar to those used to drive an electric motorbike or bicycle). To operate as a generator it would normally just need a 3-phase rectifier and the output would then be DC.

What is unique about the Smart Drive is:

- It has a very high efficiency due to precision manufacture and very tight running tolerances between the ferrite magnets and the stators steel laminations.
- The stator coils can be easily reconnected from series connected into many series/parallel wiring options. This has the huge benefit of customisation from which many voltage/rpm options are possible from one PMA design.

2.5. Smart Drive Parts



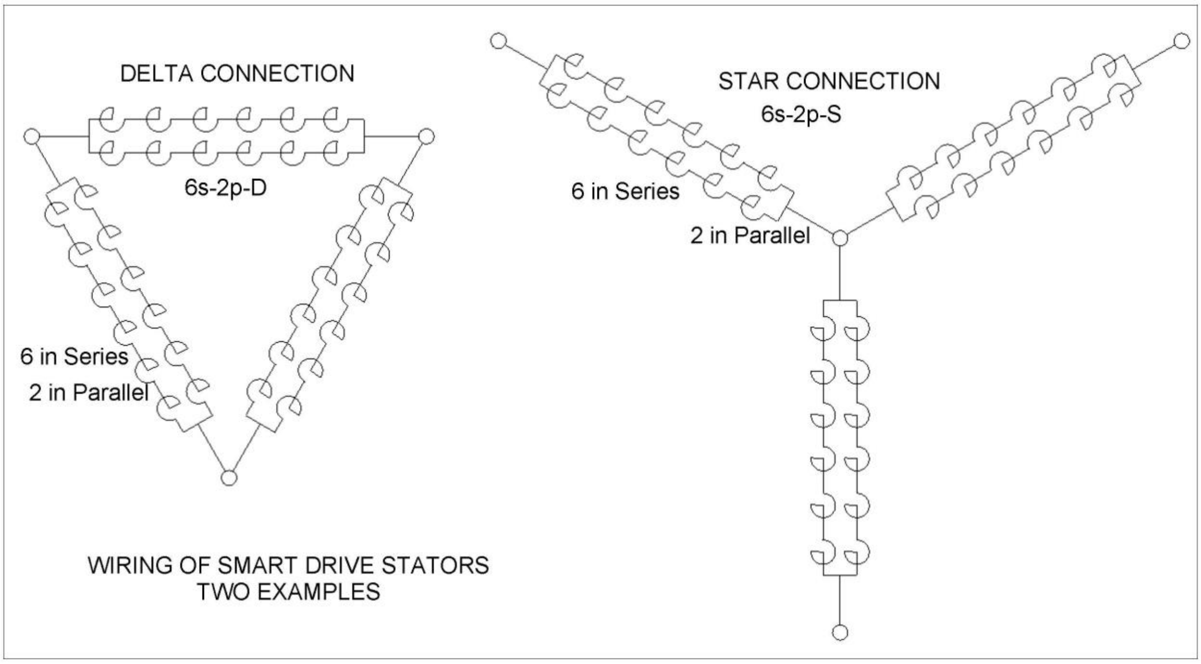
Smart Drive parts

1. 4 x ¼ UNF bolts
2. Top cap cover, washer and seal
3. Seal
4. Shaft (2 options available)
5. 6005 bearings
6. Bearing block and trim
7. M25 flat nut
8. Stator (more than 90 options in 36 or 42 pole)
9. Stator fixing set (2 washers and 4 x ¼ UNF bolts)
10. Extractor knob
11. Magnetic Rotor of which there are 4 types (rotor pole no. = stator pole no.)
    - Type 2 – 42 pole 0.75W/rpm
    - Type 2+ – 42 pole 1.0W/rpm
    - Type 3 – 36 pole 0.75W/rpm
    - Type 4 – 36 pole 1.0W/rpm (shown in picture above)

3. Smart Drive stator codes explain

We can offer a wide range of different stator options to fit the various SD models and to match your requirements for output V/rpm. Each stator variant has a numerical code, For example 100-14s-1p-S(1).

- The 1st number of the stator code is the nominal wire size (diameter):
  100 = 1mm
  80 = 0.8mm
  60 = 0.6mm
- The second number is the number of wire wound fingers that are connected in series per phase, followed by s for series. More windings in series give a higher voltage.
- The third number is the number of wire wound fingers that are connected in parallel per phase, followed by p for parallel. All of the poles need to be used, so the "s" number times the "p" number must equal the total number of fingers per phase (e.g. 7s 2p or 2s 7p for 14 in total).
- The fourth digit is a letter either D (for Delta) or S (for Star). This denotes the wiring of the three phases to each other. Star connection gives 1.73 times higher output voltage than Delta at the same rpm.
- The last number in brackets (1) if shown is the number of 1.6mm packing washers needed under the rotor to tune performance. If not shown no packers are advised.



3.1. 42-pole stator options

Each stator in early (type 2) models has 42 coils on finger poles, 14 poles per phase with 3-phases. When we come to group the coils in each phase into series and parallel, 14 is only divisible by 14, 7, 2 & 1 which gives a total of 4 options per wire size, each with possible final Star or Delta connection.

The 42 pole stator was made in 3 wire sizes 1.0, 0.8 & 0.6mm diameter copper.

All twenty-four options are listed below with their V/rpm. When these stators are fitted with type 2 rotors you will get up to 0.75 W/rpm and when fitted with type 2+ rotors you will get up to 1.0W/rpm when load tested via an MPPT regulator at their MPP (Maximum Power Point).

Wire Code	S	P	V/rpm Delta	V/rpm Star
100	14	1	0.152	0.266
100	7	2	0.076	0.133
100	2	7	0.022	0.038
100	1	14	0.011	0.019
80	14	1	0.398	0.699
80	7	2	0.199	0.350
80	2	7	0.057	0.100
80	1	14	0.028	0.050
60	14	1	0.580	1.018
60	7	2	0.290	0.509
60	2	7	0.083	0.145
60	1	14	0.041	0.073

When used as permanent magnet alternators (PMAs) these 42-pole machines will have an uneven motion known as 'cogging' that is produced by the attraction of the magnet poles to the stator poles. The jumping of flux lines from one pole to the next causes some vibration and roughness. Also the cogging torque makes the PMA harder to start up which is a significant problem from small wind turbines.

3.2. 36-pole stator options (identified as “60dc”)

In the last 10 years the Smart Drive motor design was changed:

- from 42 to 36 pole
- magnetism of the rotor ferrite into a “horse shoe” shaped field
- finger steel laminations curved
- high strength ferrite magnetising technology developed (type 2+ and type 4 rotors)

The shaping of the laminations resulted in a cog free motion, which meant that the Smart Drive could be used in small wind turbines for the 1st time - previously they would not start easily. (In washing machines this resulted in quieter operation.)

Efficiency of the 36 and 42 pole Smart Drive is about the same. Many DIY’ers are of the view that the coggy Smart Drive (42-pole) is less efficient than the newer cog free design (36-pole), but this is **not** the case.

To avoid naming confusion with earlier 42-pole stators, all 36-pole stators that are copper factory wound have the prefix 60dc. The "dc" is an abbreviation for de-cogged. It has nothing to do with "direct current" DC.

Each stator has 36 coils on finger poles: 12 coils per phase with 3-phases. 12 is divisible by 12, 6, 4, 3, 2 & 1 which gives a total of 6 options for V/rpm per wire size. In each case we also have final Star or Delta connection options.

All twelve options for V/rpm for 60dc stators with type 4 rotors are listed below. By default these stators are fitted with type 4 rotors, and you will get up to 1.0W/rpm when load tested via an MPPT regulator at their MPP (Maximum Power Point). (With optional type 3 rotors you will get up to 0.75 W/rpm and slightly lower V/rpm.)

Wire Code	S	P	V/rpm Delta	V/rpm Star
60dc	12	1	0.638	1.120
60dc	6	2	0.319	0.560
60dc	4	3	0.213	0.373
60dc	3	4	0.160	0.280
60dc	2	6	0.106	0.187
60dc	1	12	0.053	0.093

3.2.1. Aluminium wire

The 36-pole stator has only ever been made using 0.6mm diameter wire, but they switched from copper to aluminium wire. Aluminium has higher electrical resistance than copper. The change to aluminium wire (to save production cost) resulted in loss of performance and more heating. This was "fixed" in the type 4 by altering the magnetic rotor to allow for more cooling and by changing to high strength ferrite technology.

EcoInnovation has a good stock of older 36-pole **copper** wound 60dc stators but these were only manufactured for a few years, so are very hard to find. All machines manufactured today are wound with aluminium wire.

EcoInnovation do not sell these aluminium-wound stators. Instead we developed an unwinding and CNC winding machine, which enables us to Rewind 36-pole stators with copper wire. These are then called 60R. Refer to **next** section.

3.3. 36-pole stator options – CNC Rewound options (Identified with a "60R")

These 36-pole units have had their aluminium wire removed and replaced with copper. When we did this, we rewound them in such a manner so as to fill gaps in the V/rpm range. We did this by adjusting the number of wire turns per coil, so ensuring a good spread from 1.12 to 0.011 V/rpm with over 90 increments (steps). Once you own a rewinding machine you can make any V/rpm option you like, but we chose to limit our total options to <100 which still meets all realistic needs.

For example a 60R120 has been rewound with 0.6mm copper wire that has 120 turns per finger pole. The original 60dc has 180 turns.

For a complete list refer to the next section.

3.4. Complete Smart Drive options offered

This complete list in V/rpm order is all the Smart Drive stator options we offer. The code colours allow you to easily spot 42 pole, 36 pole de-cogged & 36 pole Rewound de-cogged. Prices vary and reflect the labour to reconfigure, those with high S (series) numbers will generally cost less as the labour to reconfigure them is much less.

Number	Code	S	P	S/D	V/rpm	Number	Code	S	P	S/D	V/rpm
1	60dc	12	1	Star	1.120	50	60R120	4	3	Delta	0.131
2	60	14	1	Star	1.018	51	60R90	3	4	Star	0.129
3	80	14	1	Star	0.699	52	60R85	3	4	Star	0.121
4	60R120	12	1	Star	0.690	53	60R110	4	3	Delta	0.120
5	60dc	12	1	Delta	0.638	54	60R120	2	6	Star	0.115
6	60R110	12	1	Star	0.633	55	60R100	4	3	Delta	0.109
7	60	14	1	Delta	0.580	56	60dc	2	6	Delta	0.106
8	60R100	12	1	Star	0.575	57	60R110	2	6	Star	0.105
9	60dc	6	2	Star	0.560	58	80	2	7	Star	0.100
10	60R90	12	1	Star	0.518	59	60R90	4	3	Delta	0.100
11	60	7	2	Star	0.509	60	60R120	3	4	Delta	0.098
12	60R85	12	1	Star	0.484	61	60R100	2	6	Star	0.096
13	80	14	1	Delta	0.398	62	60dc	1	12	Star	0.093
14	60R120	12	1	Delta	0.393	63	60R85	4	3	Delta	0.092
15	60dc	4	3	Star	0.373	64	60R110	3	4	Delta	0.090
16	60R110	12	1	Delta	0.361	65	60R90	2	6	Star	0.086
17	80	7	2	Star	0.350	66	60	2	7	Delta	0.083
18	60R120	6	2	Star	0.345	67	60R100	3	4	Delta	0.082
19	60R100	12	1	Delta	0.328	68	60R85	2	6	Star	0.081
20	60dc	6	2	Delta	0.319	69	100	7	2	Delta	0.076
21	60R110	6	2	Star	0.316	70	60R90	3	4	Delta	0.074
22	60R90	12	1	Delta	0.295	71	60	1	14	Star	0.073
23	60	7	2	Delta	0.290	72	60R85	3	4	Delta	0.069
24	60R100	6	2	Star	0.288	73	60R120	2	6	Delta	0.066
25	60dc	3	4	Star	0.280	74	60R110	2	6	Delta	0.060
26	60R85	12	1	Delta	0.276	75	60R120	1	12	Star	0.058
27	100	14	1	Star	0.266	76	80	2	7	Delta	0.057
28	60R90	6	2	Star	0.259	77	60R100	2	6	Delta	0.055
29	60R85	6	2	Star	0.242	78	60dc	1	12	Delta	0.053
30	60R120	4	3	Star	0.230	79	60R110	1	12	Star	0.053
31	60dc	4	3	Delta	0.213	80	80	1	14	Star	0.050
32	60R110	4	3	Star	0.211	81	60R90	2	6	Delta	0.049
33	80	7	2	Delta	0.199	82	60R100	1	12	Star	0.048
34	60R120	6	2	Delta	0.197	83	60R85	2	6	Delta	0.046
35	60R100	4	3	Star	0.192	84	60R90	1	12	Star	0.043
36	60dc	2	6	Star	0.187	85	60	1	14	Delta	0.041
37	60R110	6	2	Delta	0.180	86	60R85	1	12	Star	0.040
38	60R120	3	4	Star	0.173	87	100	2	7	Star	0.038
39	60R90	4	3	Star	0.173	88	60R120	1	12	Delta	0.033
40	60R100	6	2	Delta	0.164	89	60R110	1	12	Delta	0.030
41	60R85	4	3	Star	0.161	90	80	1	14	Delta	0.028
42	60dc	3	4	Delta	0.160	91	60R100	1	12	Delta	0.027
43	60R110	3	4	Star	0.158	92	60R90	1	12	Delta	0.025
44	100	14	1	Delta	0.152	93	60R85	1	12	Delta	0.023
46	60	2	7	Star	0.145	94	100	2	7	Delta	0.022
47	60R100	3	4	Star	0.144	95	100	1	14	Star	0.019
48	60R85	6	2	Delta	0.138	96	100	1	14	Delta	0.011
49	100	7	2	Star	0.133						

4. W/rpm, V/rpm and Vmp characteristics

So how do we choose a Smart Drive with the right characteristics for our application?

4.1. W/rpm

W/rpm is the easiest one. It is determined by the choice of the magnetic rotor. There are only a 2 options to select for each pole option:

For 42–Pole stators:

- Default Type 2 rotor = 0.75W/rpm
- Optional Type 2+ rotor = 1.0W/rpm

Note the Type 2+ are specially made for EcoInnovation by Fisher & Paykel by re-magnetising a type 3 rotor into a high power type 2 called a 2+. This was done after the type 3 and 4 had been produced, so we decided to call it a 2+. There is also a type 1 rotor made from rare earth magnets but we do not sell these as they are an inferior option and have not been made for 20 years.

For 36–Pole stators:

- Optional Type 3 rotor = 0.75W/rpm
- Default Type 4 rotor = 1.0W/rpm

Example: If you spin the Smart Drive PMA at say a constant 1600rpm and you keep increasing the electrical load, then the maximum power you can extract will be
Power = rpm x 0.75 = 1600 x 0.75 = 1200W (42 poles stator with type 2 rotor)
or Power = rpm x 1.0 = 1600 x 1.0 = 1600W (36 pole stator with type 4 rotor)

This example is quite a high operating rpm but we do have four PMA's running at up to 2000W at 2000 rpm for endurance testing at this site. So up to 2000W/unit is possible although bearing life will be shorter than at lower rpm.

Example: We have an application that requires 500 W output at 200 rpm shaft speed. We can reach 150 W or 200 W at this shaft speed with the SD but 500 W input will lead to overspeed which will take us above the desired operating rpm (the sweet spot of the prime mover). This application is outside the operating envelope of the SD and needs to be modified, perhaps by using a belt drive to raise the rpm of the SD, or by using 3 PMAs on one device.

4.2. V/rpm

V/rpm is also easy to understand. Open circuit voltage (Voc) is proportional to speed (rpm).
V/rpm is the open circuit voltage divided by the rpm.
If we select a 60dc-1s-12p-S from the table above then the V/rpm = 0.093.
If we then spin this unit at 1600 rpm, the DC voltage of the 3-phase rectified output unloaded is Voc = 1600 x 0.093 = 148.8 VDC, almost 150 VDC.
(A tolerance of +/-5% should be applied to all figures.)

150 VDC can kill you, so you must be careful not to touch any conductors when operating.

If you were to redo this calculation for a 60dc-12s-1p-S stator you would get Voc = 1792 VDC, which in addition to electrocution could result in an electrical flash over and fire in the PMA. This is because the lacquered insulation around the wires is rated for only 600V.

Unless you are qualified and experience you need to avoid working with voltages above 50 VAC or 75 VDC. A lethal electric shock is much less likely below these voltages, but the risk of fire remains if for example your wiring is too thin or there is an arc fault.

It is easy to make a mistake when playing with Smart Drives and if you confuse a stator labelled 60-1s-14p-Star with a 60-14s-1p-Star (as left handed dyslexic inventors often do), you will get 14 times more voltage that you were expecting and will kill all connected electronic equipment. This could also result in fire.

For this reason we advise you to **always do a V/rpm check** at a slow (50 rpm) speed to verify that no mistakes have been made prior to running at full rpm.

4.2.1. Effect of rotor choice on V/rpm for a stator

The V/rpm values quoted in the "complete options" table above are based on using the default rotor for that stator. In other words it is assumed that the 42 pole stators are fitted with type 2 rotors (and have W/rpm = 0.75) whereas the 36 pole stators are assumed to be fitted with type 4 rotors (and have W/rpm = 1.0). If a different rotor is fitted then the V/rpm will actually be slightly different too due to the differing magnetic field strength of the rotors.

Stator type	Rotor type	W/rpm	Advice
42 pole	2	0.75	Use the V/rpm value given
42 pole	2+	1.0	Add 5% extra voltage (multiply by 1.05)
36 pole (dc or R)	3	0.75	Subtract 10% voltage (divide by 1.1)
36 pole (dc or R)	4	1.0	Use the V/rpm value given

4.3. Maximum Power Point Voltage (Vmp)

Bear in mind that the operating voltage of the PMA when working hard will be lower at the same rpm, so you cannot simply use the V/rpm data from the table above to directly predict the operating voltage of the turbine on load.

Maximum Power Point Voltage (Vmp) is the actual voltage of the SD when producing its maximum power, as opposed to the open circuit voltage (Voc) that you can calculate from knowledge of its V/rpm and its actual speed.

Many DIY'ers think that in order in charge a 12V battery you just need a 12V PMA. Yes you can choose a PMA that gives 12V at the target operating RPM, but if the PMA and the battery both have the *same* voltage there would be no current flow (charge) from the PMA to the load (battery). You will need some extra voltage to overcome the impedance of the winding and push out the desired current.

If you check the output of a 12V solar PV panel that is disconnected (measure the Voc or open circuit voltage) you will measure over 20V, not 12V, but once connected it charges the 12V battery just fine. A Smart Drive PMA behaves in a similar way. An applied load will cause the voltage to sag. The real question is; how much load and corresponding voltage sag is needed to get to the maximum power point (MPP) for the Smart Drive PMA?

In our experience the voltage for maximum power output of the PMA is in the range 0.55 - 0.6 times the Voc at the corresponding RPM.

We can say Vmp= 0.57 x Voc or Voc = 1.75 x Vmp

Let us take for example the above case of the 60dc-1s-12p-S stator which at 1600 rpm produces Voc = 148.8 VDC as we have seen.

The voltage for maximum power or Vmp = **0.57** * 148.8 = 84.8 VDC
This is the *loaded* voltage at which we can get the full 1600W with a type 4 rotor fitted.

Conversely speaking you will need about 1.75 times higher Voc than your working Vmp if you want to pull the full power out of the PMA that you calculated. If you want 85 volts working at full power, then you will need a Voc = 1.75 x 80 = 149 volts.

The short circuit current can also be estimated from the MPP cable amps x 1.5. The only reason we are interested in this is to make sure that the cables we use are not going to overheat. In the unlikely event that our cables cannot handle the short circuit current then we might need to use circuit breakers to protect them.

Summary for this example:

- Stator = 60dc-1s-12p-S
- V/rpm = 0.093 from table
- W/rpm = 1.0 (for type 4 rotor fitted, or 0.75 with type 3 rotor)
- RPM = 1600 of electrical machine (for this example)
- Voc = 1600 x 0.093 = 148.8 VDC (this is often called the open circuit voltage)
- Maximum Power (Pmp) = 1600 x 1.0 = 1600W
- Maximum Power Point Voltage (Vmp) = 0.57 x 148.8 = 84.8 VDC
- Amps in cable = Power/Volts = 1600/84.8 = 18.9 amps
- Short circuit current (approx.) = Amps in cable x 1.5 = 28.3 amps
- PMA efficiency = 80% (this is relatively constant if MPPT controllers are used)

Let's try another example in the opposite direction starting with application "sweet spot" data as follows:

Available input power (mechanical): 800 W
Shaft speed at this power: 1000 rpm
Desired output voltage: 80 VDC

First calculate output electrical power = 0.8 x 800 = 640 W estimated electrical output.
Can we achieve this output power with an SD PMA?
Say we choose a rotor with W/rpm = 0.75, then maximum power at 1000 rpm = 750 W
So yes we can achieve the output. We won't be limited by the capacity of the PMA.

Now to choose a stator.
V is roughly 80V, so our Voc will be roughly 80 / 0.57 = 140 VDC
V/rpm is therefore 140 / 1000 = 0.14
Option number 47 or 48 in the complete table in section 3.4 looks good.

Bear in mind that we do not want to run it at 750 W output so some tweaking of the design may be required. Read on for some fine tuning.

4.4. Allowing for load factor "F"

In reality, obviously the output power Po cannot be above maximum possible Pmp. It must be a little below. This affects the ratio between operating Vo and Voc.

<u>Let's review some of the variables here and their names and definitions.</u>
Maximum power at chosen RPM is called **Pmp** = W/rpm x RPM (and W/rpm is 0.75 or 1.0)
Open circuit voltage at this RPM is called **Voc** = V/rpm x RPM (V/rpm relates to the stator)

Our operating power is called **Po** = 0.8 x input mechanical power of the prime mover.
Our operating voltage is called **Vo** = the voltage we need on the electrical side of things

If Po = Pmp (or close) then we can simply say that Voc = Vo / 0.57 and so we can find Voc and hence find "V/rpm" and thus choose a suitable stator.

If Po is very small then we can say that Voc is practically the same as Vo.

If the application power Po is significantly less than the Pmp power of the PMA at the chosen rpm then we can define the ratio between them as the **load factor F = Po / Pmp**
For example if Pmp is 750 W and the working power Po is 640 W then F = 640/750 = 0.85

The equation for Voc in such cases is as follows Voc = Vo / (1 - (F x .43))

Voc in our above example will be = Vo / (1 - (0.85 x .43)) = 80 / (1 - .37) = 80 / .63 = 127 V
It's not a lot different from our first stab calculation of 140 V, and you must bear in mind that the result is always +/- 5%, but an adjustment like this can help to choose a better stator with V/rpm = 0.127.

If the operating power is less than the maximum then we do not need such a high Voc because the droop in voltage on load will not be so dramatic. The above equation helps us to find the correct (slightly reduced) Voc (and thence the reduced V/rpm) for our application.

4.5. Packing the magnetic rotor to adjust voltage

Often the stators vary slightly and the magnetic rotors vary slightly in their properties so that the expected output is not achieved, although close. If the PMA is connected to a MPPT device (controller or inverter) then small errors will be automatically corrected.

If you are not using MPPT and you wish to tweak the output voltage downward, then this can be easily done by packing the magnetic rotor out with one or more washers so as to reduce the magnetic flux density in the stator.

Grasp the knob and turn anti-clockwise until the magnet rotor until comes off the shaft. Place the desired number of washers on the shaft and refit the magnet rotor finger tight only. As a guide, you will reduce the voltage by about 3% for every 1 mm of washer thickness that you insert behind the rotor. A washer that is 1.75 mm thick will reduce the voltage by 5%.

4.6. Summary of the design process

Let's just run through the process again to clarify the steps:

1. Find out the prime mover characteristics of speed and power. We need to know the electrical output power at a given rpm where the prime mover has its "sweet spot" to produce the most power. Bear in mind that the conversion efficiency of the SD PMA will be about 80%. So the electrical power = the mechanical power x 0.8

2. Divide the output power by the rpm to find the W/rpm of the PMA at this performance point. Each PMA cannot produce more than 1 W/rpm. If your application is under 0.75 W/rpm then you can choose a 42 pole stator (with green highlight) from the table in section 3.4. If it is more, then should must choose a 36 pole stator.

3. Decide on the operating voltage "Vo" of the output circuit. For example if you are charging a battery directly then this might be the normal charging voltage of your battery. A 24 V battery would have Vo = 28 V. If using an MPPT controller then the Vo must be higher but not so high that you risk damaging the controller.

4. Work out the load factor "F" in your situation. If you are using a 36 pole stator then this will be the same as your calculated W/rpm in step 2. If you are using a 42 pole stator then the load factor is your W/rpm divided by 0.75. For example is your electrical power is 500 W and your rpm is 1000, then W/rpm is 500/1000 = 0.5 W/rpm. If using a 42 pole stator then load factor F = 0.5/0.75 = 0.67.

5. Determine the open circuit voltage "Voc" that you will need. If you are working at 1 W/rpm then this is simply 1.75 times Vo (for a 36 pole stator). Or if you are at 0.75 W/rpm then you can use a 42 pole stator and again just multiply Vo by 1.75 to find Voc. In these cases the load factor is 1. If load factor is less than 1 (F<1) then you will not see such a big droop between open Voc and loaded Vo so use the formula from section 4.4 as follows:

$$Voc = Vo / (1 - (F \times .43))$$

Using the example in the previous step, if F= 0.66 and Vo = 28 then we can find Voc as follows:

$Voc = Vo / (1 - (F \times .43)) = 28 / (1 - (0.67 \times 0.43)) = 28 / (1- 0.29) = 28 / 0.71 = 39$ V

6. Find the V/rpm of the stator we need. This will be Voc divided by the operating rpm. In our example thus far it will be 39 / 1000 = 0.039

7. Search the table in section 3.4 to find the nearest match, bearing in mind that you must choose a stator with the right W/rpm as well. So in our example above, if we are looking at 42 pole stators we might choose the 100-2S-7P-Star. The listed V/rpm is 0.038 which is close enough, given that stators have some random variation in their properties anyway.

8. The job is done. This stator should hit the sweet spot under our application operating conditions, or close enough to work well. If we have chosen to use an MPPT device in the output circuit (MPPT controller or grid tied inverter with MPPT) then it will likely correct any small errors. Or if not then we can increase the rpm at the operating voltage by using packing washers behind the magnetic rotor to fine-tune the PMA for our task.

9. Check the short circuit current. This will be roughly 1.5 times the current of the stator at its maximum power. Maximum power = rated RPM. (or 0.75 x rated RPM).
Short circuit current = 1.5 x (power/voltage)
or for the 42 pole stator = 1.2 x (rated RPM/ Vo), due to W/rpm being only 0.75.
In our example RPM = 1000 and Vo = 28
so short circuit current = 1.5 x (rated RPM/ Vo) = 54 A (or 40A for lower wattage PMA).

4.7. Some basic testing

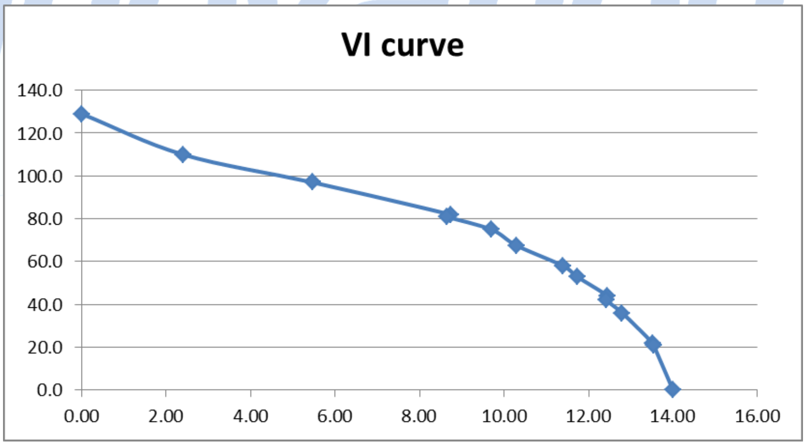
As the characteristics of a Smart Drive PMA are fully understood, we do not need to test each and every Smart Drive PMA option (in the table above) in order to accurately predict what will happen in a given situation.

The table opposite is the raw test data for a 60-2s-7p-S (option 46 in the table above) tested at 1000 rpm into an MPPT regulator with a type 2 rotor fitted. We would expect to see MPP Watts of 1000rpm x 0.75W/rpm = 750W, we can see 728W, a little less due to the efficiency of the MPPT regulator used and the fact that a +/- 5% tolerance applies.

1000 rpm	60-2S-7P-Star			
%load	Amps	Volts	Watts	
0	0.00	129.0	0	Unloaded
14.7	2.40	110.0	264	
24.8	5.47	97.0	531	
36.4	8.73	82.0	716	
37.2	8.65	81.0	701	
41.9	9.70	75.0	728	
47.7	10.30	67.5	695	
55.0	11.40	58.0	661	
58.9	11.73	53.0	622	
65.9	12.45	44.0	548	
67.4	12.42	42.0	522	
72.1	12.80	36.0	461	
82.9	13.52	22.0	297	
83.7	13.54	21.0	284	
100.0	14.00	0.0	0	short circuit

- The MPP amps = 9.70
- Short circuit amps (measured)= 14.0
- Estimated short circuit amps = 1.5 x 9.70 = 14.6 amp (close enough)
- Vmp / V unloaded = 75/129 = 0.58 (close to the **0.57** we used above)

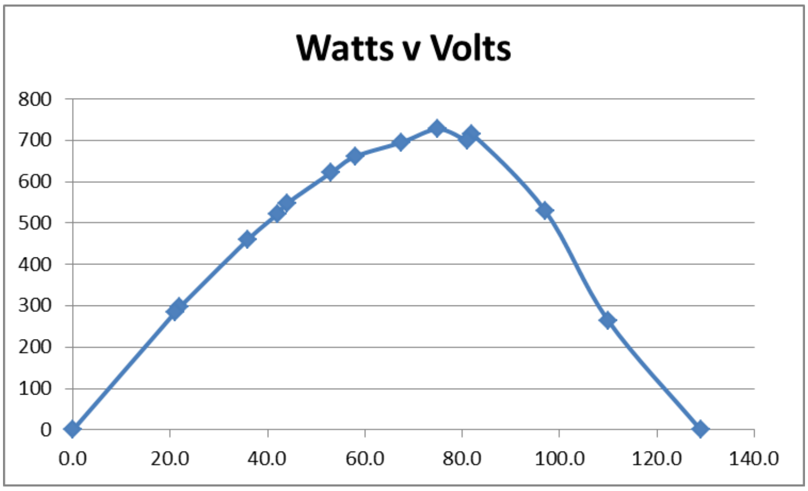
From the above data table we can graph a typical VI curve as shown opposite.
The vertical "y" axis is operating voltage.
The horizontal "x" axis is load current.



This next graph of W versus V clearly shows the MPP at about 79 V working.

The working range of this Smart Drive PMA is between 129 Voc and 79 Vmp
(In this example).

All Smart Drive PMA's will follow the same trends. By choosing the stator we can increase or decrease the voltage of operation.



By altering the magnetic rotor (to a type 2+) we could increase the Watts for a given rpm, but as we do not get more power for free, we'd also have to increase the input torque to get more power at the same speed. We might have to pack the rotor slightly to obtain the same rpm as the type 2 rotor was giving us.

Although the above process of selecting a stator appears slightly approximate, it is very accurate in comparison to the level of knowledge most users will have of their prime mover. Fortunately the "sweet spot" for maximum power is often quite a wide band of rpm. Furthermore the PMA performance can be tweaked a little on site by using packing washers behind the magnetic rotor to increase the rpm for a given output voltage. Or in most cases the MPPT device attached to the PMA will optimise the output.

What follows are examples for common machines you may want to make. You can then use this information to select the correct PMA for your application and then order it from our online store.

5. Examples for various rotating machines

PMA examples

- Hydro turbines:
    - Pelton
    - Turgo
    - Propeller
    - Overshot water wheel
    - Undershot water wheel
    - Cross flow turbine
    - Water pumps as turbines
- Human powered machines
    - Exercise machine
    - Education – Hand cranked lights
- Wind turbines:
    - Horizontal axis
    - Vertical axis
- Engine drives

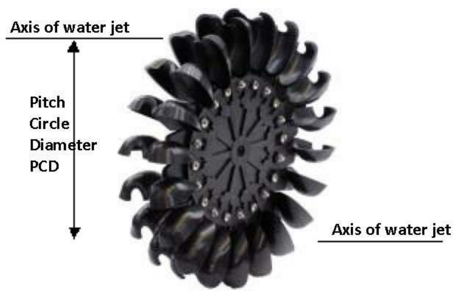
This section looks at some typical examples to ensure that the resource you wish to harness is well matched to the Smart Drive PMA. We look at some machines in detail - some less so.

5.1. Hydro turbines

Hydro turbines are easy because we have already written calculation tools that will locate the correct PMA to use. You can find the "Advanced Calculator" on our web site at http://www.powerspout.com/advanced-calculator/
The process is fairly intuitive but it's a good idea to read the pdf manual for the calculator called **PS all Calculator Manual Jan 14** in the document index.
Provided you buy both the PMA and the Pelton (or Turgo) runner from EcoInnovation (PowerSpout) you can use the calculator to get all your answers. If you want to try the Smart Drive PMA with a different hydro runner then you will need to figure out the rpm based on the PCD of the runner you are planning to use.

5.1.1. Runner RPM

The "Sweet spot" RPM for a Pelton or Turgo runner depends on the water jet velocity and on the diameter of the circle at which the jet is positioned (the "PCD" - see diagram).



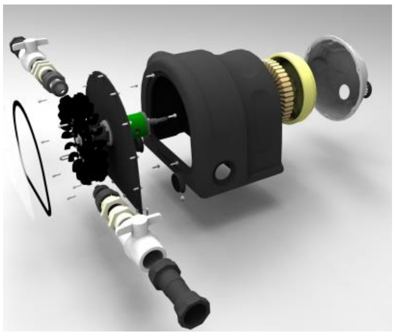
PowerSpout PLT runners have PCD = 0.235 metres and the TRG runners have PCD = 0.09 metres which means they will run at higher RPM.

Here are some equations that you can use to arrive at the sweet spot for your turbine: -

Net Head = Gross head x pipe efficiency
Turbine RPM = 39 x square-root(Net Head) / PCD
Electrical Power output = (Net Head) x (flow litres/sec) x 5

For example take gross head 80, and pipe efficiency 0.8 (80%).
Net head is therefore 64 metres
Turbine RPM = 39 x root(64) / PCD = 39 x 8 / 0.235 = 1328 rpm
If flow rate is 2 l/s then electrical power = 64 x 2 x 5 = 640 W

5.1.2. Pelton Turbine example (MPPT)



PowerSpout PLT

For this example our PLT calculation tool will do all the hard work for us. But this tool assumes you are using our Pelton wheel. If you intend to use a different make/size of Pelton wheel then these calculations will not be accurate and will not locate the correct Smart Drive PMA to use.

For example, I have surveyed our hydro site data and determined the following:

- Head = 110m
- Flow available in stream = 2 l/s
- Pipe length = 800m
- Cable length = 50m

I have a 24V battery bank and wish to use a 150V MPPT regulator.

We enter this data into the tool (the completed web page can be located here.) We play with the pipe size. 50mm ID pipe gives 937W. Note that this takes account of the pressure loss in the pipe and mentions 82% pipe efficiency. So the net head that the turbine sees is 90 metres.

For an MPPT controller the operating voltage, Vmp must be above the battery voltage. The runaway voltage (Voc) of a free spinning Pelton will be about 3 x times higher again than the Vmp. (This ratio is a well-documented fact about the Smart Drive when used with our impulse turbines. Pelton and Turgo are both impulse turbines and we can assume Voc= 3 x Vmp.)

For our 150V MPPT controller, we note it stops working at 140V. We must enter a "load voltage" into the calculator tool that is about 1/3 of the maximum operating voltage of the MPPT regulator rating: 140/3 = 47V.

We also play with cable size and decide to use 10mm^2 cables, as the cable loss is acceptable at 5%.

We save this data file by entering our email address so as to be sent a summary file by email.

The tool advises that the following stators (top 10) can be used that also appear on the table above.

SD code	Vo	Voc	V/rpm
100-2S7P-S-HP	50	134	0.038
80-1S14P-S	53	158	0.05
80-2S7P-D(1)	47	170	0.057
60dc-1S12P-D	50	150	0.053
60-1S14P-D(1)-HP	48	139	0.041
60-1S14P-D	44	131	0.041
60R100-1S12P-S(1)-HP	50	143	0.048
60R90-2S6P-D(1)-HP	51	147	0.049
60R110-2S6P-D(2)-HP	51	170	0.06
60R85-2S6P-D(1)-HP	48	138	0.046

I decide to check the 2nd option just to make sure. Here below are some manual calculations.

- Stator = 80-1s-14p-S
- V/rpm = 0.050 from table
- W/rpm = 0.75 (for type 2 rotor fitted as HP was not selected or needed)
- Rpm for best turbine output = 1579 rpm (from the calculator)
- Voc (at above rpm) = 1579 x 0.050 = 79.0 VDC
  (This is the Voc at fixed rpm. The free runaway Voc on the turbine would be higher still at about 3 x Vmp due to higher rpm as well)
- Maximum Power available using this PMA at this rpm = 1579 x 0.75 = 1184W
- Maximum Power Point voltage (Vmp) = 0.57 x 79 = 45 VDC
- Runaway Voc = 45 x 3 = 135V
- Amps in cable = Power/Volts = 1184/45 = 26.3 amps
- Short circuit current (approx.) = Amps in cable x 1.5 = 39.5 amps
- PMA efficiency = 80% (this is relatively constant)

I note that the calculation tool stated 937W at 53.0 VDC, so it is close but not the same as the maximum Watts and the Vmp calculated manually…... why?

The answer is that the Smart Drive PMA is capable in this case of delivering more power at 1579 rpm than you have available in your resource and pipe selection. 1184 W capability with only 937 W of site potential. Load factor (see section 4.4) is only 79%.

The calculation tool has therefore not applied full load to the PMA, but a load sufficient to equal the power of your resource while allowing for PMA, pipe and cable efficiency. If we generate less power than the maximum we can, then the operating voltage will be higher. Hence there are two versions of Vmp: one for the site and one for the PMA. These two are only the same if your site can exactly match the maximum output of the PMA. You will note that the calculation tool refers to the site Vmp as Vo (Voltage operating).

Let's try the equation Voc = Vo / (1 - (F x .43)) from section 4.4

Vo = 53

F= 937/1184 = 0.79

so Voc = Vo / (1 - (F x .43)) = 53 / (1 - (0.79 x 0.43)) = 80 V (close enough to 79V)

Errors may still have been made. My site head may be more than I measured, which would result in a higher RPM and higher runaway Voc, so it is essential to check before I hook up my MPPT regulator by performing a Voc test. If this reading is under 140V, then all is good and I can hook up. I note the comprehensive “PS all Install manual” in the INDEX gives advice on how to do this.

Here is a picture of my DIY Pelton turbine that I made.

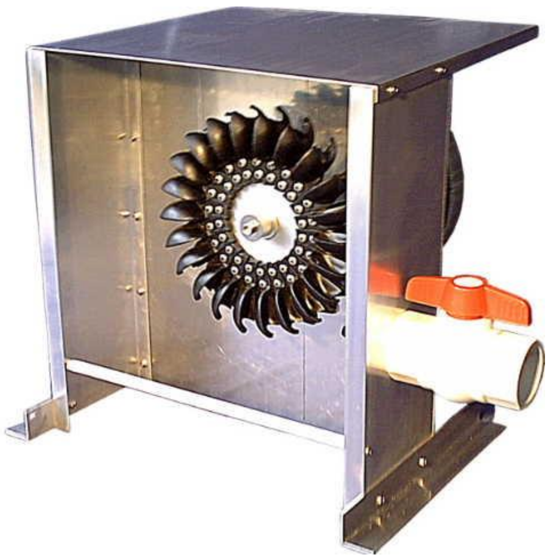
I made my own Pelton rotor the same size as the PowerSpout Pelton rotor but used some low cost spoons I found online. I mounted it in an old steel cabinet, it cost me about half the cost of buying one and took be a few days to make.

If you can locate an old washing machine you can even use the whole machine turned on its side, but rewiring the Smart Drive is tricky and it is much easier to buy a stator of the correct V/rpm.

This video outlines what you need to do if your head is similar. Very crude but it works.

A DIY example made from plywood.

A tidier example, this below is an early prototype of what eventually became our PowerSpout PLT.



5.1.3. Turgo Turbine example (MPPT)

For this example our TRG calculation tool will do all the hard work for us. But this tool assumes you are using our Turgo wheel. If you intend to use a different make/size of Turgo wheel then these calculations will not be accurate and will not locate the correct Smart Drive PMA. See Section 5.1.1 for help with adapting to a different size of runner.

As our Turgo rotor spins much faster than our Pelton rotor the maximum head is limited to 30m.

I have surveyed our hydro site and determined the following:

- Head = 30m
- Flow available in stream = 11 l/s
- Pipe length = 100m
- Cable length = 50m

I enter this data into the tool (see the completed page here). I play with the pipe size, and find that100mm ID pipe gives 1663W electrical output taking account of the pipe loss.

I have a 48V battery bank and wish to use a 250V MPPT controller. We note it stops working at 240V. To avoid exceeding this in the event of runaway, we must enter a load voltage about 1/3 of the maximum operating voltage of the MPPT regulator rating, 240/3 = 80V. I also play with cable size and decide to use 10mm^2 cable.

I saved this data file. A copy is sent to the email address that I enter on the page.

The tool advises that the following stators can be used that also appear on the table above.

SD code	Vo	Voc	V/rpm
60R85-3S4P-D-HP	84	192	0.069
80-2S7P-D-HP	78	177	0.057
60R120-2S6P-D-HP	80	182	0.066
60R90-3S4P-D-HP	90	205	0.074
60R110-2S6P-D-HP	74	167	0.060

As we desire an operational voltage close to 80V, the 3rd option looks promising.
I decide to check this option just to make sure.

- Stator = 60R120-2s-6p-D
- V/rpm = 0.066 from table
- W/rpm = 1.0 (for type 4 rotor fitted)
- Rpm = 1892 of electrical machine
- Voc (at above rpm) = 1892 x 0.066 = 125 VDC (free runaway voltage is about 3 x Vmp)
- Maximum Power Point (MPP) = 1892 x 1.0 = 1892W
- Maximum Power Point voltage (Vmp) = 0.57 x 125 = 71.2 VDC
- Amps in cable = Power/Volts = 1892/71.2 = 26.6 amps
- Short circuit current (approx.) = Amps in cable x 1.5 = 39.9 amps
- PMA efficiency = 80% (this is relatively constant)

I note that the calculation tool stated 1663W at 80.0 VDC, so it is close but not the same why?

The answer is the same as the Pelton example above.
The Smart Drive PMA is capable of delivering more power at your optimum site rpm than you have available in your water flow resource and pipe selection. The calculation tool has therefore not applied full load to the PMA, but a load sufficient to meet the power of your resource while allowing for PMA, pipe and cable efficiency. If we generate less power than the maximum we can, voltage will be higher. (The ratio of Voc to Vo will be less than 1.75)

Let's try the equation Voc = Vo / (1 - (F x .43)) from section 4.4

Vo = 80

F= 1663/1892 = 0.88

so Voc = Vo / (1 - (F x .43)) = 80 / (1 - (0.88 x 0.43)) = 129 V (close enough to 125V)

Errors may still have been made, my site head may be more than I measured, which would result in a higher RPM and Voc that might damage the controller or at least prevent it starting up. So it is essential to check before I hook up my MPPT regulator by performing a Voc test. If this Voc reading is under 240V, then all is good and I can hook up. I note the comprehensive "PS all Install manual" in the INDEX gives advice on how to do this.

Note the Voc = 125V is at 1892 rpm, the rpm will almost double if allowed to free spin, hence a 250V MPPT regulator is required

5.1.4. Turgo Turbine example (PWM)

I wish to consider connecting this turbine directly to the battery and use a low cost PWM diversion mode charge controller to save cost and keep it simple. How do I go about this?

DIY Turgo turbine

I have surveyed our hydro site and determined the following:
(same data as previous example)

- Head = 30m
- Flow available in stream = 11 l/s
- Pipe length = 100m
- Cable length = 50m

I enter this data into the tool and play with the pipe size, 100mm ID pipe gives 1663W.

I have a 48V battery bank and wish to connect directly to it.

The voltage is fixed by the battery. A charging 48V battery is about 56V. I note the PowerSpout make a TRG56 for this reason. So I enter 56 VDC into the load voltage, my cable is undersized so I increased the size to 16mm^2.

I saved this data file. It can be located here.

The tool advises many options, I need to select an option with a voltage higher than 56V and allowing for cable voltage loss say 60V. I also need to allow for the fact that my site data may not be accurate which is more critical when PWM regulation is used. MPPT can compensate automatically for errors in the site data. So I will look for a voltage about 10%

higher than I require, I note that I can then optimise manually on site using packing washers to reduce voltage and to locate the MPP for my site. I note the 60R110-2S-6P-D looks to be a good choice.

SD code	**Vo**	**Voc**	**V/rpm**	
60R90-2S-6P-D-HP	60	137	0.049	
60-1S-14P-D-HP	57	129	0.041	
60R100-1S-12P-S-HP		59	133	0.048
60R85-2S-6P-D-HP	56	128	0.046	
60dc-1S-12P-D-HP	**65**	**148**	**0.053**	
60R110-1S-12P-S-HP		64	146	0.053
60R90-1S-12P-S-HP	53	120	0.043	

As we desire an operational voltage close to 65V (56 + 3V cable loss + 10% error), this option looks promising. I decide to check this option just to make sure.

- Stator = 60dc-1s-12S-D-HP
- V/rpm = 0.053 from table
- W/rpm = 1.0 (for type 4 HP rotor fitted)
- Rpm = 1892 of electrical machine
- Voc (at above rpm) = 1892 x 0.053 = 100 VDC (runaway voltage is about 3 x 65V = 195V)
- Maximum Power Point (MPP) = 1892 x 1.0 = 1892W
- Maximum Power Point voltage (Vmp) = 0.57 x 100 = 57 VDC

So it looks close. The power (1982W) is greater than needed (1663W), hence Vo (65V) will be larger than Vmp (57V). Packing the magnetic rotor reduces these, which will allow me to manually locate the MPP for my system once installed.

5.1.5. LH (Low head) propeller turbine example

Low head propeller turbines have been around for many years. There are many of these turbines made in China and Vietnam that drive 230 VAC 50 Hz single phase PMA's. The quality and efficiency is very poor but the price is low. See more of our experiences with these machines below.

EcoInnovation manufacture the PowerSpout LH and LH Pro, that use stainless steel propellers and when combined with a Smart Drive PMA, and MPPT controllers, have impressive conversion efficiency.

Our LH turbine uses a 154mm propeller. The ideal rpm is a function of the blade pitch. Many 6 inch propellers used for jet skies will work fine.

These propeller turbines are negative head machines, using a draft tube to suck water through the turbine, and as water boils at minus 10m head (called cavitation), they can only operate up to about minus 5m. They are perfect replacement turbines for waterwheels, they do the same job at a fraction of the cost and weight, and being at the top of the fall is not easily damaged by flood water. Often the water is brought to the turbine along an elevated flume running with very little gradient, rather than using a pipe.

I have surveyed our hydro site and determined the following:

- Head = 5.0m
- Flow available in stream = 55 l/s
- Flume length 25m, made of 300mm PVC pipe with a 0.1m fall
- Pipe length = 25m
- Cable length = 100m

I enter this data into the PowerSpout calculator tool for LH turbines and play with the flume size and fall. I can get 1462W at 1539 rpm.

I saved this data file. It can be located here.

I have a 48V battery bank and wish to connect directly to it (using an older type PWM diversion charge controller) to save on costs. I seek some advice and am told that this is very unwise for this turbine type. An MPPT controller optimises the blade rpm by adjusting the operating voltage. The battery voltage will vary but not with any particular advantage to the performance. Propeller type turbines are very sensitive to rpm, because rpm also affects the flow of water through the turbine. After hearing this I decide to change my mind and use a Midnight Classic 250V MPPT controller between the PMA and the battery.

I enter 250 VDC for the maximum voltage the MPPT can cope with and 60V for the minimum, as below 60V I might not be able to charge my 48V battery (50 V is the lowest value it allows you to enter).

The tool presents all the possible options of PMA codes. In this case the calculator chooses the cable voltage and I note that cable loss calculations have been done at about 100 VDC, so I need to select a PMA that has a V operating = 100V approx. and V no load less than 250V.

I note the 60R90-4S-3P-D looks to be a good choice.

SD code	Vo	Voc	V/rpm
60R90-4S-3P-D-HP	128	227	0.098

The calculations state:

- Power = 1462 W
- Rotor speed = 1539 rpm
- No load speed = 2308 rpm

I decide to check the calculations just to make sure.

- Stator = 60R90-4S-3P-D
- V/rpm = 0.100 from table
- W/rpm = 1.00 (for type 4 rotor fitted as HP was not selected or needed)
- Running Rpm = 1539 of electrical machine
- No load speed = 2308 rpm
- V no load (at 2308 rpm) = 2308 x 0.098 = 226 VDC (close to above and <250V)
- Maximum Power Point (MPP) = 1539 x 1.0 = 1539W (close to above)
- Maximum Power Point voltage (Vmp) = 0.57 x 1539 x 0. 0.098 = 86.0 VDC !?

The Vmp seems wrong, as surely it must be close to 122.4V? On further reading it is apparent that characteristics for impulse turbines (Pelton and Turgo) are different to reaction turbines (Propeller).
The Vmp is approximately half the voltage measured at no load for propeller turbines fitted with Smart Drive PMA's.

- Maximum Power Point voltage (Vmp) = 226 / 2 = 113 VDC, which it close to the above.

I appreciate that the calculation tool is more advanced then my basic analysis, but it looks to be correct. I appreciate that if I use a 6 inch propeller which has a different pitch to the one PowerSpout use, then the rpm and SD code will not be correct, but hopefully much closer than just a guess - all jet skis must be similar right !?

It is essential to check before I hook up my MPPT regulator by performing a Voc test. If this is under 240V, then all is good and I can hook up. I note the comprehensive "PS all Install manual" in the INDEX gives advice on how to do this.

5.1.6. Powerpal and similar AC turbines - our experience

We do not advise that you buy one based on our experience to date. With such small PMA's the AC voltage and frequency would be adversely affected by applied loads and would cause major issues with modern electrical appliances. Some DIY'ers think that they can escape the need for a battery, inverter and regulator by installing such equipment, but they soon find out the hard way that you cannot.

The picture above shows a 1000W PowerPal turbine made in Vietnam that died the day after it was installed. The original PMA fitted was under powered and ran hot - which killed it.

A Smart Drive PMA fitted via a belt drive fixed the issue. It was a costly lesson not to buy such products in the 1st place.

EcoInnovation imported PowerPal units from Vietnam about 15 years ago, but unfortunately the quality of these turbines was so poor and the weight so high that they have proved unusable. We modified several units by fitting Smart Drive units, but there were so many other issues that in the end we gave up. The labour cost to fix them up was more that is was worth and we threw all 10 units into the scrap metal bin.

About 10 years later we looked at it all again, and the experience we had gained from the few units we had tested proved invaluable in designing a much better solution. This is called the PowerSpout LH & LH Pro.

The LH mini will be on the market in late 2016.

Testing of a small 200W PowerPal propeller turbine worked much better than the larger 500 &1000 Watt turbines we tested.

5.1.7. Overshot water wheels

Water wheels have been used for 1000's of years and still have applications in power generation at low head sites, particularly those that are carrying high quantities of leaf litter and have high flow variability. The overshot design is the most efficient. The internet contains much information about water wheels and companies still make them for aesthetic and water pumping applications. It is much less common these days to see them used for power generation, since low head propeller turbines have been available in the last decade.

Advantages:

- Low tech, you can build it yourself from low cost materials
- Suitable on low heads (1-4m typical)
- Suitable on rivers where flow varies greatly
- Nice to look at
- Do not harm fish, fish can pass over a wheel unharmed
- Do not get clogged with flood debris such as leaves and twigs

Disadvantages:

- Large and therefore more expensive than a propeller or crossflow turbine
- Requires a gearbox to increase speed to run generator which adds to cost

In the early days EcoInnovation produced most of its winter season power from a 3m water wheel driving a Smart Drive generator. It ran for over 10 years but was displaced a few years ago by a PowerSpout LH turbine. There will be no going back, as the ease of servicing a light LH turbine relative to a heavy water wheel makes for a much easy life, as one ages, one in less able to service heavy equipment.

The gearbox is always the weakest link in designing a water wheel for power generation. The gearbox box is often heavy and costly. Industrial gearboxes bought new would be too expensive. Second hand ones are available - if you know where to look. The problem is you may have difficulty purchasing parts for old gearboxes in the future.

When designing a water wheel, keep the following in mind:

- Make it strong
- Keep it simple
- Make it reliable
- Over design the gearbox (it runs 24 hours a days 365 days a year)
- Double protect bearings from water ingress
- Use commonly available parts
- Make it easy to fix
- Mount on sturdy foundations protected from flood waters
- If using oil lubrication ensure that it cannot leak into the water way (if there is any chance of leakage then use grease instead).

Much work has been done on water wheels over the centuries, read this Wikipedia link for more general information.

5.1.8. Overshot Water Wheel Example:

You have a 2.2 m waterfall with a flow of 50 L/s and you wish to install a 24-volt battery based inverter power system to meet your domestic power needs.

Allowing for clearance you decide to install a 2m water wheel.
The theoretical power you can generate = flow (l/s) x wheel diameter (m) x 9.81 (m/s^2 gravitational constant) x efficiency.

The overall efficiency will we determined as follows:

- Wheel efficiency = 80%
- High ratio gearbox efficiency = 80%
- Smart Drive efficiency = 80%
- Overall efficiency = 0.8 x 0.8 x 0.8 = 51%

Power Output = 50 L/s x 2m x 9.81m/s^2 x 0.51 = 500 Watts.
This adds up to 12kWh units of electrical energy per day, enough to power an energy efficient home excluding hot water needs.
1000 Watts (24kWh per day) would be needed if electrical hot water was also required.

A water wheel cannot spin quickly, as centrifugal forces would counter gravitational forces and water would be expelled from the wheel buckets. Hence the rpm of a water wheel governs itself to a large extent.

The free running rpm is about 2-2.5 x the ideal rpm.

The optimal rotational speed of an overshot wheel is approximately:

RPM of the wheel = $21/\sqrt{D}$

D = diameter of the wheel in metres

This is summarized in the table opposite.

Wheel diameter	Ideal rpm
1.0	21.0
1.5	17.1
2.0	14.8
2.5	13.3
3.0	12.1
3.5	11.2
4.0	10.5
4.5	9.9
5.0	9.4

For a 2m wheel, the wheel rpm is about 14.8 rpm, but if we use a Smart Drive we will need much higher rpm.

To generate 500W with a 1.0W/rpm rating it needs to spin at 500rpm.
Hence we need a gearbox ratio of 500/14.8 = 33.8:1.

Designing a drive belt

The simplest drive would be a belt drive running off the outside rim of the 2m wheel to a notched pulley, similar to a very large cam belt in a modern car. This pulley would have to be (2000/33.8) 59mm (say 60mm) in diameter - a good simple solution. To ensure the wheel runs true, the timber wheel edge can be machined in-situ with an electric planer. A concave surface will ensure that a timing belt (correctly tensioned) will run true on this machined surface. Buying a belt this long may be a problem as it may need to be 10m long. Also such a long belt may need support rollers to prevent oscillations of the belt in the straight sections between the 2 wheels.

If you search www.aliexpress.com for “open ended timing belt W=30mm” you will get some hits. Look for 5mm pitch, polyurethane with steel core. These you can run at about 25N/mm, so for 30mm wide that is 750N of tension (76kg).

- Power = torque x angular velocity
- Torque = belt force x belt radius
  = 750 x 0.060/2 = 22.5 Nm
- Angular velocity = rpm x 2 x pi / 60
  = 500 x 2 x 3.14 / 60
  = 52.3 radians/second

This power belt can transmit = 22.5 x 52.3 = 1176W.
The mechanical power = electrical power / PMA efficiency = 500W/0.8 = 625W (less than 1176 W).
So such a solution is possible, but it only works for low power wheels that can use mass-produced timing belt material. Once set up it is a simple low cost solution.

Joining such a belt is tricky but can be done by sticking a 1m length over the join and then stitching them both together between each tooth. Clearly a join will not be as strong as the base material, so 625W would be a realistic rating for such a belt and should run for many years.

Another possible option is to attach such a belt to the outer rim of the wheel, teeth facing out and drive your 60mm pulley directly against this. The pulley will only have very limited tooth contact but with so many teeth on the large wheel it will still take a long time to get worn. Power rating will be less due to small tooth contact area, so it likely to be suited to 100-200W water wheels only.

The PMA is easy to select:

- rpm = 500
- Vmp= 28 VDC for 24V battery bank on charge
  and allowing for some cable loss let's call this 30V
- Vmp = V/rpm (from table) x rpm / 0.57

Hence V/rpm = Vmp / 0.57 / rpm = 30 / 0.57 / 500 = 0.105
From the table a 60R110-2s-6p-S would work well.

If we wanted to use a 150V MPPT controller then a PMA with a V/rpm almost twice as high would be suitable, but there is a danger of damage if the Voc gets too high in a runaway situation. Always check after the Smart Drive PMA has been installed and prior to connecting the MPPT controller that the runaway voltage (with full water flow onto the wheel) is under 140 VDC.

You can still use our online calculation tool to do cable loss calculations. Just select the PLT tool and enter data to get the same generation Watts (500W in this example). You can then enter your cable length and locate a suitably sized cable and see the % power lost in the cable selected.

For larger wheels, a mechanical multi-stage gearbox will be required, as can be seen in the picture opposite. This gearbox was located at a scrap yard and ran for over 10 years powered by a 4m water wheel that we made and installed about 15 years ago.

Below are some waterwheels we have made over the years. This was prior to us making the PowerSpout LH range of turbines


3m wheel cantilevered, directly connected to a 50:1 gearbox and Smart Drive PMA


3.6m wheel mounted on two bearings also connected a gearbox and Smart Drive PMA


2m wheel cantilevered, connected to a 35:1 gearbox and Smart Drive PMA


3.6m wheel mounted on two bearings, belt driven 2-stage gearing to a Smart Drive PMA

5.1.9. Undershot water wheels (not recommended)

Overshot wheels as shown above can produce good mechanical power output with efficiency comparable to a turbine, but undershot wheels as shown in these pictures do not have the benefit of a head of water falling.

It's much easier to find a site for a wheel like this but much less likely that it will repay the effort that went into building it.

This one shown is unlikely to do more than 100W !

Solar PV would cost much less!

Here is another example situated in a fast-flowing river this time. Here is the youtube video

The wheel is doing 8 rpm, so assuming 2 x 7:1 drives = 8 x 7 x 7 = 392 rpm
So the maximum output of the PMA = 392W

It also pumps water. It is my opinion that today a solar PV array would be much more cost effective, using surplus PV power to pump water. A good university project well done.

5.1.10. Crossflow (Banki) water turbines

The picture opposite was sent to us by a DIY client. It shows a Smart Drive attached to a crossflow rotor. Crossflow rotors are very similar looking to the rotors used in fans designed to move air. They are an impulse turbine type that is simple to construct and can accept a lot of flow, making them suitable for very low heads

For more information on such turbines refer to this Wikipedia link.

For a basic crossflow turbine made by some Scouts click here click here.

For a crossflow using an LG PMA (looks similar to a Smart Drive) click here.

As DIY cross flow turbines are rare, we leave you to experiment. Send us a picture if you make one with a Smart Drive PMA! Remember you need to match the power and RPM of the crossflow rotor to the power and RPM of the PMA if you want to get the best results.

5.1.11. Water pumps used for water turbines driving induction motors or PMAs

Common centrifugal water pumps have been widely used to make hydro turbines, as this DIY picture shows.

Such pumps are very common, low cost and can be easily located in scrap yards all over the world. They are heavy and made of cast iron so are not that suitable for commercial production of domestic scale hydro turbines that need to be airfreighted globally.

How a pump works when runs in reverse as a turbine has been the subject of much study and project work by students over the last 20+ years.

An excellent publication to read if you wish to do this is “Pump As Turbines – A user’s guide” by Arthur Williams (ISBN 1 85339 285 5), which is easy to locate online. Note that this book looks at using the pump and the attached motor as a turbine and induction generator (self-excited with capacitors) to run 230 VAC loads directly. The head and flow of the pump-as-turbine must be cleverly matched to the rpm of the chosen motor which in turn is dictated by the number of poles and the nominal frequency of the AC. The AC voltage needs to be regulated by a diversion load controller.

It is generally much easier these days to fit a Smart Drive PMA, and let an MPPT controller determine the best rpm for maximum power extraction. You can use a small 48V battery to store energy and meet peak power demands via a 230 VAC inverter that supplies clean AC power to the loads.

This is what is being done in the picture above. A small 500-1000W hydro resource can then power your home, whereas if you were to design a 230 VAC direct system you would need at least a 3000W hydro site to handle the peak load. Such sites are rare, and your cost will be more once you allow for the much larger penstock cost. It is for this reason that most domestic-scale hydro is not 230 VAC direct these days. The poor power quality just does not work well for modern appliances, and the limited peak output is a big handicap.

Over the years we have converted many old 230 VAC generation systems to PowerSpout turbines, MPPT regulation, battery storage and inverter for home AC loads. This solution has the added benefit that solar PV can be easily added to supplement the hydro resource that may struggle in the dry (sunny) season.

5.1.12. Domestic scale Hydro – overview & further reading

Much work has been done over the last 30 years on domestic scale hydro. What has changed has been the mass production of high efficiency small PMA's by companies like Fisher & Paykel, which has reduced cost and weight and increased the range of voltage options.

CADCAM technology has allowed turbine composite components to be injection moulded rather than being cast, bringing reductions in cost and weight.

International airfreight has become a common and affordable means of freight for low volume production, provided the freight mass is < 30 kg.

Advances in MPPT technology have made possible automatic optimisation of the electrical PMA rpm to maximise the efficiency of mechanical turbines. This technology is so good that there is little room for any significant improvement and MPPT prices continue to fall over time.

Solar PV prices have tumbled to very low levels (from about $10/W to $1/W) and this technology is a perfect augmentation for hydro in dry (sunny) low flow periods.

Inverter technology has advanced, becoming affordable, efficient and durable. Working life >15 years being common.

Battery technology has not moved much yet. The next 10 years will see the mass production of large lithium batteries for use in cars and homes. Prices will fall, because this technology is important for mobile applications. Once it arrives, the ability to generate your own power for home and transport at a cost similar to or lower than at present will have arrived for those who have the hydro and solar resources to do so.

EcoInnovation at the moment is upgrading its own off-grid power system to enable electric car charging during the day. Fuel bills are effectively being exchanged for generation, traction, electronic and storage equipment. There is still no free lunch, but this lunch just tastes better!

John Furze has put together a "Compendium in Small Hydro Selected" which can be easily located online for those interested in further reading. Much of the material is 10-20 years old.

5.2. Human powered generators

Over the years we have supplied Smart Drives to many human power generators. These tend to be either educational hand cranks or exercise bicycles.

5.2.1. Hand crank PMA's

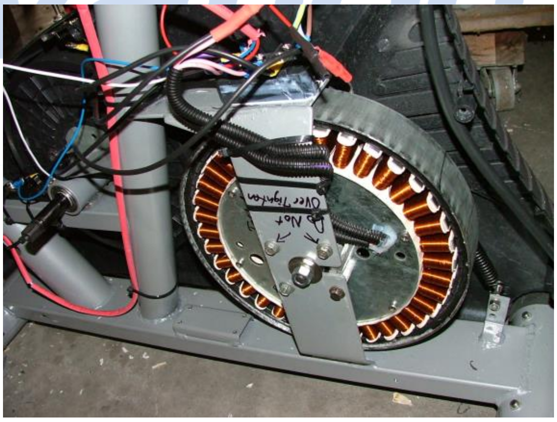
Hand cranked PMA's are easy to make and lot of fun for use in the education market. Incandescent bulbs, CFL and LED bulbs are directly connected to the rectified output of a Smart Drive PMA. For 12V loads you can often use a small universal power supply that happily works with DC input rather than AC input to give a stable 12V output.

Humans can comfortably turn a hand crank at between 80-120rpm. If you want to power 120 VAC (USA voltage) then a stator core with a 1.08-1.12 W/rpm is perfect.

Humans can do up to 100W with 1 arm power, so the 60dc-12s-1p-S or 60-14s-1p-S are perfect for the job. For very smooth operation we advise the 1st option (36-pole) with either a type 3 or 4 magnetic rotor. The 42 pole will feel coggy which is a less pleasant user experience.

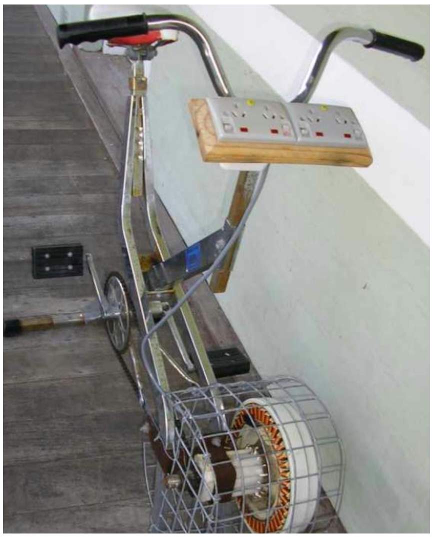
If you want to use 230 VAC bulbs then a simple voltage doubler circuit can be employed to do this, otherwise the rpm needed to spin the PMA by hand is a little too fast for comfortable use. These voltages are potentially very dangerous, even when produced by hand, so all wiring must be suitably enclosed before being powered up.

5.2.2. Exercise bicycles



This pictures show the normal internal flywheel and magnetic brake replaced with a Smart Drive PMA. This unit was designed to generate 150-300 VDC (at normal pedalling speeds) so that 230 VAC light bulbs and hand-held power tools can be used. Equipment with universal motors (using brushes) and without speed controllers run equally well on AC or DC.

A fit human can generate over 1 HP (750 Watts) for a very short time (Lance Armstrong for much longer). This is enough power for a small skill saw to cut through a piece of 4x2 lumber, which makes for an impressive demonstration.



Many an old exercise bikes have had a new life making power for educational demonstrations. A great project for school kids with suitable supervision.

5.3. Wind Turbines

Wind turbines are either:

- Horizontal axis
- Vertical axis

There is much debate about which is the best. You will never see a megawatt scale vertical axis wind turbine but you will see large wind farms of horizontal axis wind farms in many countries of the world.

Vertical axis has been pushed for domestic wind often with advertising that claims:

- Good low wind performance
- Low noise
- Can work in turbulent wind conditions
- No slip rings needed
- No tail needed
- No governor needed
- Get two strokes at the same wind - often implied to be more efficient than horizontal axis.

Many such claims are baseless. If you have a light wind turbulent site there is little power in the wind to be harvested so you would not be wise to install a wind turbine. If you have a high wind turbulent site, your turbine will be destroyed quickly. Vertical axis turbines as very prone to fatigue failure because the blades see a force (lift) reversal for every rotation.

For more information view this video or search the internet, there are many hits on this topic, but read those of experienced practitioners.

In my opinion, and that of most respected practitioners, horizontal axis has more benefits and hence a lower $/W life cycle cost. That said, we do get many DIY'ers buying Smart Drive PMA's to build a vertical axis machine, and if you still want to do this after reading this section then I am not going to waste time trying to convince you not to buy a Smart Drive PMA from us.

Vertical axis is often low to the ground, which can be an advantage for easy access for experimentation, but there is much less wind energy available at this height. They are also easier to make - but other than these, I can see no benefit that would convince me to make a vertical axis machine. I have made many horizontal axis wind turbines in my life from 1.2m to 3.6m, but I will never make a vertical axis one as the numbers just do not support it.

5.3.1. Vertical axis Smart Drive wind turbines

A crude machine such as the savonius type shown opposite cannot ever work well, but can be a fun low cost project to do with your children. Just do not kid yourself you can power you home with it! It is too small, has very low efficiency and without a tall tower it will never see the windspeeds it would need to work consistently.

The net is full of examples, some poorly done, some excellent.

The links below for you interest:

- https://www.youtube.com/watch?v=U_fYqtlXVYs
- https://www.youtube.com/watch?v=mBe0_XqUaNs
- http://www.thebackshed.com/Windmill/articles/Lenz2.asp
- http://ozwindgen.tumblr.com/
- http://www.watchtv.net/~rburmeister/smart.html

5.3.2. Horizontal-axis wind generators

Smart Drive PMA on a Chinese turbine in strong winds

Smart Drives can be used for wind turbines, in fact we used to manufacture a wind turbine with a Smart Drive PMA fitted to a 2.2m Chinese wind turbine (shown opposite) and still have one helping to power our property some 10 years after we started production. At first wind turbine sales were strong and outnumbered our hydro turbine sales, but then the price of solar PV crashed and it was clear that many small wind turbine makers would not be able to survive and we ceased production and focussed our efforts on the PowerSpout hydro turbine product line.

Wind turbines are heavy and bulky so are not easy to export which limits your market size, installation expertise is limited and a failure can result in every part being broken. Few companies seem to have lasted in this small and demanding market. The low cost of solar PV means that most reputable renewable energy resellers no longer list wind turbines for sale.

There is a steady interest is DIY wind, many inspired by the work of Hugh Piggott. If you search the net for "Smart Drive F&P wind" you will get many hits and there are a number of forums that can assist DIY'ers. Making a wind turbine is not that difficult, but making one that can handle storm conditions is a testing and time consuming exercise.

There is very little power in light winds (as the power goes up with the cube of the wind speed). Most people try to avoid living in very windy places. Northern Scotland and Southern Chile are two places where winter sun is poor (so solar PV is of little use) and wind speeds are reliably high in winter. Domestic scale wind can work well in these places, but their use becomes much rarer as you move closer to the equator where solar PV can work all year and is much more reliable.

DIY wind projects are a lot of fun. You can make it all from scratch using plans, or buy a propeller (1.8-2.2m is a good size) and a suitable Smart Drive PMA and have a go yourself.

You will need to fit a tail governor to reduce wind load in strong winds.

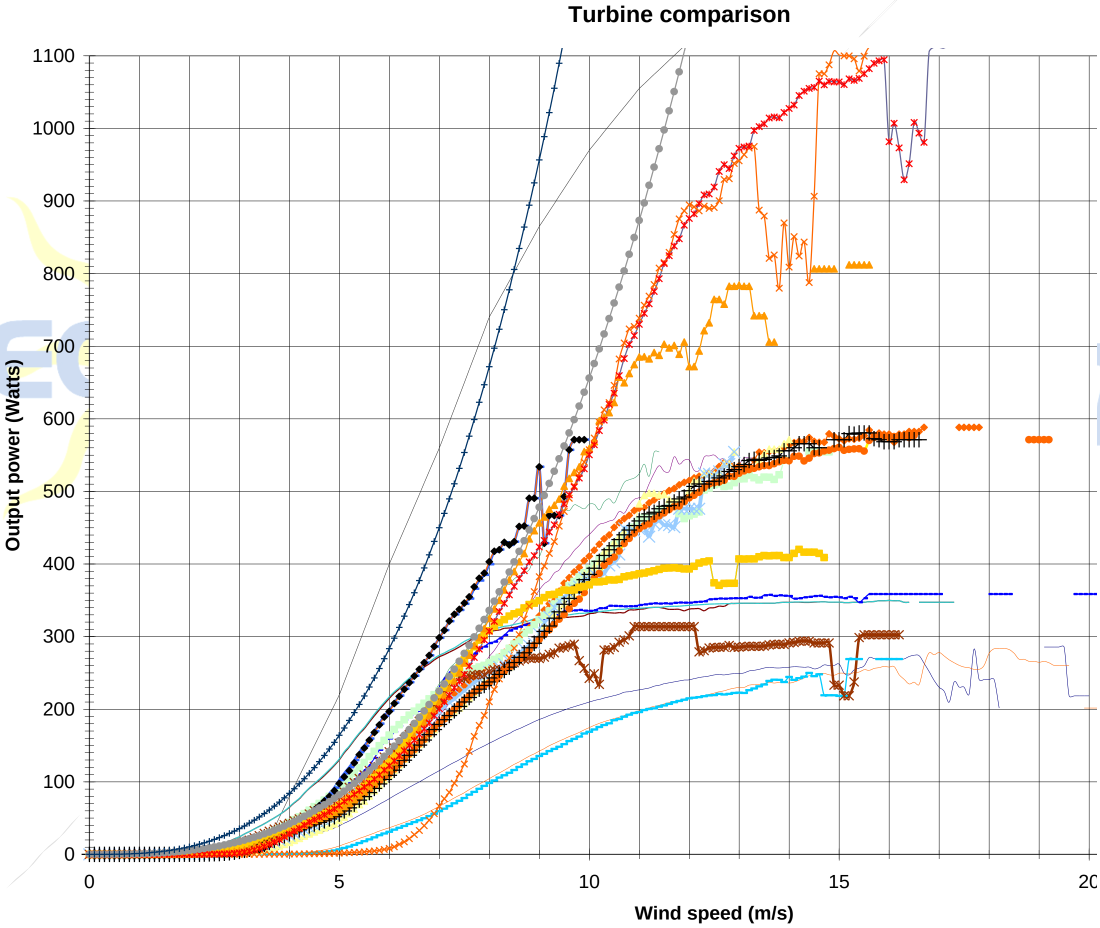
5.3.3. Over speed control

A wind turbine needs protection from over speed caused by strong winds. A side furling tail governor is a very simple solution. The tail is hinged on an inclined pivot (like a door on hinges that always closes itself). In a light wind the tail keeps the turbine facing into the wind. The turbine blade is offset from the swivel point. As the wind speed increases and the rpm of the blade increases the blade produces more lift (just like an aircraft wing). This lift force pushes back on the body of the wind turbine and because is it mounted on an offset pivot it turns itself out of wind.

If the tail were fixed, the tail would try and prevent this from happening. This is the clever part; the tail is hinged so that as the body of the turbine turns the tail stays where it is, in order to do this the tail lifts on the inclined hinged, the body of the wind turbine turns relative to it.

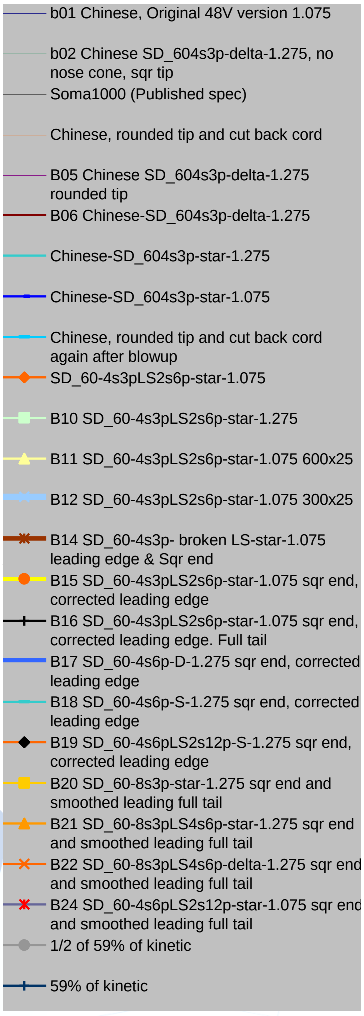
As the body of the turbine turns out of wind you will notice the tail lift slightly. When the wind speed reduces the weight of the tail on the inclined hinge pin causes it to close (just like the door example) turning the wind turbine back into wind. It is important that the tail pin pivot is robust and does not seize due to corrosion.

Pictures of tail pin and side furling tail



We developed a monitored test site where we researched many options. The results are recorded above with the key on the following page. The grey line is the theoretical power line for a 2.15m diameter turbine that extracts 50% of the power available in the wind, a realistic figure for a well-designed domestic turbine. The blue line is the same for a 2.55m blade. Most testing was done for the 2.15m blade.

No turbines tested performed above these limits.
Collecting test data is not easy, as wind gusts and turbine inertia can distort the raw data. So data points in the above were only included if the wind speed remained stable for 3s or more.



You will notice that at about 8 m/s and 300 Watts some PMA's start to level off. This is because if you want a low cut in speed (low winds and low rpm) you need to put on a stator with high V/rpm. Such a stator is not well suited to work at that same battery voltage at higher RPM and higher power output because it can only produce a limited current.

RPM monitoring showed that we rarely exceeded 1500 rpm even in storm high gust conditions, partly due to the tail governor limiting excessive speeds.

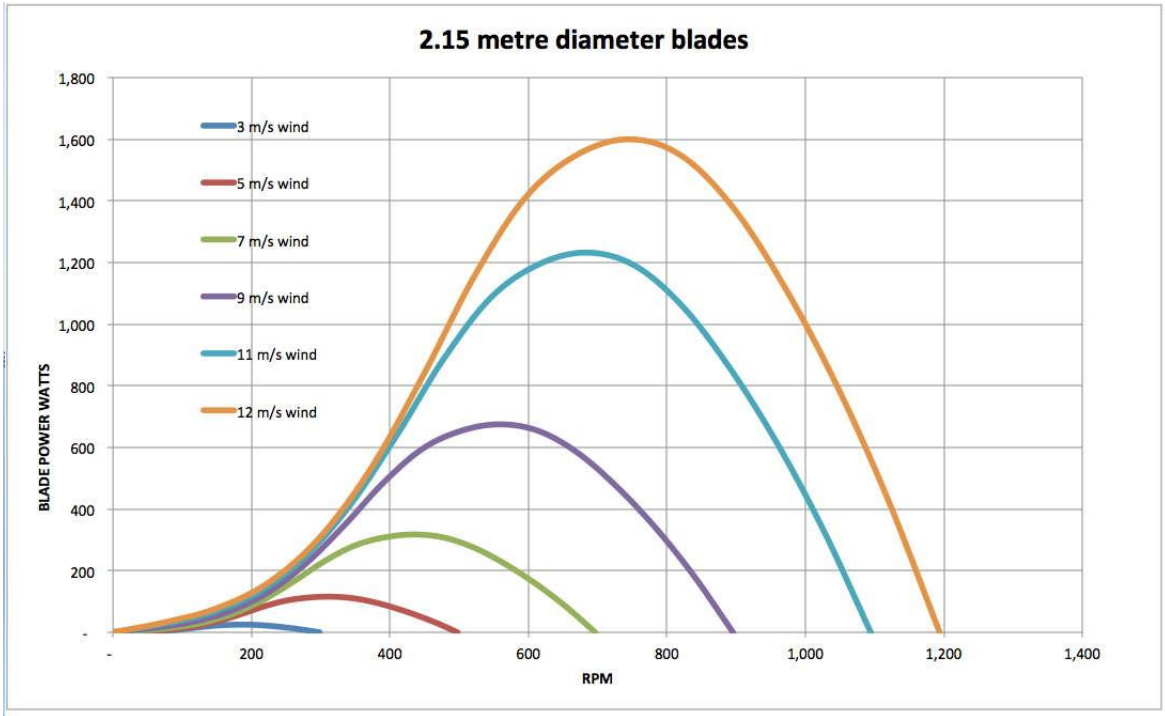
These tests were done before the advent of MPPT controllers with table modes suitable for wind turbines. Such controllers can allow the PMA voltage to rise in higher winds and thus capture more power without hitting the current limit.

To make a turbine that can work well in the 4-7m/s band is easy. As domestic wind speeds are mainly in this range a Smart Drive can work well. Output power is low but operating hours are long.

If you want to pursue 1000W at 1000 rpm, then this is possible in about 12 m/s wind if you either use a suitable MPPT controller programmed with a wind table mode, or you sacrifice lower wind speed performance. Winds this strong are very rare (in operating hours per month) where most people live. So in stronger winds survival is actually more important than generation Watts.

5.3.4. The sweet spot for wind turbines

The sweet spot is a moving target as the wind is always changing. The optimum rpm increases in direct proportion to the speed, whereas the power available rises with the cube of the speed which is much more dramatic. So you have a family of curves to consider as in the chart below. Output power here is mechanical power for a decent set of high speed blades with 2.15m diameter.



Notice that the rpm rises to much higher in "runaway" when the power is zero. You need to try to hit the sweet spot at the top of each curve over a range of common windspeeds.

5.3.5. 300W turbine at 7m/s and 2.15m blade

This would be a good option for your 1st wind turbine directly connected to your battery bank. You will need to control battery charging with a PWM diversion load controller.

With the output directly connected to the battery, the voltage is clamped to the battery voltage. However a free spinning 12V turbine (disconnected for the battery load) in a storm event could put out up to 140V! It's important to keep that battery connected all the times.

Battery Voltage	Stator	V/rpm	Rotor	Cut in RPM	Voc at 1500 rpm
12	60dc-1s-12p-S	0.093	3 or 4	129	140
24	60dc-2s-6p-S	0.187	3 or 4	128	281
48	60dc-4s-3p-S	0.373	3 or 4	129	560

5.3.6. 1000W turbine at 12m/s and 2.15m blade

The above table shows that for a 12V battery bank the maximum Voc is less than 150 VDC, the rating of many common MPPT regulators. A Midnite Classic 150 would be a good choice for experimenting with wind table mode up to 1000W. (Midnite Solar do not recommend doing this without their "Clipper", so it is your job to make sure that the controller is never exposed to excessive voltage. Midnite sell a "Clipper" product for wind turbine applications, and this is required for warranty cover, but it is very costly. Or you can contrive your own "Clipper" using the aux output of the Classic.)

For 24V operation you could use a Midnite Classic 250 and use the "PV on high" mode driving the AUX relay output in PWM to clip any voltage above say 240V. See our **PS MPPT Midnite Classic Guide** (from the index of pdf files) for more information.

For 48V operation, more complex Voc protection will be needed. The Midnite Clipper is ideal.

5.3.7. Where to buy wind turbine blades

If you search for “wind turbine blades” at www.aliexpress.com you will locate plenty of blade options to choose from, www.ebay.com also list many options or you made prefer to carve your own from wood.

You are looking for a 3-blade set about 1.8-2.2m in diameter, ideally with a hub and nose cone.

Your will also locate complete wind turbines with 2.2m blades rated for 1000W at 12m/s from about $750US. The quality of these machines are somewhat hit and miss and performance is often greatly overstated. We wish you all the best with your DIY wind project.

For aluminium extruded blades in Australasia try this web site.

5.4. Engine Applications

I am not a big fan of fuel-burning generation as I spend most of my life trying to displace/prevent this equipment. There is no point in spending capital on a good engine driven generator that you rarely need to use. It is better to spend this money on more solar PV panels so the gen-set may not be needed at all.

That said, is it an easy matter to make a battery charger from a small petrol/diesel engine and a Smart Drive PMA.

The pictures show a few examples. Small 3-4 HP engines are common and easy to connect to a Smart Drive via a belt drive.

Most small petrol engines run at about 3000 rpm.
To make a 1.5kW battery charger you will need a 4 HP engine and a 2:1 belt drive reduction driving a Smart Drive PMA.

A 200mm V pulley off the Smart Drive and a 100mm pulley on the engine will do it. The Smart Drive options below are suitable for direct battery connection. You can prevent overcharging by either installing a PWM diversion load controller or by noting the state of charge and limiting the fuel used so that the engine stops before you overcharge your battery bank.

A well designed system will only require very infrequent charging in this manner, so if you have wet cell batteries you are likely to be doing an EQ charge every time you use the generator. After some experience you will be able to gauge how long you need to run the generator to achieve this and limit the fuel accordingly.

You will notice from the table below that the Voc for each battery type is under 150V. This means you can connect the rectified DC from the Smart Drive to the battery via a MPPT regulator, often the same MPPT regulator that your solar PV system uses. This is exactly what we do and it works fine. You may need to limit the charge setting in the MPPT to ensure that you do not overload the engine.

Battery Voltage	Stator	V/rpm	Rotor	MPPV	Voc at 1500 rpm
12	100-1s-14p-S	0.019	3 or 4	16	29
24	60R85-1s-12p-S	0.04	3 or 4	34	60
48	60R90-3s-4p-D	0.074	3 or 4	63	111
12/24/48 MPPT	60dc-1s-12p-S	0.093	3 or 4	80	140

Remember: whenever you use an MPPT regulator, always check that your Voc at full throttle is less than the MPPT voltage maximum input rating.

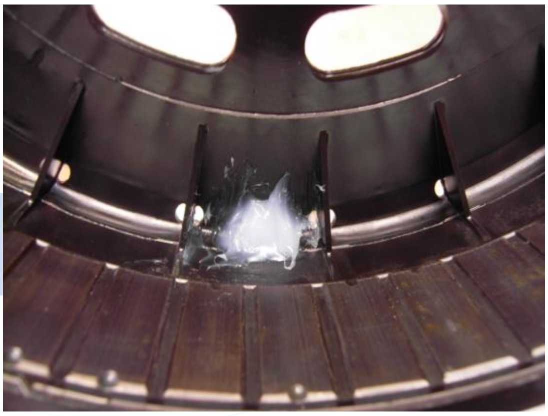
6. Balancing of parts

For high speed applications, Smart Drive magnetic rotors need to be balanced. They can be up to 0-20g out balance which at 1500 rpm creates a 62N (6.3kg) centrifugal force. An oscillating force of 6.3kg will result in serious vibration. All rotors sold on our web site will have been balanced to better than 1g, which is 0.3kg out of balance force at 1500 rpm. If you have obtained magnetic rotors from elsewhere you will need to balance them, otherwise you must expect a short bearing life and shaft journal damage.

If making a wind turbine you should balance the blade and magnetic rotor assembly all together.

20g at 125mm radius - out of balance force			
RPM	Rads/s	Force (N)	Force (kg)
100	10	0	0.0
200	21	1	0.1
300	31	2	0.3
400	42	4	0.4
500	52	7	0.7
600	63	10	1.0
700	73	13	1.4
800	84	18	1.8
900	94	22	2.3
1000	105	27	2.8
1100	115	33	3.4
1200	126	39	4.0
1300	136	46	4.7
1400	147	54	5.5
1500	157	62	6.3

We balance rotors by mounting them on a free-to-rotate 6mm shaft. The heavy side will turn to the bottom. Opposite this position we fill a cavity or two (as shown) with silicon sealer until the rotor no longer has a heavy side. For rotors that would require an excessive amount of silicon we push a small weight into the silicon. Do not remove this weight/silicon.



The reason for the imbalance is due to the overlap in the steel laminations behind the magnets.

7. Corrosion protection

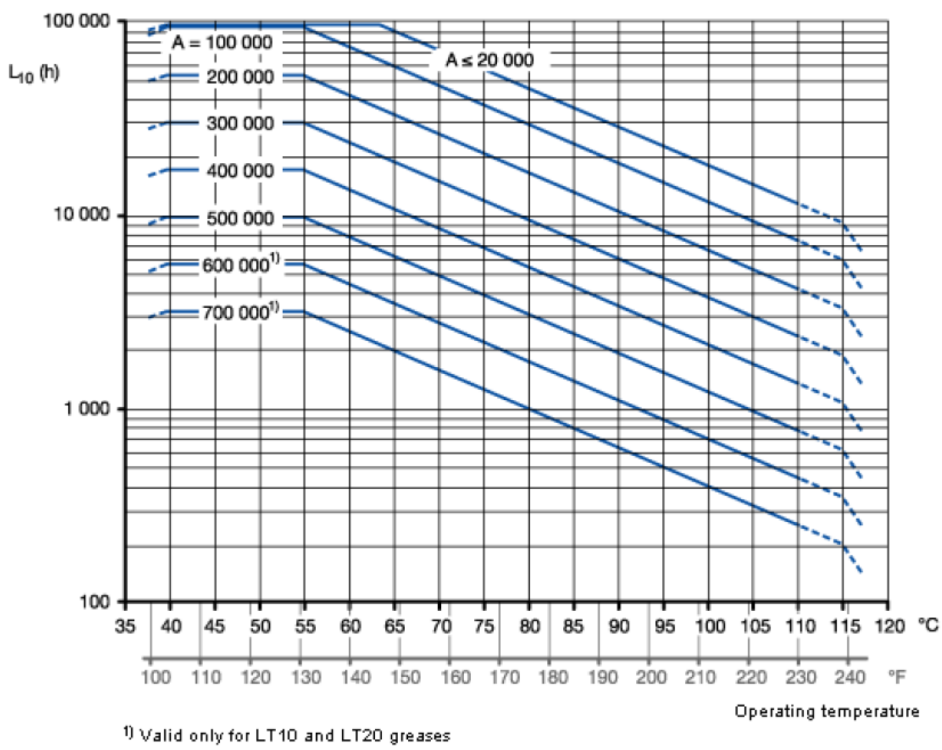
The steel laminations in both the stator and rotor can rust. In operation the warmth generated normally drives off moisture and keeps rust under control. In wet environments and in situations where the Smart Drive is used infrequently then rust prevention is strongly advised. Soaking both the stator and rotor in a fish-oil based corrosion inhibitor overnight, and then allowing it to drip dry for 1 hour and then wiping with a rag will cure rust for many years. All parts sold by us have been rust treated in this manner.

8. Bearing Life

We get a few emails every month from the public who believe that a sealed bearing lasts for 10+ years and cannot understand why we advise replacement every 1-3 years? This is not an unreasonable assumption.

“Grease for life” sealed bearings have the shortest life rating, as wear debris cannot be flushed out and the lubricant easily replaced. Such bearings are designed for say an induction motor that runs for 8 hours each day in a dry industrial process for say for 10+ years. This is not the case for a small hydro & wind turbines.

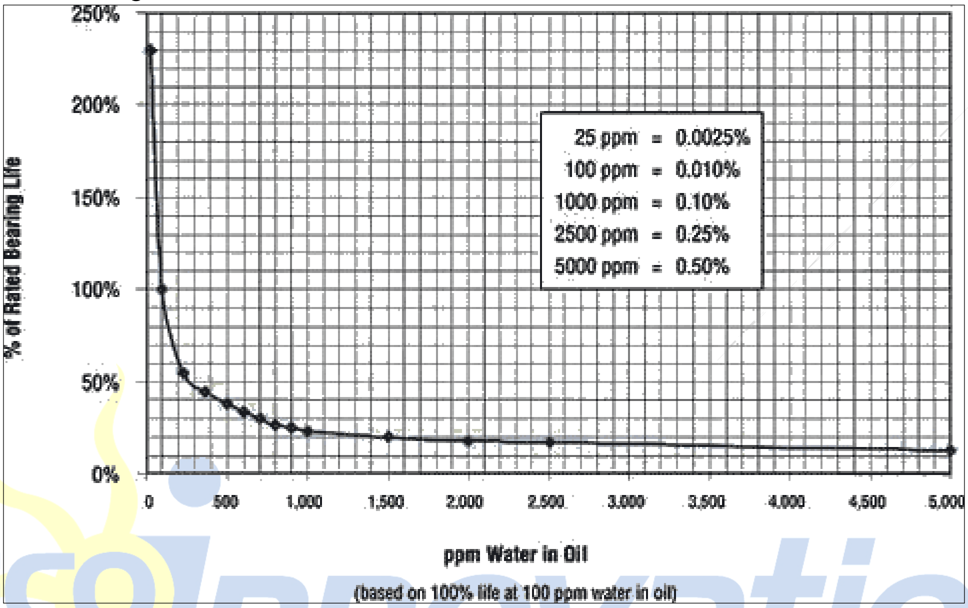
Diagram 1 - Grease life for sealed SKF bearings with MT33, MT47, LT10 or LT20 greases



The diagram above (from SKF web site) provides grease life estimation depending on operating temperature and speed - valid for light loads. The speed is considered using the speed factor A = rpm x bearing mean diameter, which for our turbines is 36-38.5 mm. For turbines running at the maximum of 1600 rpm, A = 61,600.

So “greased for life” bearing can do 100,000 hours = 11.4 years. So you can see where the public perception that such bearings will last 10 + years comes from.

The above graph assumes the bearing environment is free of moisture and condensation. This is not the case for small hydro turbines that have cold surfaces from the water flow and are often operating surrounded by moist air close to dew point temperatures. Moisture from condensation is what initiates corrosion in the bearings and breaks down the lubrication. We have over the years observed clients that (instead of following our advice and using an auto grease canister) have put in stainless steel bearings. This does solve the corrosion issue but not the breakdown of the lubrication. Where clients have tried this, the life has often been very similar or less. Hence automatic or regular manual greasing is your best defense against moisture ingress.



The above graph illustrates that moisture ingress of only 0.5% will reduce life from 10 years to 0.7 years.

We used to manufacture wind turbines with the same SKF bearings fitted and these typically lasted 5+ years and could not be easily re-greased. Wind turbines do not spin 24/7, they operate in warmer air mainly above the dew point and when operating the warmer conditions help to drive out moisture, hence the bearings on wind turbine tend to last longer than those of hydro turbines.

We do have clients that report 5+ years from a hydro bearing sets, but they tend to be in dry, condensation free environments. We have to give advice based of the worst receiving environment - not the best.

9. Stator Cracks

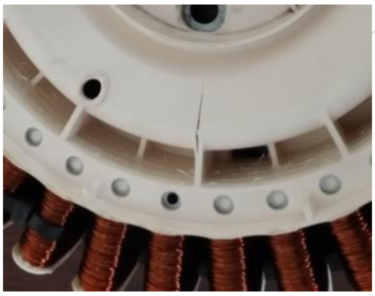
You will often see cracks in the stator.

These cracks are post injection stress-relief/shrinkage cracks and will not cause any issues at all. They are not caused by operational stress, but by stresses caused by injection moulding plastic over the top of the steel laminated core. These cracks appear soon after they are first used, as they are the result of stress relief.

In the early days F&P (the manufacturer) went to great lengths to control these cracks, but once it became apparent that they did not grow or cause any issues, less crack relief holes were implemented in recent design variants.

This picture below shows an old 100 stator. Despite it being 20 years old it looks like new (we have cleaned it). You can see a lot of crack control holes, which help to prevent shrinkage cracking. Next to this picture is an almost new 60R stator and you can see a crack and only a few crack control holes. The more material you remove the less cracks you have, but the weaker it is. This might sound a little odd, but it is the case as you can clearly see.

Old 100 - no cracks



New 60R – crack visible

Some clients seem to think the sky has fallen in when they see a crack like this. Just leave it alone, do not try to fill it or glue it, it is fine. If you drop it onto a concrete floor yes it will be cracked and ruined.

Rotors on the other hand should have no visible cracks in the plastic body. Hairline cracks in the magnets themselves as in this photo are fine and are no issue.

10. Send us project pictures

We are always keen to see your DIY Smart Drive project pictures, and with your permission may include them in future document updates.