

BANKI-CROSSFLOW SYSTEMS DESIGN GUIDE

1. INTRODUCTION

The design of a micro-hydro system in regards to the selection and sizing of the individual components so that optimum performance is obtained at the chosen site is not trivial. This is especially so where a single turbine is required to perform well over a wide range of head and flow conditions.

Crossflow turbines are often used for these applications. They exhibit good part flow efficiency over a wide range. As well, they are a flexible; both length and diameter can be individually chosen to suit the characteristics of the site.

WalshHydro is an Excel spreadsheet developed by Planetary Power to test designs for its Walsh River range of micro-hydro systems. The name is derived from the Walsh River in Far North Queensland, where the prototype system was installed. The system concept was developed and prototyped in 1991 by Jerry Jeffress and features the integration of custom made Banki-crossflow turbines, with Baldor DC generators and AERL Hydromax DC:DC step down controllers. Subsequent support for these systems including development of **WalshHydro** has been the responsibility of Max Enfield.

WalshHydro can be easily adapted to other micro-hydro design applications, particularly those that include either a crossflow turbine and/or a DC generator. The author encourages its use for other micro-hydro design applications. **WalshHydro** and these notes may be freely disseminated, copied and modified for this purpose. For commercial or educational use it would be appreciated that acknowledgement of the source be given.

2. THE BASICS

2.1 power train

A micro-hydro system is designed to harness the power of flowing water and to deliver electricity in a useable form. It does this by transforming and/or transmitting the power through a series of discrete stages. The stages are collectively known as the "power train".

WalshHydro assumes that the power train comprises the following stages:

1. a crossflow turbine transforms the hydraulic power of flowing water to mechanical rotating shaft power
2. a coupling, usually of the speed increasing type, connects the turbine shaft to the generator shaft
3. a DC generator converts rotating shaft power to DC electric current
4. a transmission line transmits the DC current to a DC:DC step down controller.
5. the DC:DC step down controller provides DC current for battery charging, to be used subsequently either directly or further conditioned into AC power using an inverter.

The systems designer may wish to consider a different design, in which case the spreadsheet can serve as a template, with just the useful parts selected. For example, the spreadsheet can be used just to explore the effect of changing the turbine parameters.

2.2 part flow

Crossflow turbines are able to operate over a wide range of head and flow conditions. The high part flow efficiency of this design makes it very suitable for these applications. Part flow operation is made



possible by any of several methods, such as: a simple valve or segment (Banki), hydraulic flap (Ossberger) or profile shaped semicircular segment (Cink).

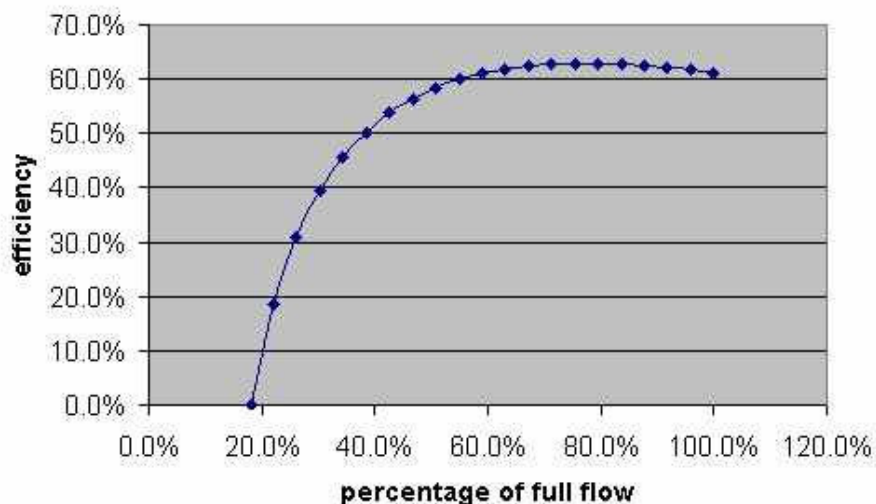
The ability to evaluate performance at part flow is a feature of [WalshHydro](#).

3. SETUP

Before the evaluation of designs can commence, some values need to be established.

3.1 turbine efficiency and part flow

Turbine efficiency graph



The efficiency of the turbine itself varies with the flow fraction. The default values used by [WalshHydro](#) are shown in the accompanying graph. You may want to adjust this to suit the characteristics of your particular turbine. On the *turbine efficiency curve* worksheet there are a number of parameter values that can be adjusted to alter the shape and amplitude of the curve. The most useful parameters are the *shape factor* and the *efficiency constant*. The turbine efficiency graph will instantly be redrawn to show the effect of any parameter changes.

The default fraction of full flow below which no power is produced is 0.18. This value can be adjusted by altering the formula in cell B32 of the *calculation sheet*.

3.2 nozzle size fraction

The nozzle is assumed to have a length equal to the runner width and a width equal to 0.095 x runner diameter. Your turbine may require a slightly different value – it can be adjusted at the *nozzle size fraction* cell on the *turbine efficiency curve* worksheet.

3.3 hydraulic data

A wide variation in head and flow rates are typically encountered at sites where crossflow turbines are selected. Usually the net head will fall slightly as flow increases because of increased intake and penstock friction losses. However these may be overshadowed by changes in water levels as the stream flow changes. In high flow, including flood conditions, there may be little difference between intake and tail pond levels, however the reverse may also apply.

[WalshHydro](#) permits the performance of any design to be rapidly evaluated over a range of head and flows. This is accomplished by setting up from 1 to 25 hydraulic data points on the *hydraulic data sheet*



worksheet. Each hydraulic data point consists of a flow rate and a matching net head.

The format provided is designed for the case where net head varies with flow rate due to penstock intake and friction losses. The static head is entered in cell B5 and a program such as SF Pressure Drop 5.0 is used to calculate the intake and pipe losses entered in columns F & G. However the format can be easily adapted to suit other hydraulic scenarios.

3.4 generator datasheets

WalshHydro contains a *generator datasheet* with sufficient data for evaluating the performance of 15 Baldor VP/CDP series DC generators. Other generators to be considered can be added as needed.

WalshHydro uses the following generator constants in its performance calculations:

- back EMF constant, K_e** in volts/(rad/sec)
- torque constant, K_t** in newton.metres/amp
- terminal resistance, R** in ohms
- viscous friction coefficient, D_v** in Nm/(rad/sec)

A detailed explanation of these terms is given in the Appendix.

3.5 Other set up parameter values

There are some other values that need to be specified that are unlikely to be changed in the course of evaluating system designs. They are described here.

3.5.1 turbine viscous friction coefficient [*calculation sheet*, cell B6]

This coefficient quantifies turbine losses that depend on rotational velocity. They include losses in the bearings and couplings. Its value is specified in Nm/(rad/sec). Planetary Power uses a value of 0.068.

3.5.2 coupling efficiency [*calculation sheet*, cell B19]

For direct coupling between turbine and generator, the coupling efficiency will be 100%. For other types of coupling the efficiency will be about 95%.

3.5.3 DC converter efficiency [*calculation sheet*, cell B21]

This is the efficiency of the DC:DC step down converter expressed as a percentage. If there is to be no converter set this value at 100%. For AERL Hydromax DC:DC step down controllers, Planetary Power uses a value of 92% for 12V systems and 96% otherwise.

4. SPECIFYING A DESIGN

This section describes how to specify a design to be evaluated against the hydraulic data points. Typically many designs will be evaluated in the course of determining the one or two designs that perform best over the range of expected hydraulic conditions.

4.1 turbine dimensions

The width and diameter of the turbine runner in millimetres are entered at *calculation sheet*, cells B4 & B5.

4.2 coupling step-up ratio

The speed increase ratio between the turbine shaft and the generator shaft is entered at *calculation sheet*, cell B18. For direct drive, enter a value of 1.

4.3 cable resistance

The resistance of the transmission cable between the generator and the controller is entered at *calculation sheet*, cell B20.

4.4 generator



Go to the *generator datasheet* and select the generator to be used. Select the entire row that describes the generator, then copy and paste it into the row indicated.

5. EVALUATING A DESIGN

Now that the design has been specified, we are ready to evaluate its performance at each of the hydraulic data points. This takes place in the *hydraulic data sheet* worksheet. The hydraulic data point to be evaluated is selected at cell B15.

5.1 Turbine speed and output power

The output power of a turbine depends on its speed, with maximum power generated at close to half of the freewheel speed. However the efficiency of other stages of the power train depend on the turbine speed, so that maximum delivered power may occur at a slightly different speed.

The minimum and maximum limits of the range of speeds to be considered by **WalshHydro** are entered in cells B10 & B11. They are specified as a percentage, with 0% being stationary (i.e. being stalled) and 100% being the absolute freewheel speed. Output power is calculated for the minimum and maximum limits specified and also at 19 equally spaced intermediate speeds, with the best result being returned as the current maximum powerpoint (MPP) estimate to cells B19 to B24. Calculation details for all 21 points are shown in the *calculation sheet* worksheet.

It is suggested that initial limits of 25% and 80% be selected. They can then be progressively narrowed to refine the MPP estimate to within any desired level of accuracy.

A micro-hydro system is made to operate at its MPP by the system controller, that applies just the correct electrical load, either by drawing a particular current or holding the voltage at a particular level. These current and voltage values are displayed as part of the MPP estimates.

Sometimes there are constraints that require the system to operate away from its MPP. This can be catered for in **WalshHydro** by selecting the minimum and maximum limits to force the constraints to be satisfied.

5.2 Feasibility

WalshHydro does not perform any editing of the data or perform reasonableness checks on the results. Remember the adage, garbage in means garbage out. The user must satisfy himself that the results are feasible and reasonable. Here are some things to look out for:

- The part flow fraction does not exceed 1.0 (*calculation sheet*, cell B31)
- The turbine speed is about half of the freewheel speed.
- The generator shaft torque, rotational speed, terminal voltage and output current values displayed on the *calculation sheet* are safely within the limits specified for the chosen generator.
- The delivery voltage is suitable for the controller, battery and/or appliances to be powered by the system

5.3 Completing the evaluation

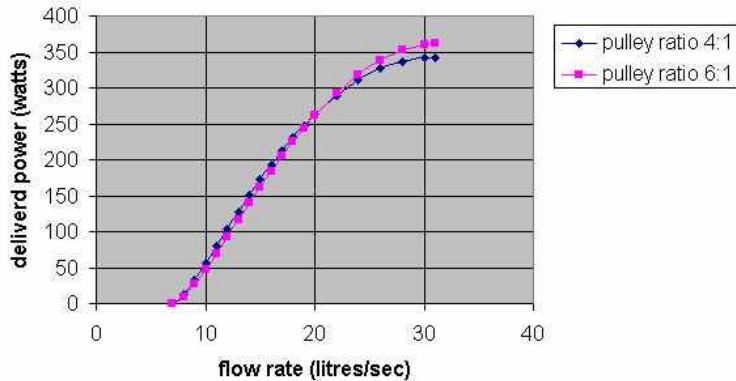
Once the MPP has been determined and its feasibility established, the value in cell B15 is changed so as to move on to the next hydraulic data point and the process is repeated.



6. DISPLAYING OUTPUT & EVALUATING DESIGNS

Data relating to the most recently calculated MPP for each hydraulic data point is posted to the system output table on the *hydraulic data sheet* worksheet. A graph displays them progressively as they are posted.. The user is encouraged to save the data from promising designs to a separate worksheet for later evaluation and comparison.

turbine design comparison



An example of comparing results is given in the accompanying graph, where the effect of varying the step up ration between turbine and generator shafts is displayed. For most conditions a step up ratio of 4:1 is preferred, however at flows above 25 litres/sec increasing the ration to 6:1 will improve performance.

7. A NOTE ON THE EXCEL SPREADSHEET

WalshHydro opens with a warning about a circular reference – please ignore it, it works fine in Windows 2000. If you find a way of removing the circular reference warning, please let me know.

Cells requiring data to be entered are all coloured salmon pink.

APPENDIX

8. DC GENERATORS, WITH REFERENCE TO THE BALDOR RANGE

8.1 Basic ideas – motors and generators

When a permanent magnet (PM) DC motor rotates it generates a back EMF that is proportional to the speed of rotation. This back EMF will be a little less than the applied voltage due to losses in the windings of the motor. These losses increase as a load is applied and the motor draws more current. Hence, if the applied voltage remains constant the speed of a motor will decrease a little as the load is increased.

Each motor has a nominal voltage rating. The applied voltage can range from a few percent of the nominal voltage up to 125% or more of the nominal voltage. For Baldor motors the useful range is from 15% to 120% of nominal voltage depending on the motor.

The current drawn depends on the applied load i.e. the torque together with a small overhead due to friction. Ignoring friction, the current is proportional to the torque. Each motor has a maximum full load current that it can handle. This current can be exceeded intermittently, however exceeding the rating risks the motor getting too hot and burning out.



When a PM DC motor is run as a generator the same principles apply. The generated voltage is proportional to the shaft RPM, less voltage losses in the windings and the current supplied is proportional to the shaft torque less frictional losses. The speed and current limitations that apply when operated as a motor, apply equally when operated as a generator.

As a motor, the power required to overcome friction and the copper losses in the windings comes from the electrical input, whereas as a generator it is the mechanical input which provides this power. So when operated as a generator, compared to being operated as a motor, the voltage is a little lower for a given RPM and the current is a little lower for a given torque. The difference is a few percent and will be discussed further below.

8.2 describing the performance of dc motors and generators

For a PM DC motor or generator running at constant speed only a few constants and equations linking them are needed to describe the relationship between speed, voltage, torque and current. We will be interested in operating Baldor units as generators only, however since Baldor specify the performance parameters of their units running as motors, this mode of operation needs to be considered also.

The **back EMF constant**, K_e , is defined as the ratio between the back EMF and the speed of rotation. In the metric system its units are volts/(rad/sec).

The **torque constant**, K_t is defined as the ratio between the torque and the current. In the metric system its units are *newton.metres/amp*. In the metric system K_e and K_t have the same numerical value.

Let V be the voltage at the terminals of the motor/generator, I be the current, R be the resistance in ohms across the terminals and ω be the speed in radians/sec. Let us use the suffix m to denote operation as a motor and g to denote operation as a generator. Then:

$$V_m = K_e \omega + I_m R \quad (1a)$$

$$V_g = K_e \omega - I_g R \quad (1b)$$

The corresponding equations for the torque T_m delivered by a motor and the torque T_g applied to a generator are:

$$T_m = K_t I_m - F(\omega) \quad (2a)$$

$$T_g = K_t I_g + F(\omega) \quad (2b)$$

where $F(\omega)$ is the frictional loss, being dependent on ω .

Now $F(\omega)$ is the sum of three individual friction components, known as **coulomb friction**, **viscous friction** and **windage**. We write:

$$F(\omega) = D_c + D_v \omega + D_w \omega^2$$

where D_c is the coulomb friction coefficient in Nm , D_v is the viscous friction coefficient in $Nm/(rad/sec)$ and D_w is the windage friction coefficient in $Nm/(rad/sec)^2$.

The performance parameters tabulated by Baldor allow $F(\omega)$ to be determined only at full rated load and this is insufficient to determine the individual friction components. The approach adopted here is to consider $F(\omega)$ to be a linear function of ω , that is, to consider all friction as viscous. At full load this assumption will yield the correct value, the relative error increasing the further the operating point is from full loading. In any case, the absolute error introduced by this assumption will be small.



With this assumption equations (2a) and (2b) become:

$$T_m = K_t I_m - D_v \omega \quad (3a)$$

$$T_g = K_t I_g + D_v \omega \quad (3b)$$

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