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Digital Hydraulics for Renewable Energy.

Stephen Salter

Engineering and Electronics, University of Edinburgh. S.Salter@ed.ac.uk

Abstract

The wet and windy sources of renewable energy tend to have large forces and low velocities with widely variable and sometimes alternating energy flows. Furthermore productivity is better if the force presented to the input is able to respond to changes in magnitude, often in a complicated way. Finally it may not be economic to generate from the very largest power levels and so there has to be a graceful way to shed unwanted peak inputs. These characteristics are directly incompatible with the strict specifications for electricity networks, especially weak ones in remote places which are likely to be the first places where the renewable sources will be exploited.

At the start of design work on the Edinburgh duck we tried to resolve these uncertainties with off-the-shelf high-pressure oil pumps and motors. We found that power levels were not high enough, that efficiency was too low, that it was difficult to combine power from different sources and inconvenient to control machines by computer.

This paper describes the design of a new type of hydraulic machine to overcome the difficulties. Variable-displacement is achieved by enabling or disabling poppet valves rather than by the variation of machine geometry in the same way as switch-mode control in electronics. This can produce large reductions in part-load losses. The paper shows how machines can be used for wind, wave and tidal-stream generators and gives guidance on dimensions and weights. Torque ratings up to 10^8 Nm for slow machines and power ratings up to 10 MW for fast motors are possible.

Keywords: High pressure oil, variable-displacement, switch-mode, continuously-variable transmission, pump, motor, ring-cam, poppet valve, radial-piston, multi-bank, energy storage, regenerative braking.

Differences

Most hydraulic pumps motors and control valves have evolved for conventional 'dissipative' energy uses with large forces and slow velocities, such as earth-moving, ship-steering and heavy metal-forming, where the cost of fuel was a very small part of the total operation. This gave no incentive to design for high efficiency. In renewable energy the electricity is the only output: a very small improvement in efficiency multiplies the value of all upstream investment.

Most conventional industrial hydraulic systems operate over a rather narrow range of power levels close to well-defined upper limits. However, in renewable energy the power levels vary widely and the extremes are uncertain asymptotes of non-linear probability functions. Losses that are a constant fraction of the full power rating are very serious at low power levels.

The conventional hydraulic power trains used at the end of the fossil fuel age begin with a fast prime mover such as an electric motor or Diesel engine. This would drive a fast pump. Velocities would be transformed *down* and the forces *up* to the values suitable for the slower motors and rams needed for the required mechanical function. With renewable energy the direction is usually the other way around. While fast hydraulic pumps can look very like motors there are subtle differences.

Engines for vehicles work quite well with variations of speed of two to one or more. But a synchronous electrical generator has to follow exactly the frequency of the network and small changes of the phase angle of the rotor relative to the rotating magnetic field affect the behaviour profoundly.

The designers of conventional hydraulic machines work on the assumption of accurate geometry with rigid parts and flat surfaces that are parallel and square to shafts. But as sizes and pressures increase it becomes necessary to think of floppy parts that are deforming through much greater distances than are desirable for hydraulic clearances. Indeed if parts are *not* suffering a strain corresponding to the fatigue endurance limit of the material (about one thousand micro-strain for steel), they will be too heavy and expensive. Designers for renewable energy hydraulics must remember all the lessons about kinematics, redundant location and degrees of freedom. They must imagine that everything is made of soft rubber with deflections very much larger than hydraulic clearances.

Machine geometry

A very wide range of mechanisms can be used for linking mechanical movement to fluid flow. These include meshing gears, splines, orbiting rotors with clever shapes like the Rootes, gerotor or Wankel, deformable tubes and bags, tilting U-tubes, nozzles, rotating turbine blades and even reciprocating fishtails. However we need high pressures to make compact machines which can exert big forces with low losses from fluid turbulence. High pressures are much more satisfactory with round pistons in round, close-fitting cylinders. It is cheap to make accurate round shapes, even very long ones but, most importantly, round objects will *stay round* under pressure and do not suffer stress concentrations at corners. For renewable energy we can therefore exclude every other shape at the outset.

The most basic input to a wave device provides a direct reciprocating input to an hydraulic ram. The glossy black Ceramax cladding developed by the Dutch company Hydraudyne allows rams to be used in direct contact with sea water. Rods could also be protected and oil leakage avoided with large Belofram seals which work like a rolling fold in a stocking. However a disadvantage for the use of rams with wave energy is that somebody has to decide on the working range and what will happen if it is ever exceeded. Well-designed wave devices can move through quite large multiples of the wave amplitude. So far only the Swedish IPS buoy has a satisfactory solution to the stroke limit problem.

End stops can be avoided if we use rotations instead of translations, with the further advantage that all the parts can work all the time. For high torques at low velocities a ring-cam pump is excellent. Standard ring-cam motors, such as those produced by Hagglunds and Mactaggart Scott, have a number of cam lobes on the inside of a ring. The cam lobes are driven by rollers from radial pistons with connections to high and low pressure going through a central port-face valve. The Hagglunds Marathon range goes up to 1.4 MN metres of torque. Every roller can operate every lobe at a rate much faster than rotation speed.

The same idea can be used to make very large pumps. The ring-cam idea gets better as cams gets bigger. Big ring-cams can have lobes on two or even four faces, as in figure 3b, so that roller force is opposed through the thickness not round the circumference. The cam lobes for very large machines could be made in the form of separate beads with scarf joints at the troughs, pulled together by internal cables and ground to final profile in situ. There is plenty of room for valves and oil manifolds which have lower losses than the passages to central flow commutation. Torque change decisions are made at several thousand times a second. A quad cam with intelligent control of sector pressures can even act as a bearing.

Gearing causes much of the misery in wind turbines. Comparisons between gears and poppet-valve ring-cam machines are informative.

- An ordinary spur gearbox is sending all its work through the one contact line of a tooth pair while all the other teeth are idle. The common designs of epicyclic gear usually have three contact lines working in parallel. Some very advanced epicyclic gears with clever force-sharing use 5 lines. The ring-cam for a spine-based duck uses 294 rollers driven by 109 pairs of cam lobes so that at any instant nearly 150 contact lines are active. This means that the ratio of weights of a ring-cam pump to an equivalent gear box for a given torque is very great.
- Involute gears are designed to transmit a constant velocity. This means that there must inevitably be a small amount of sliding between teeth and the consequent loss of energy of about 1% per mesh. With ring-cams, the contact is nearly perfect rolling with 'friction coefficients' of 0.0003.
- The pitch of gear teeth and the separation of their axes must be carefully controlled. In the ring-cam, the roller diameters, cam heights and wavelengths can safely have gross dimensional errors and distortions under load. There is no equivalent of the torsional strain of a gear face which turns the theoretical line contacts into smaller elliptical patches when contact lines are skewed by torque.
- The output of a ring-cam pump can be stored as pressure energy in an accumulator.
- Damage to a single gear tooth will quickly infect all the others. The injured one cannot be skipped. But a microphone on the ring-cam can detect early spalling of the cam or roller surfaces and the computer which controls poppet valves will know to avoid their future use. We can achieve long working life by providing some spare initial capacity.
- Finally, gears transmit a fixed ratio and cannot be disengaged. Ring-cam pumping modules can be fitted with poppet-valves that can be selectively enabled or disabled to control the pump output and so provide *variable displacement* with all the benefits for matching forces to velocities.

Fast machines

Clever hydraulic control is all about changing gear ratios. When a pump is connected to an hydraulic motor the speed ratio depends inversely on the volume of fluid moved per rotation of each of the machines, less a small correction for their leakages. If you want to make a continuously variable ratio you need a way to change the volume per rotation. In conventional machines this was often done by a change of angle of a swash plate or sometimes by the change of angle between two linked shafts in a design known as the bent axis. The mechanism needed to change angle involved an analogue mechanical change of geometry, which was slow and which made for an awkward interface to digital computers.

Conventional fast pumps (which we need to modify for use as motors) use a mechanism known as a port face which behaves like the commutator of a DC brush motor and connects a chamber alternately to high and low pressure pipes depending on the angle of shaft rotation. The port-faces needed for fast machines have to be made with very accurate geometry, even when distorted by high pressures, if they are to reach the best compromise between leakage and shear loss.

The major innovation, which affects every other aspect of the design, was the decision to control displacement in a digital rather than an analogue way. For the pumps described above this can be done by holding open the inlet valve on a chamber if the controlling computer decides that its delivery is not immediately required. The decision is best taken just before bottom dead centre of the piston stroke.

While it is easy to see how disabling poppet-valves can vary the displacement of a pump it is harder to see how this can be done with a motor. The solution shown in figure 1, due to Win Rampen, is as follows:

1. The valve timing-sequence starts just after top-dead-centre with oil flowing from the high-pressure manifold into the chamber through the high-pressure poppet. Work is done on the eccentric which behaves just like a crankshaft.
2. Just before bottom-dead-centre the high-pressure poppet is closed by a signal to the coil from the computer. The piston stroke continues, using the energy stored by the compressibility of the oil in the chamber. Bulk modulus values of 1.8 GPa are typical. The chamber pressure decays until, at bottom-dead-centre, it is possible to open the low-pressure poppet valve by a pulse to its coil.
3. The oil in the chamber can now be discharged to the low-pressure gallery. This piston moves towards top-dead-centre but, just before it reaches the top, the inlet poppet is closed. The machine now imitates the action of a Diesel engine and begins to compress the oil. Pressure in the chamber rises until the high-pressure valve can be opened so that the sequence can be repeated.

The valve timings shown in the figure are accurate for typical hydraulic oils. The idea relies on the finite bulk-modulus of the working fluid and the fact that computers are very good at precise timing.

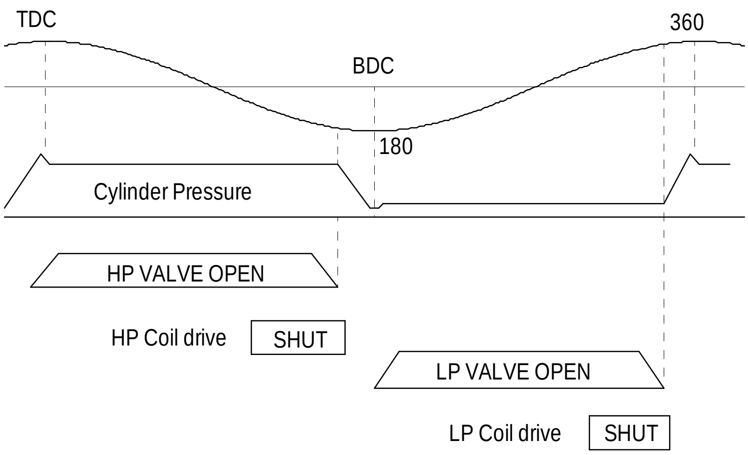

Figure 1. The valve timing sequence needed to make a poppet-valve motor. No magnetic actuator can oppose the force of high- pressure oil but operations are always in the direction of flow and are close to a slack point in the flow cycle.

Improving efficiency

For renewable energy applications we set ourselves the target of reducing losses by a factor of ten over the best commercial designs. To do this we had to study all loss mechanisms in the finest detail. This close energy analysis pointed directly to suitable solutions shown in figure 2.

If the displacement of a machine is to be reduced, a low-pressure valve will *not* be shut and the oil will flow back out to the low-pressure tank. We have to pay for the energy associated with pressure drop but, with attention to the shape of flow passages, this can be made as little as one-thousandth of the energy that would have been delivered if the valve had closed and a chamber full of oil had been delivered to the high pressure manifold. Since no pressure is being developed there will be no leakage from idle cylinders. Leakage from a working chamber is also reduced if we admit oil to the inside of hollow elastic pistons to make them *expand* inside more rigid cylinders. This gives a fine clearance and low leakage when the chamber is under pressure. But when it is off pressure the clearance increases to give a low shear loss. Two major loss mechanisms have been greatly reduced.

The third loss reduction mechanism involves the bulk modulus of oil. When a swash-plate machine is at zero swash, the oil in every chamber and connecting passage is charged to a high pressure for part of the rotation and then immediately connected to the low-pressure manifold. There is also energy associated with the elastic stretch of the surrounding metal so that the total compressibility loss of a port-face machine at 400bar can be nearly 2% of maximum power, even when it is idle. With a poppet-valve machine compression energy is not stored during an idle stroke and is fully recovered after an active one.

The greatest loss reduction is associated with the elimination of the port-face, always the most difficult part of the design of conventional machines. Two faces have to spin at high speed close to one another while sealing high pressures for half the circumference. Leakage rises with the cube of clearance or an even higher power if the fall in viscosity is included. However shear losses rise with the inverse of clearance. The amount of clearance depends on the dimensional difference between highly, but differently, stressed blocks of metal. The designs for fast machines use an axial arrangement of close pistons so as to minimise the leaking perimeters and shearing areas. The large separating forces at this port-face have to be opposed by a thrust bearing with its own additional leakage and shear losses.

Poppet-valves allow large, fast machines to use the radial configuration. The shearing and leaking areas are now formed by the 'big-end' where the pad of a piston contacts the eccentric crank shaft. Shearing speeds are slower because of the reduced diameter. Clearance can be set accurately by a combination of hydrostatic and hydrodynamic forces and is not compromised by machine deflections. The radial arrangement gives plenty of room for large valves with short flow passages so that breathing losses are reduced. Machines up to 2500 rpm do not require boost pressure.

Poppet valves that are properly seated have zero leakage and no shearing velocity. One concern is the fatigue life at the seat, which suffers a Hertzian stress. For large machines this can be greatly reduced by the use of an annular rather than a spherical valve because *two* contact lines are taking the full load of a much smaller area exposed to pressure, giving a much lighter valve and two flow passages rather than the single one of a spherical valve head. Although the passages look small in section, the flow area is large. For example an annular valve with a 100 mm major diameter and a 2 mm gap has a flow area of 1256 square mm for just one chamber. This is the same as a round port of 40 mm diameter.

The start of the valve development program involved the fatigue testing of valve materials. It was found that the ideal material is PEEK, poly-ether-ether-ketone reinforced with carbon fibre. It has a compressive strength of 240 MPa and a density of only 1440kg/m3. It can work continuously to 250C, far above any oil. Its elasticity of 20 GPa reduces Hertzian stress at the valve seat and gives some tolerance for valve seat dimensions. We built a fatigue testing rig which took 12 valve seats to 50% over the expected Hertzian stress for 1.5×10^9 cycles. Optimisation of the magnetic circuitry by Niall Caldwell has allowed large increases of valve operating speed, well above the critical 1800 rpm needed for 60 Hz generators.

The most wonderful result of the radial configuration is that we have escaped the tyranny of the axial geometry used by large, fast machines. We can have many independent banks acting on a common shaft as in figure 3a so that energy can flow to or from diverse sources or sinks or energy stores with change of mode from pumping to motoring to idling within half a shaft revolution and true synchronous generation. The limit to the number of banks is set only by the torsional strength of the crank shaft. The ease of interfacing with a short-term energy store will be of crucial importance to the acceptability of renewable energy by electricity distributors for fault ride-through and black-starts. Storage can also be used for regenerative braking in road vehicles where it can reduce urban fuel consumption by about 40%.

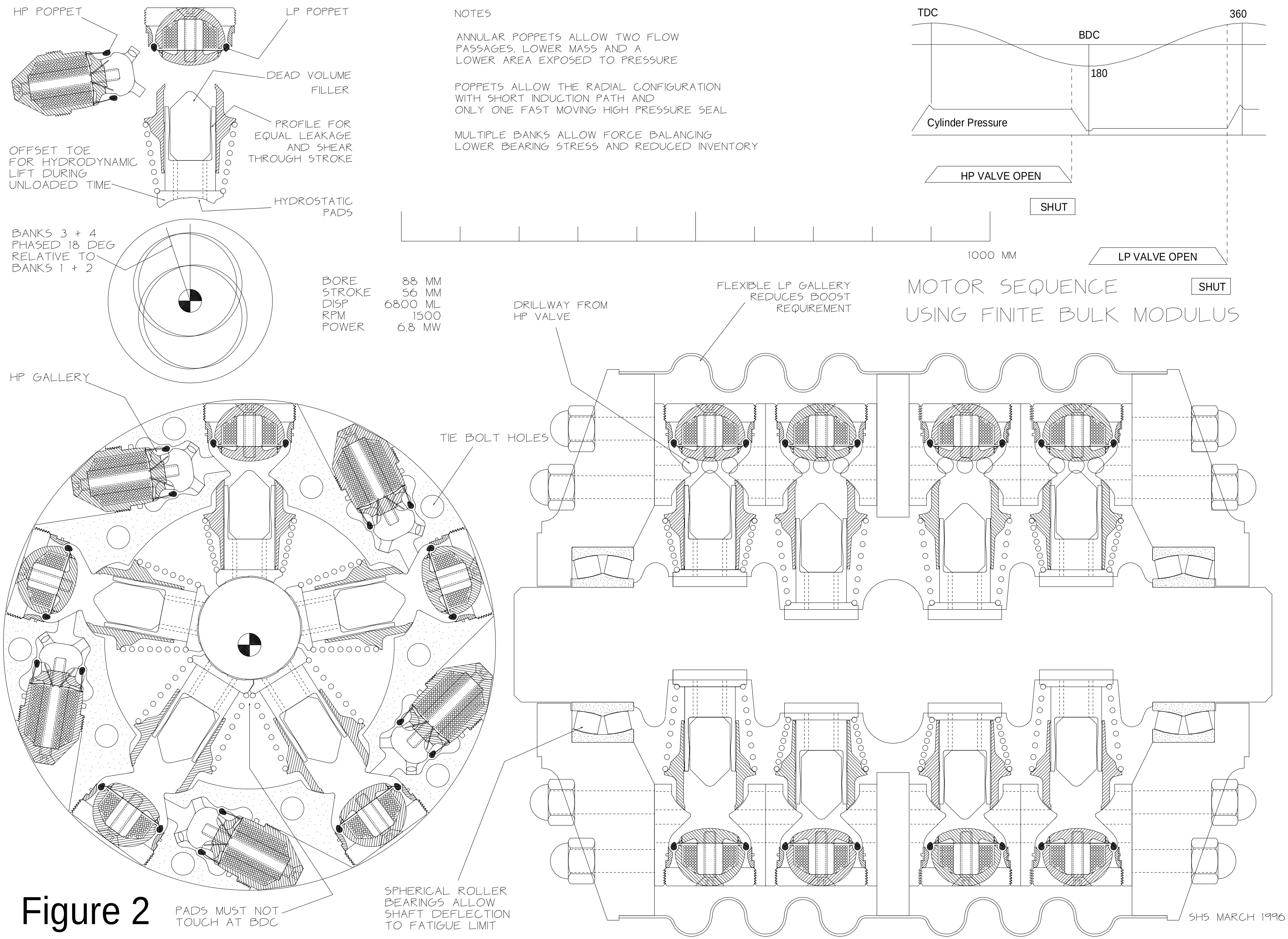
HP POPPET
LP POPPET
DEAD VOLUME FILLER
PROFILE FOR EQUAL LEAKAGE AND SHEAR THROUGH STROKE
OFFSET TOE FOR HYDRODYNAMIC LIFT DURING UNLOADED TIME
HYDROSTATIC PADS
BANKS 3 + 4 PHASED 18 DEG RELATIVE TO BANKS 1 + 2
NOTES
ANNULAR POPPETS ALLOW TWO FLOW PASSAGES, LOWER MASS AND A LOWER AREA EXPOSED TO PRESSURE
POPPETS ALLOW THE RADIAL CONFIGURATION WITH SHORT INDUCTION PATH AND ONLY ONE FAST MOVING HIGH PRESSURE SEAL
MULTIPLE BANKS ALLOW FORCE BALANCING LOWER BEARING STRESS AND REDUCED INVENTORY
1000 MM
BORE 88 MM
STROKE 56 MM
DISP 6800 ML
RPM 1500
POWER 6.8 MW
TDC
BDC
360
180
Cylinder Pressure
HP VALVE OPEN
SHUT
LP VALVE OPEN
SHUT
MOTOR SEQUENCE
USING FINITE BULK MODULUS
FLEXIBLE LP GALLERY REDUCES BOOST REQUIREMENT
DRILLWAY FROM HP VALVE
HP GALLERY
TIE BOLT HOLES
PADS MUST NOT TOUCH AT BDC
SPHERICAL ROLLER BEARINGS ALLOW SHAFT DEFLECTION TO FATIGUE LIMIT
SHS MARCH 1996

Figure 2

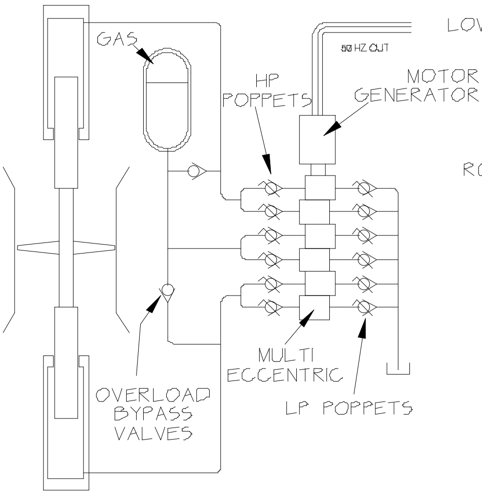

Figure 3a.Storage and power sharing.

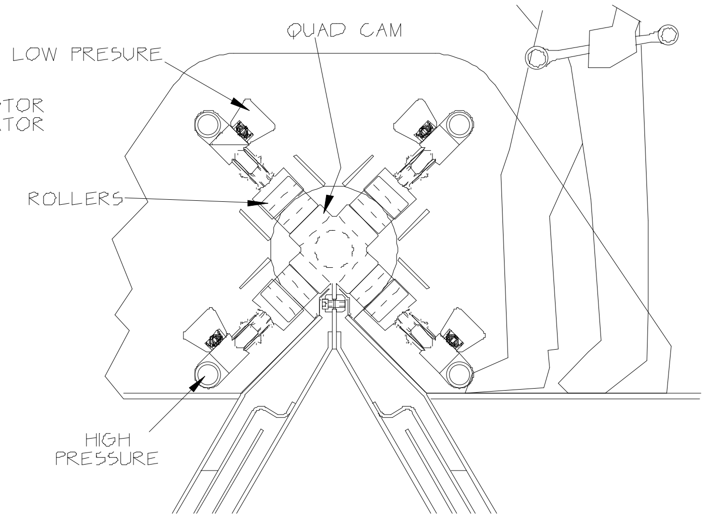

Figure 3 b. The quad ring-cam for a tidal stream generator.

Weights and dimensions

In addition to a series of low-power machines now being tested in road vehicle transmissions, there has been design work on a series of machines for various renewable energy applications. The table below gives estimates for weights and dimensions. The weight to torque ratio relative to conventional gearing should make large poppet-valve ring-cam machines attractive for wind applications, where low weight is desirable. The pumping modules can easily tolerate the piston stroke errors that could arise from deflections of the main shafts of large wind turbines.

Application	Wind turbine, two simplex outward radial action.	Tidal rotor, one quad cam with bearing function.	Fast generator drive with multi-bank eccentrics.
Overall diameter	3370 mm	50 m	960 mm
Axial length	1064 mm	900 mm	1240 mm
Chambers	2 x 26 = 52	4 x 144 = 576	5 x 4 banks = 20
Cam lobe stations	2 x 22 = 44	309	-
Stroke	68 mm	65 mm	56 mm
Bore	86 mm	48 mm	88 mm
Displacement/rev	0.452 m3	21 m3	6800 mL
Pressure	400 bar	400 bar	400 bar
Torque	2.8 MNm	133 MNm	43 kNm
Speed	22 rpm	3 rpm	1500 rpm
Peak power	6.6 MW	42 MW	6.8 MW
Weight	6475 kg	72 tonne	3300 kg

The design allows intensive development of quite small components which combine to make multi-megawatt plant. Simultaneous operation in pumping and motoring mode on test rigs which can recirculate energy allows the development and in-life testing of large machines at quite low total energy consumption.

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