THE ELECTRIC SIDE

Power Transmission

by Jerry Ostermeier & Joe Schwartz

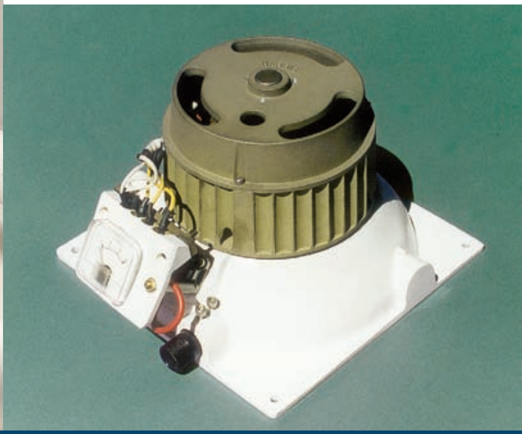
When people dive into developing hydro-electric systems, a lot of thought goes into diverting debris-free water from the creek and sizing the pipeline to carry it from the intake to the turbine. Both of these topics have been covered in recent issues of *Home Power* (*HP124* & *HP125*).

Designing the electrical side of your hydro system deserves equal attention. When it comes to transmitting and regulating the energy generated by your hydro turbine, making the right design choices for your site will result in maximum energy production and minimize up-front costs.

One of the smaller turbines from Canyon Industries, this 16 KW Pelton unit powers 120 and 240 VAC loads directly without batteries or inverters.

Shawn Schreiner

Alternative Power & Machine manufactures a variety of turbines that produce up to 3.3 KW and transmit up to 480 volts AC or DC.



The Harris Hydro Pelton turbine uses a permanent-magnet alternator to produce up to 2.5 KW and transmits at 12, 24, or 48 VDC.

Choosing a hydro turbine with the optimal mechanical characteristics (runner type and flow capacity) for your particular application is an important step in system design. So is designing the ideal intake and penstock setup. But all these will be for naught if the electrical side of your system is poorly thought-out.

Turbine Output Options

There are two basic types of hydroelectric turbines—high-power AC-direct plants and low-power DC or AC/DC turbines. Generally, high-power AC direct turbines are suitable for sites that have enough hydro potential to meet the peak demand of the combined electrical load on the system—most or all of the appliances running at once. Appropriate sites often have high flow rates (think cubic feet per second rather than gallons per minute). In a residential application, and depending on the water source and site characteristics, these turbines may generate from 4 to 15 KW (or more) continuously. Batteries are not necessary in these systems. Instead, the turbine produces 120 or 240 VAC at a controlled frequency (60 hertz in the United States) and output is fed directly to the electrical loads. Any excess power output beyond what the appliances require is routed to an electrical diversion load, typically either a water- or air-heating element.

Since most people don't live on a property with enough hydro potential for a high-power AC-direct turbine, the majority of residential hydro systems utilize low-power DC or AC/DC units. The output of this range of turbines may be from 100 to 1,500 W (and up) depending on the

OF HYDRO POWER

& Regulation Considerations

hydro resource. In most cases, the turbine charges a battery bank, and an inverter (instead of the turbine itself) is sized to meet the peak electrical demand. Another relatively new design approach using low-power turbines in grid-tied applications involves coupling the turbine with a batteryless inverter that, in turn, synchronizes system output with the utility grid (see page 48 of this issue for more information).

Low-power turbines are available in an array of output voltages, 12 to 120 VDC, and 120 to 480 VAC. The ideal turbine voltage for a given site will depend on the transmission distance between the turbine and the batteries. It's important to note that the output of low-power turbines at higher voltages (120 to 480 VDC) is almost always three-phase and the frequency will vary with the rotational speed of the turbine. Unlike high-power AC-direct turbines, the electricity generated is not compatible with your electrical loads without some additional power processing—the variable frequency three-phase AC output is rectified (converted) to DC and used to charge batteries.

The Nautilus Francis-style turbine is designed for low-head applications and produces up to 3.4 KW. It can be used with a variety of generators and voltages.

The Hi Power hydro unit matches a Harris Pelton turbine to an induction motor to generate wild three-phase AC at up to 480 V, and 3.6 KW.

Energy Systems & Design turgo turbines use permanent-magnet alternators to produce up to 1 KW at 12 to 240 VDC.

Transmission Basics

If your turbine will be located within a couple of hundred feet of your home, you are fortunate—your wire routing, wire sizing, and associated costs will be relatively easy to deal with. But in many situations, geographic circumstances necessitate locating the turbine far from where the electrical energy needs to end up. Transmission distances of 1,000 feet are common, and distances up to 1 mile or more are surmountable with today's hydro and control technology.

Similar to penstock design, longer wire runs require larger diameter wiring—the pipeline for electrical energy. The power equation (watts = volts x amps) shows us that voltage and current share an inverse relationship to each other. Higher turbine/transmission voltage results in lower amperage for the same amount of power (watts). Lower amperage means less energy loss in transmission and smaller-diameter (and therefore, less costly) wire can be used. To drive the point home, take a look at the Conductor Sizing table. The transmission distances, wire sizes, and conductor costs are based on a turbine output of 500 W.

Higher-voltage transmission strategies will keep wire costs down, and allow you to site the turbine farther from the electrical loads, which may also give you access to additional vertical drop (and power output) along the stream course. In the field, most hydro system installers end up making a lot of trade-off decisions based on cost, topography, the amount of energy that's required, and the distance between the turbine and the batteries. For example, siting the hydro plant a little closer to the house may shorten the wiring run enough to make it affordable, and not result in a significant reduction in turbine output. Or maybe an extra 50 feet of cable will make it possible to move the whole penstock upstream far enough to use a natural spillway for an intake. The bottom line is that there is a lot of give-and-take during the design process. This is where experience-based advice will result in optimal system production.

Conductor Sizing for 500-Watt Turbine

100 Ft. to Batteries

Turbine Voltage	Conductor Gauge Needed (AWG)	Phase	Conductors Needed	Total Wire Cost
12	0000	Single	2	$960
24	2	Single	2	230
48	8	Single	2	78
120	14	Three	3	30
240	14	Three	3	30
480	14	Three	3	30

500 Ft. to Batteries

12	*	Single	2	*
24	*	Single	2	*
48	2	Single	2	$1,150
120	12	Three	3	240
240	14	Three	3	150
480	14	Three	3	150

1,000 Ft. to Batteries

12	*	Single	2	*
24	*	Single	2	*
48	00	Single	2	$4,800
120	10	Three	3	690
240	14	Three	3	300
480	14	Three	3	300

2,500 Ft. to Batteries

12	*	Single	2	*
24	*	Single	2	*
48	*	Single	2	*
120	6	Three	3	$4,275
240	12	Three	3	1,200
480	14	Three	3	750

5,000 Ft. to Batteries

12	*	Single	2	*
24	*	Single	2	*
48	*	Single	2	*
120	2	Three	3	$17,250
240	8	Three	3	5,850
480	14	Three	3	1,500

Notes: *Sizes larger than 0000 AWG not viable due to expense. All sizing for 5% maximum voltage drop. Prices for THHN/THWN copper conductors. Ground wire & conduit not included in cost. 14 AWG is smallest wire size recommended.

Turbine-Specific Strategies

Before you get to work installing your hydro system, make sure you're up to speed on all of the available turbine and transmission options. The most common approaches are listed below, and the specific characteristics of your site—primarily how far you need to move the energy generated—will be the main driver in your transmission design.

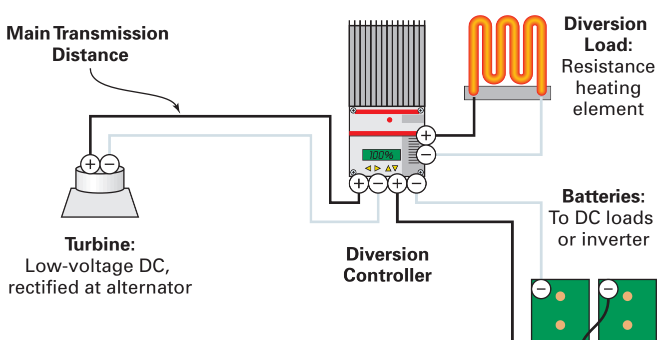
Low-voltage DC. If your turbine will be located within a few hundred feet of your home, choosing a hydro plant with output at the nominal voltage of the battery bank (12 to 48 VDC) is the simplest approach. Some home-scale hydro plants use generators that produce low-voltage DC directly. But most modern turbines have brushless permanent-magnet alternators that produce wild three-phase AC, which is rectified to DC at the turbine. The output of both turbine types can be routed right to the battery bank without further processing or conversion.

High-voltage DC. Some manufacturers offer turbines with DC output voltages above the standard battery voltage in most modern residential systems (48 V). The higher the transmission voltage, the smaller the wire size required. At the battery bank, a maximum power point tracking (MPPT) controller with voltage step-down functionality can convert the higher transmission voltage down to the nominal voltage at the battery, just like it's done in many battery-based PV systems. UL-listed controllers manufactured by Apollo, OutBack Power Systems, and Xantrex all have this functionality.

While high-voltage DC transmission is an option to consider, the controllers needed to step down the voltage are sophisticated and relatively expensive electronic devices. Most importantly, they will be damaged if they're subjected to voltages that are higher than they are designed to handle. Most of these controllers max out at 140 to 150 VDC open circuit. If the hydro turbine ever generated a greater voltage, or a breaker was inadvertently shut off, allowing the turbine to overspeed, the controllers will be damaged. Because of this, the simplicity of using a high-voltage alternator with a step-down transformer at the battery may be preferable—reliability is better, net efficiency is about the same, and the cost is less.

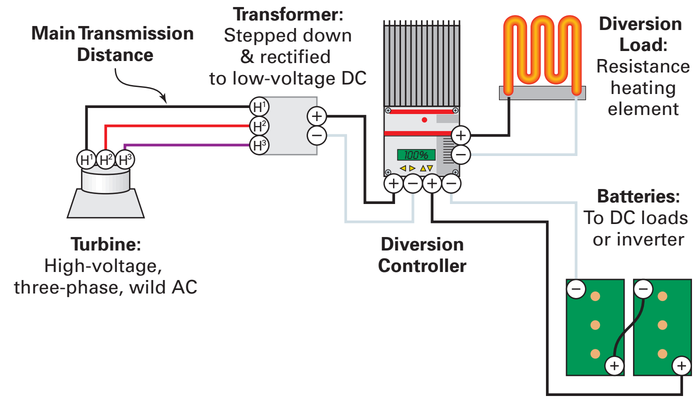
Wild three-phase. If you're facing a long wire run between the turbine and the batteries, one option is to purchase a turbine with a high-voltage alternator and transmit the three-phase AC output over the wire run. At the battery bank, a transformer drops the AC voltage down to the battery voltage, and it is rectified to DC for battery charging. A transformer/rectifier used in this application will typically have a conversion efficiency of about 90%. This approach will require a third power conductor for the third-phase, but is almost always cost-effective compared to DC transmission due to the smaller wire size required. Turbines with AC output voltages between 120 and 480 V are available.

Low-Voltage DC Transmission



Note: System grounds and other necessary safety components not shown.

High-Voltage AC Transmission



AC-coupled systems. The vast majority of off-grid systems are DC coupled—PV arrays, and wind and hydro turbines ultimately feed DC to the battery bank. In contrast, AC coupling uses one or more batteryless inverters to parallel charging sources on the *AC* side of the system. An additional battery-based inverter sets a baseline voltage and frequency to which the batteryless inverters synchronize. In an AC coupled hydro application, a dedicated batteryless inverter can be located at the turbine. The inverter's 120 or 240 VAC output will in turn be synchronized with the AC waveform

MPPT controllers, like OutBack's Flexmax, can step down high-transmission voltage to match the nominal battery voltage.

Hydro Wiring Tips

Bury It. Local codes may vary, but, typically, conductors in conduit need to be buried 18 inches deep, and direct-burial runs need 30 inches of cover.

Protect It. Running wire without conduit on top of the ground may be tempting, but it is a bad idea for the safety of critters (two-leggeds included) and the cable. Any depth of burial is preferable to none, with or without conduit. In addition, breakers should be installed to protect the wiring in the event of a short circuit. Always size the breakers based on the wire's rated amperage. Because the conductor size is specified with voltage drop over a long transmission run in mind, the ampacity rating of the conductors usually ends up being significantly higher than the actual amperage generated by the turbine. Because of this, you can often use a breaker that's two times the turbine amperage, which will eliminate nuisance breaker tripping, and minimize the possibility of the breaker tripping and allowing the turbine to overspeed.

Ground It. Hydro turbines can produce lethal voltages and should be grounded to minimize risk. Drive a ground rod at the hydro plant and connect it to the ground terminal provided on the turbine. A dedicated equipment-ground conductor should be run along with the power transmission wiring so your entire system is bonded and has the same voltage potential to ground. In lightning-prone areas, it's a good idea to include surge protectors at each end of the transmission run.

Don't Bond It. Do not connect the negative power conductor to the equipment ground at the hydro turbine. The *NEC* requires that only one negative-to-ground bond exists on the DC side of the system. This should only be done at the DC breaker panel located near the inverters and battery bank. Some low-cost hydro plants use modified automotive generators that are already grounded to negative, which puts the generator at risk if there's a close lightning strike and can also result in a ground differential throughout the power system that may damage components.

of the battery-based inverter. While this approach is still uncommon in single-household off-grid applications, it does offer some potential advantages in village-scale applications, or when a single battery-based system is charged by multiple power sources that are not located close to one another. Because multiple inverters are required, AC-coupled systems are usually more expensive. The main advantage is that, in some cases, this type of system can overcome design hurdles that a DC-coupled system can't.

Conductors, Conduit & Connections

Conductors. Two main kinds of conductors can be used for the transmission run—aluminum and copper. Aluminum has more than 1.6 times the resistance per gauge (diameter) than copper. Because of the higher resistance compared to copper, aluminum requires a larger wire size to handle a given amount of current. Even so, aluminum conductors can still be less expensive than copper depending upon current metal prices.

If the wiring will be run in conduit, larger wire size means larger conduit and increased overall cost. Aluminum wire is stiff and more difficult to pull through conduit and route into electrical boxes, and is not flexible enough for direct connection to the power terminals of most hydro plants. Finally, moisture has a greater corrosive effect on aluminum than copper. If conductors rated for direct burial are used, aluminum wiring will be more susceptible to damage if a wire is nicked. For all these reasons, copper is the preferred choice. For direct burial, the wire type should be USE, RHW, or UF. In conduit, THHN/THWN is typically used.

Conduit. Using wire rated for direct burial is tempting for hydro systems with long transmission runs, since skipping the conduit means less expense up-front, and makes installation a bit faster. However, protecting the conductors in conduit is recommended. In the case of direct burial, unless care is taken to bed the conductors in sand and remove rocks that might come in contact with the cable, damage can occur during backfilling. Trust us—trying to locate a broken conductor in a 1,000-foot wire run buried 30 inches deep isn't something you want to experience. In addition, it's desirable to use conduit for high-voltage transmission runs so there's one more layer of protection for both the conductors, and for anyone that might inadvertently come into contact with them.

Connections. For making electrical connections at the turbine, soldered copper-lug connectors are ideal. If the transmission run is aluminum, use a short length of copper wire from the turbine's output terminals to a junction box, where split bolts can be used to join to the aluminum and copper conductors. Apply a corrosion inhibitor wherever dissimilar metals are joined. Wound-field hydro turbines (which use modified vehicle alternators) have electrical terminals that are somewhat exposed, so caution is advised when servicing them.

Diversion controllers, like Morningstar's TriStar, divert excess energy to a dump load when batteries are at full charge.

Voltage Control

Because hydro turbines run 24 hours a day, most systems produce a lot of energy. As a result, the battery bank spends much of the time completely charged and in float mode. To keep the batteries from being overcharged, voltage control is required. Unlike PV arrays, hydro plants must remain electrically loaded at all times to keep both the turbine's rpm and the peak output voltage in check. That means that series-type voltage regulators, like the one in your car, cannot be used because they simply open the circuit when they hit their voltage set point. In a car, this isn't an issue because the alternator speed is limited by engine speed—but hydro plants have no such limitation.

Diversion loads are usually electric heating elements to dump excess energy in the form of heat to air (left) or water (right).

Shawn Schreiner

Courtesy Hi Power

Transformer/rectifier units convert high-voltage, wild three-phase AC hydro turbine output to lower-voltage DC for battery charging. This package, manufactured by Hi Power, includes overcurrent protection, an amp meter, and terminal strips for system wiring.

Electrically unloaded, a hydro turbine's rpm will almost double, and output voltage may triple. Most turbines can handle the increased rpm, but the extremely high output voltage will destroy system controls. To avoid this scenario, hydro systems rely on diversion controllers that shunt (route) the turbine's output to a diversion load when the battery bank is fully charged. The TriStar controller manufactured by Morningstar is a very popular diversion controller, as are the C-series controllers manufactured by Xantrex. MPPT controllers manufactured by Apollo, OutBack, and Xantrex all have an auxiliary output-control feature that's capable of driving a separate high-current relay to shunt excess power to the diversion loads. In addition, several battery-based inverter models feature auxiliary control functionality.

In off-grid hydro systems, resistive loads like water- or air-heating elements are used to dissipate excess energy. These diversion loads are usually sized to handle the turbine's full power output. The *National Electrical Code (NEC)* requires a second independent diversion setup to protect the battery bank from overcharging if one controller fails. One common approach is to use a dedicated controller and water- or air-heating element as the primary diversion system. The secondary diversion setup can utilize the inverter's auxiliary output and a relay to dump AC power to a standard 120-volt space heater.

In battery-based grid-tie applications, the grid functions as the primary diversion load, with excess hydro-generated energy fed back via a utility-interactive inverter. But even grid-tied systems require a separate, dedicated diversion controller and load as a backup. Without it, in the event of a utility outage, the system's battery bank would still be vulnerable to overcharging since the primary diversion load (the grid) is no longer available.

The Best Approach for Your Site

There are a lot of design options to consider when it comes to the electric side of your hydro-electric system. Every site is different, and many pitfalls and unnecessary expenses can be avoided by getting some expert help when the time comes. Most hydro manufacturers are willing to work hand-in-hand with the customer or a professional installer to design a safe, durable, and efficient system that will not only work, but also work hard for years to come.

Access

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Joe Schwartz (joe.schwartz@homepower.com), *Home Power's* CEO and editor, lives off grid outside of Ashland, Oregon. While PV currently supplies all the electricity for his homestead, there's a hydro site, with 140 feet of vertical drop (and an 1,800-foot transmission distance), waiting to be developed.

Hydro Turbine Manufacturers:

Alternative Power & Machine • www.apmhydro.com

Canyon Hydro • www.canyonhydro.com

Energy Systems & Design • www.microhydropower.com

Harris Hydro • 707-986-7771

Hi Power • www.hipowerhydro.com

Diversion Controller Manufacturers:

Morningstar Inc. • www.morningstarcorp.com

Xantrex • www.xantrex.com

MPPT Controllers with Auxiliary Output Functionality:

Apollo Solar • www.apollosolar.com

OutBack Power Systems • www.outbackpower.com

Xantrex • www.xantrex.com