# 13 SELECTING THE LOADS



The LOADS are the devices which are connected to a pico hydro system and which work as a result of the power generated by the turbine. They can be divided into **electrical** and **mechanical** loads.

## *13.1 Electrical loads*

Electrical loads use the electricity produced by the generator. Many kinds of electrical loads can be used with a pico hydro system. A few common electrical loads are listed below. They have been divided into two groups: those that use a motor and those which do not. There are additional considerations when connecting motor driven loads to a pico hydro scheme. These are explained in Section 13.2.

**Non-motor driven loads**, for example:

- Lighting
- Battery chargers
- Radios
- Televisions

**Motor driven loads**, for example:

- Food processors and liquidisers
- Refrigerators
- Ventilation Fans
- Workshop tools (grinding wheels, drills, saws, planners, sanders)

The type and number of electrical loads that can be connected depends on the amount of electricity being generated. The following sections discuss the technical considerations for each type of load more carefully.

### Lighting

Lighting is often the primary use of the electricity that is generated from a pico hydro system. The provision of electric lighting in an unelectrified rural community can improve the quality of life by a large margin. There are three types of electric lighting which are most commonly used for domestic purposes.

**Incandescent lighting**. Light bulbs of this type use a filament made of wire that heats up and gives off light when a suitable current is passed through.

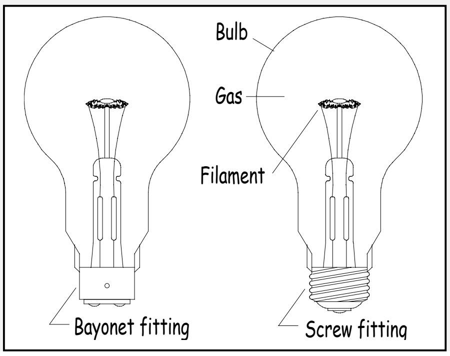



**Figure 13-1 Incandescent lamps**

Incandescent light bulbs are commonly used because they are cheap and easily available. However, they have quite a short lifetime and make inefficient use of the electricity. The problem is that only 8 to 12 % of the electrical energy is converted to light. The rest escapes as heat. Although there are a few lighting applications which use this waste heat such as chicken hatcheries, in most cases light bulbs of this type are a highly inefficient way of using the electricity which has been generated. In addition, constant heating and cooling of the filament eventually causes it to burn out and then the bulb has to be replaced.

**Tubular Fluorescent Lighting**. This type of lamp has electrodes at either end of the tube. These release small particles called electrons which cause ultraviolet light to be produced from the argon gas that is held inside. UV light is converted into visible light by a fluorescent coating on the inside of the glass.

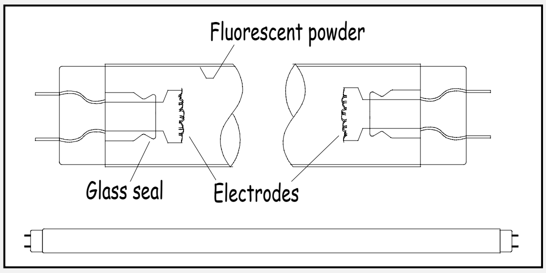
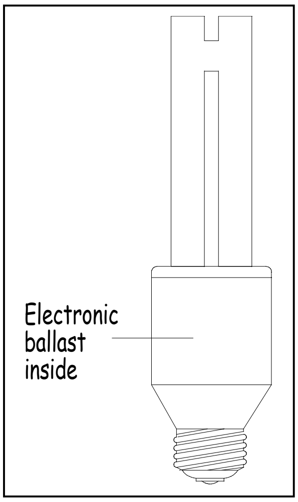



**Figure 13-2 Tube lights**

Tube lights require an electrical circuit called a ballast in order to control the electric current flowing through the lamp and to give a high voltage at the electrodes. An inductive ballast (a coil of wire on an iron core) was commonly used up until recently when electronic ballast's were developed. Electronic ballast's can operate at a higher frequency and this helps to improve the performance and increase the life of the lamp.

**Compact Fluorescent Lamps (CFL's)-**
These have been developed more recently and are already widely available. They work in the same way as fluorescent tubes except that the tube is narrower and folded over several times. The electronic or inductive ballast is usually contained in the base of the lamp. The design allows the lamp to be fitted to a conventional socket, with either a bayonet (BS) or Edison screw (ES) fitting. You can usually tell if an inductive ballast is fitted as the lamps are heavier.




**Reliability of Fluorescent Lamps**
Electronic circuitry in fluorescent lamps makes them sensitive to the quality of the electricity supply. If the voltage and frequency vary by large amounts then it is possible that the lamps will be less reliable and have a shorter life. Otherwise their life should be at least 5 to 10 times longer than an ordinary light bulb. It is therefore important that the voltage and frequency are kept near their rated values.

The rated value of voltage and frequency is the value that the device has been designed for. This is written on the side of the bulb.

The life of a ballast (and hence the lamp for CFL's because the ballast cannot be replaced separately) will be reduced if the frequency is less than the rated value (50 or 60 Hz) or if the voltage is higher than the rated value (110V, 120V, 220V etc.). Both these conditions cause the amount of current drawn to increase and will therefore have an adverse effect on the life of the windings or circuitry because of over-heating. Small rises in frequency or reductions in the rated voltage will probably be tolerated.

The lifetime of CFL's and tubes is also reduced if they are switched on and off many times. This makes them unsuitable for places where a light is only required for a short period e.g. a cupboard or a toilet.

**Power Factor Correction of Fluorescent Lamps.**
The term 'power factor' is explained in Appendix A on Electricity. Power factor correction means to adjust the power factor of the system nearer to one. The power factor already has a value of one for incandescent lamps so no correction is required. For fluorescent lamps which contain inductive ballast's, the power factor can be as low as 0.5. This has two impacts on a scheme where large numbers of the lamps (50+) are connected:

1. Power losses in the cable increase due to large amounts of reactive power which are drawn.
2. Low load power factor causes the generator frequency to rise and could cause de-excitation of the windings of the induction generator. This would cause the generator to stop working until some of the lamps are disconnected.

Power factor can be improved by connecting capacitors across the inductive loads. The amount of capacitance required will depend on the number of fluorescent lamps which are connected. Ideally each house with fluorescent lamps should have its own capacitors. Larger capacitors cost less per micro Farad (μF) than smaller ones so it is wise to power-factor correct all the lamps in one house with a single capacitor. Metalised polypropylene lighting capacitors that are available in size from 4μF are ideal for power factor correction of small lighting loads.

Although it is difficult to estimate the size of the inductive loads on a system until it is built, the approximate amount of power factor correction required should be estimated at the initial planning stages and priced in to the scheme costs.


**Figure 13-3 Metalised Polypropylene Lighting Capacitors for power factor correction of fluorescent lamps**

**Example Capacitance required for power factor correction of inductive loads**

A pico hydro scheme has 100 houses connected to a 2.5 kW generator. In each house there is a 20 W fluorescent tube. The power factor of these tubes (according to manufacturers' information) is 0.5. If the scheme operates at 220V and 50 Hz :

a) What value of capacitance should be connected to each tube to bring the power factor up to a value of 1?

b) If the capacitance is considerably cheaper when purchased in larger units and each house has four 20W fluorescent tubes, what size of capacitor should be chosen to correct the complete domestic lighting circuit?

a) How much current does each fluorescent tube require?

$$I = \frac{Power}{V \times \cos\phi}$$

$$I = \frac{20}{220 \times 0.5} = 0.182A$$

What capacitance is required to power factor correct given this current value?

$$C = \frac{I \times \sin\phi}{6.3 \times V \times f}$$

C = Capacitance required (Farads)
I = Current rating of device (Amps)
cos $\phi$ = Power factor
V = nominal voltage (Volts)
f = frequency (Hertz)

$$C = \frac{0.182 \times 0.87}{6.3 \times 220 \times 50} = 2.27\mu F$$

To fully power factor correct this fluorescent lamp, a capacitance of 2 micro-Farads (μF) should be connected across the supply. Under correction of the power factor is recommend when the precise value of capacitance for full power factor correction is not available (see note.)

b) In order to power factor correct four lamps per house then the capacitance required is 4 x 2.27 = 9.08 μF. Two 4μF capacitors connected in parallel across one of the lamps is the best solution in this case. If capacitors of only one or two sizes are available, then connect to the appropriate number of lamps to bring the power factor to 1. Always connect capacitors directly across the inductive load, otherwise there will be too much capacitance connected when other lamps are switched off.

**Note:** Do not over correct the power factor. This will reduce the supply frequency and increase the current in the wiring.

**Voltage Rating of Capacitors**

The price of capacitors depends on the voltage rating as well as their size. (i.e. the number of micro farads) The voltage rating of capacitors should be at least that of the loads to which they are connected. Capacitors with higher voltage rating than the load will have a longer lifetime. For small loads such as lights, which are used intermittently and for short periods, it is best to choose capacitors with the same voltage rating (i.e. 220V) as these will be the cheapest option. For power factor correction of larger loads such as motors it is worth spending more on capacitors with a higher voltage rating. For example, capacitors rated at 415V would be a good choice for a 220V motor.

Advantages and disadvantages of the three types of lamps are compared in Table 13-1.

| | Advantages | Disadvantages |
|---|---|---|
| **Incandescent lamps** | ✓ Low cost, widely available therefore easy to replace.<br>✓ Not damaged by low voltage operation<br>✓ Power factor of 1 | × Low efficiency, made worse if the voltage falls. Therefore, not the best choice when the power available is limited.<br>× Short life-span (750-1000 hours) |
| **Fluorescent Tubes (ordinary type)** | ✓ Relatively Low cost<br>✓ Widely available<br>✓ Good efficiency so a good choice for village lighting using pico hydro<br>✓ Long life-span (5000-8000 hours) | × Require different socket (can also be an advantage, see below*)<br>× Larger than other types of lamp for the same output.<br>× Must be disposed of carefully as contains mercury vapour.<br>× A separate ballast is required. This will require periodic replacement in addition to the tube.<br>× May require power factor correction.<br>× Not suited to frequent on/off switching. |
| **Compact Fluorescent Lamps (CFL's)** | ✓ Very good efficiency and are a good choice for a scheme where the voltage and frequency are correctly controlled.<br>✓ Fit into standard sockets<br>✓ Ballast is usually contained in the lamp.<br>✓ Very long life-span (8000-10000 hours) | × Initial cost is more than previous types although prices are falling.<br>× More sensitive to variations in the supply which can affect lifetime and performance.<br>× Require careful disposal (contain mercury vapour).<br>× May require power factor correction<br>× Not suited to frequent on/off switching. |

**Table 13-1: Different types of electric lighting compared**

*A pico hydro scheme which provides lighting can become overloaded if CFL light bulbs fail and are then replaced by incandescent lamps (these are cheaper). An additional advantage of tube lighting is that there is less temptation to replace with incandescent bulbs since the sockets will also require changing to allow them to be connected.

## Battery Charging

Battery chargers are useful in rural areas that are not grid -connected. Using hydro-power as a charging source, they can be left running for long periods and, depending on their design, may charge several batteries at the same time. Batteries can be used by people who live too far away to be connected directly to the generator. A battery allows the use of simple electrical loads and can be recharged when required for a small payment that is much less than the cost of disposable batteries.

**Figure 13-4 Battery charging with hydro power (Peru)**

Batteries store low-voltage dc electricity which is different from the higher voltage ac electricity which is produced by the generator.
Two common types of rechargeable batteries, used for providing power to small electrical appliances in remote areas, are lead-acid and nickel-cadmium (Ni-Cad). Lead-acid batteries are used to provide 12V electricity in most motor vehicles and often used for lights, radios and TV's in rural homes because they have relatively high energy storage and are widely available. There are different types of lead-acid batteries. The older motor vehicle type, allow the electrolyte to be topped up with distilled water. Modern designs are maintenance free and sealed to prevent spillages. A more expensive type of lead acid battery is the deep-cycle battery. If available, these provide a more reliable and long lasting form of energy storage than motor vehicle batteries.

Nickel Cadmium batteries are more expensive per unit energy stored and used to power small electrical goods such as torches and radios. They give a smaller voltage than lead-acid batteries but are easier to handle and more reliable.

Battery chargers convert the electricity from AC to DC and prevent overcharging which is important to maintain the life and reliability.

**Charging Lead-acid Batteries Safely**

- Explosive gases are produced during the charging of vented lead-acid batteries so the presence of flames or sparks nearby is extremely dangerous and must be avoided.
- Charge batteries in a well ventilated area
- Use gloves and goggles when handling to avoid burns from sulphuric acid which forms the electrolyte. Wash any spillage's immediately with clean water.
- Even quite flat batteries can cause a fire if the terminals are accidentally shorted out with a cable or other metal conductor.
- Always disconnect the charger before disconnecting the batteries under charge.

## Battery performance

Lead acid batteries should not be fully discharged as this damages them. Motor vehicle batteries are only intended for shallow discharging and ideally should not be discharged by more than 20% of their capacity. A small battery charge indicator (quite cheaply available in some countries) is useful to monitor this. Deep-cycle batteries can be discharged up to 80% of their capacity without damage.

The reliability of a battery reduces the more it is cycled (charged and discharged). Generally a new, good quality motor vehicle battery will fail after 200 cycles to 50% of its capacity. A suitable depth of discharge for a motor vehicle battery is therefore is 20%. This will prolong its useful life. Deep-cycle batteries can be cycled many more times, typically 1000-2000 times at 80% depth of discharge. This means that they will last many times longer than a motor vehicle battery even though they are more expensive initially.

Ni-Cad are the opposite to lead acid in that they perform better and last longer if fully discharged before re-charging. This is advantageous as no charge monitoring required and the natural tendency is to use batteries until they are fully discharged.

## Battery Capacity

Capacity indicates how much energy a battery can store. A 60 amp-hour battery can deliver one amp for 60 hours or 20 amps for 3 hours. Multiply the amp-hours by the battery voltage to get Watt-hours.

**Example**

How long could a 12V 60Ah motor vehicle battery be used to power a black and white television which requires a 40W 12V DC supply before recharging if the maximum depth of discharge is 20%.

Answer:
Storage capacity of battery
= 12 x 60 = 720 Watt-hours.
Useful capacity before recharging =
=720 x 20% = 144 Watt-hours
Hours of TV viewing (40W TV)
= 144 / 40 = 3hrs 30mins

## Emergency Lighting

A product sold for emergency lighting has recently become available in many countries. This is a tube light with a built in battery and charging unit. In areas where the grid is unreliable, these lights are popular because they can be used during power cuts and then plugged into the mains for recharging when the grid comes back online. They can also provide a useful lighting solution in rural areas and be charged when required from an induction generator. Since they are also portable, they remove the need for torches.

**Figure 13-5 Example of emergency lighting sold in Kenya with 2 x 8W fluorescent tubes and plug for recharging (Cost = $35).**

## Radio and Television

After lighting, radios or televisions are probably the most common domestic loads. The main considerations when operating these loads from a pico hydro system or other isolated electricity supply are as follows:

- Operating at under-frequency or over-voltage is harmful. The life of internal components such as transformers will be shortened due to excess current.
- Small increases in frequency should not be harmful
- Protect expensive televisions with a separate voltage regulator.
- Operating from a DC supply such as batteries will not cause damage providing that electricity at the correct voltage is supplied and the TV or radio is designed to work with batteries.

## 13.2 Motor-driven loads

Many modern appliances are driven by electric motors. However, connecting motor driven loads to an isolated electricity supply requires additional considerations. The main differences between a motor and other common types of electrical load are that the current required can vary greatly:

- during motor starting, much more current is required than when the motor is running.
- the current required by a motor can vary during use depending on the load connected.

For example, a motor connected to a saw will draw more current when a plank of wood is being cut than when the saw blade is spinning freely. Alternatively, a motor driving a fan will draw a constant amount of current when the fan is running because the load on the fan does not change.

A number of undesirable things can happen if the wrong size of motor is used with a particular generator:

- the motor will not start and the generator de-excites.
- the supply voltage dips sharply when the motor is started. When the motor is running the voltage is lower than its rated value indicating that the scheme is overloaded.
- the MCB in the powerhouse may trip and disconnect the all the loads, if the machine which the motor is driving becomes jammed

Being unable to start the motor, or tripping the circuit breakers whenever the motor is in use, may cause frustration and disillusionment with the system. These problems can be minimised by careful planning.

## 13.3 How to avoid problems with motor starting

To avoid problems with motor starting, the following should be considered:

a) the **size of motor** which is connected to the generator
b) the **type of motor** which is connected
c) the **type of load** which is driven by the motor
d) the **length and size of cable** between the motor and generator.

### a) Size of motor

Motors use much more power at starting than when running. Also when switched on they cause an initial drop in voltage which reduces their starting torque. If too large a motor is switched on , the starting torque will be insufficient to turn the shaft.

What is the largest motor that can be started using a pico hydro system?
Use this general rule to decide:
**Max. Motor power = 10% of Generator power**
For example, the largest motor that could be started and driven by an induction generator producing 2.5kW is: 10% of 2500W = 250W

### b) Type of motor

**Universal motors** are used in many small and hand-held appliances, such as electric drills. They are compact, available in smaller sizes than induction motors and easier to start. The type of motor that is used for most loads requiring more than about 200W is the **induction motor**. This is the same type that is used as a generator for the Pico Power Pack. Capacitors are often connected to help induction motors to start and to improve the power factor whilst running. The motors are then classified depending on which capacitors have been connected. The type of induction motor which is used, should consider the load that is being driven

| Type of motor | Characteristics | Suitable loads |
|---|---|---|
| **Capacitor start** | High starting torque | Fridge compressors, mills, |
| **Capacitor run** | Good power factor/ low starting torque | Grinding wheels, drills, fans |
| **Capacitor start and run** | Best all round performance | Saws, planers, |

### c) Starting different types of loads

The type of load connected, affects how easy a motor is to start. The turning force (or torque) required, for example to start turning a mill is different from the force required to begin turning a fan. A high starting torque is needed to start the mill in order to overcome the friction of the grinding wheels.

For some types of machines that are easy to start, like fans, the motor power can be increased to 20% of the generator power. Machines that can be sized for 20% of the generator output include the following;

- Fans
- Grinding wheels (for tool sharpening)
- Electric drills

### d) Position of the motor

The motor is likely to be one of the largest single loads in the distribution system. It is important the voltage is kept within the required range. If the motor is situated near to the generator then it will benefit from a higher voltage. This will reduce starting problems. If the motor is a long distance from the generator, the cable to connect it will be expensive and there will be a lower starting voltage.

## *13.4 Mechanical end-uses*

In addition to supplying domestic electrical loads such as lighting, pico hydro-power can be put to good use during the daytime. The power can be used to make money and quickly repay the loan that was taken to help buy the equipment.

Many money-making activities which are useful to the community such as grain milling, need mechanical power. In areas that are serviced by a national electricity grid, the mechanical power is usually provided by electric motors. It is still possible to run some motors using the electricity generated with a pico hydro plant, but there are significant constraints on this as explained in the previous section.

Fortunately with pico hydro-power, there is also an opportunity to drive mechanical loads directly. The mechanical energy of the turbine runner can be transferred directly to the loads without conversion into electricity. This is usually achieved by means of pulleys and belts. The main advantage of using mechanical power directly is that much larger loads can be driven than would otherwise be possible with electrical motors. For a comparison of electrical and mechanical drives, look at Table 12.2.

If the mechanical power is used directly by linking the end-use machinery with pulleys and belts to the turbine, then it is possible to drive equipment requiring almost the full rated power of the turbine. A small efficiency loss occurs in the belt drive. This will be, at most, 10% of the power in the turbine shaft if the pulleys and belts are correctly sized and tensioned. This leaves 90% of the power to drive the load. Compare this with the maximum size of induction motor that ca n be driven, calculated on Page 13-6.

| | **Electrically Driven Machines** | **Mechanically Driven Machines** |
|---|---|---|
| **Ease of Starting** | Difficult or not possible except for relatively small motors. | Excellent , since turbine torque is highest at zero speed. |
| **Efficiency** | low (50% of turbine power) | High (90% of turbine power) |
| **Location** | Very flexible | Very inflexible (must be located next to the turbine) |
| **Maintenance and Repair** | More complicated therefore maintenance and repair needs are greater | Simple to maintain and repair. |
| **Cost** | Cost may be lower than mechanical equivalent if device is mass-produced. The cost of cable and power factor correction must be included. | Pulleys, belts and tensioning equipment must be included. Locally produced machinery may be more expensive than mass-produced electrical appliances. |

**Table 13-2 Comparison of electrically and mechanically driven loads**

**Example : Calculate the mechanical power available to drive a load.**

The power in the turbine shaft is 3.5 kW
The efficiency of the belt drive is 90%
Answer
90% of 3.5 = 3.5*0.9 = 3.15 kW
Power available = **3.15 kW**

Some examples of mechanical loads which are commonly driven by hydro-power are listed in Table 13-8. Typical power requirements and speeds for small loads (suitable for use with some pico hydro systems) have also been given. Before purchasing mechanical equipment, consult manufacturers' information and ensure that the power output of the turbine is sufficient. The choice of equipment will determine the pulleys and belts required. Read the next section carefully to make sure these are appropriately selected.

## *13.5 Pulleys and Belts*

Pulley belt drives are used to link mechanical equipment to the turbine shaft where the equipment has a different operating speed to that of the turbine.

**Note: Direct drive of mechanical loads**
If the load can be directly driven from the generator shaft then no pulleys and belt are required. These are the considerations:

- Turbine speed must match the load speed
- Turbine must have the same centre point as the load. (Is it practical to position the load near the floor?)
- Disengaging the load from the turbine is more complicated.

Direct drive is practical with particular loads in certain circumstances (e.g. grinding wheels) but this is seldom the case.

Two types of pulley belt are commonly associated with hydro power schemes, the V-belt and the flat belt. V-belts are the most suitable for pico hydro. They are smaller, lighter, easier to install and maintain, and lower in cost compared with flat belts.

V-belt drives are an efficient and robust method of transmitting power between the turbine and other machinery. Wedge belts are a more modern version of the V-belt. They can transmit more power because they wedge themselves deeper in to the pulley and can therefore get more grip. The differences in size between the two types are illustrated in Figure 13-6

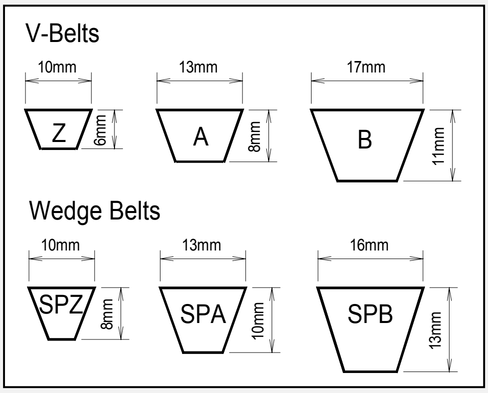



**Figure 13-6 Cross-sections of different belt sizes**

V-belts are named Z, A, B in increasing order of size and similarly wedge belts are named SPZ, SPA and SPB. V-belts and wedge belts of the same size range (Z and SPZ for example) can both be used on the same pulley. However, care must be taken not to confuse the two types. V-belts are generally much cheaper than wedge belts which can make them appear attractive to use when a spare is required. However, if a wedge belt is replaced with a V-belt then there is a strong possibility that the drive will no longer work because the belt will slip.

In order for pulleys and belts to function correctly and have a long lifetime, they must be carefully selected. The following questions must be answered to allow the correct pulley and belt combination to be selected:

- How much power does the load require?
- How fast does the turbine shaft run when driving the generator?
- What is the required running speed of the load shaft?
- What is the centre distance between the two shafts?
- How many hours per day will the load be in use?
- What is the diameter of the turbine shaft?
- What is the diameter of the machine shaft?

### Speed Ratio

By choosing appropriate pulleys, the speed which one shaft spins can be different from the other. This is useful for a pico hydro system. The speed of the turbine may be around 1000 rpm (revolutions per minute), more commonly at 1500 rpm and sometimes even 3000 rpm. That is 50 complete turns in one second! Most machines connected to the turbine need a slower speed than this. A small flourmill for example, may require only 500 or 600 rpm. The difference in speed between the shafts is called the speed ratio. It is calculated as follows:

**Speed ratio**= turbine shaft rpm / load shaft rpm

The speed of the turbine shaft will depend on the site conditions and the type of generator used. Usually the manufacturer selects the operating speed. It is advantageous to use the generator and controller as an over-speed controller. If the mechanical load requires less power than is available from the turbine, the excess power will be delivered to the generator and controller. If the mechanical load requires all the turbine power then the speed will fall by about 10% as at this speed the generator will not excite and there will be no electrical load.

A speed reducing drive means that a small pulley is fitted to the generator shaft and a larger one to the mechanical load. This will mean that the larger pulley will turn more slowly so that the load, such as a mill, doesn't spin too fast. A speed increasing drive is the opposite way round: A large pulley drives a smaller one, making it spin faster. Certain types of saw, for example, may require a speed increasing drive.

A turbine shaft speed based on the number of generator poles should be used to calculate the speed ratio. The number of poles (usually 4 but sometimes 2, 6 or 8) can be found on the information plate on the side of the generator. 4 pole generators are most commonly used.

| **Number of Poles** | **Approx. Head (m)** | **Design Speed of Turbine / Generator Shaft (rpm)** |
|---|---|---|
| 2 | >80m | 3000 |
| 4 | 25 - 80 | 1500 |
| 6 | <25 | 1000 |

**Table 13-3 Generator shaft speeds and head range for direct drive**

For more information about selection of design turbine shaft speed, please read the notes in Appendix B.

### Minimum pulley diameter

A final consideration when selecting the pulleys is that particular sizes of induction motor specify minimum pulley diameters that can be connected. This is because a higher belt tension (and therefore a greater bearing load) is required for smaller pulleys. Common sizes of induction motor and the corresponding minimum pulley diameters are shown in the following table:

| **Induction motor frame size** | **Common Power ratings (kW)** | **Minimum pulley diameter (mm) 4 pole** | **6 pole** |
|---|---|---|---|
| D80 | 0.37 / 0.55 / 0.75 | 71 | 71 |
| D90S&L | 0.75 / 1.10 / 1.50 | 71 | 71 |
| D100L | 1.50 / 2.20 / 3.00 | 71 | 71 |
| D112M | 2.20 / 4.00 | 90 | 71 |
| D132S | 3.00 / 5.50 | 90 | 85 |
| D132M | 4.00 / 5.50 / 7.50 | 112 | 95 |

**Table 13-4 Minimum pulley diameters**

### Power per Belt

The amount of power that can be transferred depends on the thickness of the belt (whether it is an SPZ, SPA, Z or A for example) and also on the size of the smallest pulley. Larger pulleys transmit more power because there is more contact area with the belt and less chance of it slipping. Wedge belts can transmit more power than V-belts. The power that can be transmitted by one belt is shown for different sizes of pulley and belt in Table 13-5 and Table 13-6

| **Z** | Rated Power (kW) per belt for small pulley of various pitch diameters (diameter in mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| **rpm** turbine shaft | **71** | **80** | **85** | **90** | **95** | **100** | **106** |
| **1000** | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 |
| **1500** | 0.9 | 1.1 | 1.3 | 1.4 | 1.5 | 1.7 | 1.8 |
| **3000** | 1.5 | 1.9 | 2.1 | 2.3 | 2.5 | 2.8 | 3.0 |

| **A** | Rated Power (kW) per belt for small pulley of various pitch diameters ( diameter in mm) | | | | | | **B** |
|---|---|---|---|---|---|---|---|
| **rpm** turbine shaft | **90** | **100** | **112** | **125** | **132** | **140** | **140** |
| **1000** | 1.1 | 1.4 | 1.8 | 2.1 | 2.3 | 2.6 | 2.9 |
| **1500** | 1.5 | 1.9 | 2.4 | 2.9 | 3.2 | 3.5 | 3.9 |
| **3000** | 2.3 | 3.0 | 3.8 | 4.6 | 5.0 | 5.5 | 5.3 |

**Table 13-5 Power per belt tables for V-belt drives**

| SPZ | Rated Power (kW) per belt for small pulley of various pitch diameters ( diameter in mm) | | | | | | |
|---|---|---|---|---|---|---|---|
| **rpm** turbine shaft | **71** | **75** | **85** | **95** | **112** | **125** | **140** |
| **1000** | 0.8 | 0.9 | 1.2 | 1.4 | 1.9 | 2.2 | 1.7 |
| **1500** | 1.1 | 1.3 | 1.6 | 2.0 | 2.7 | 3.2 | 3.7 |
| **3000** | 1.8 | 2.1 | 2.8 | 3.5 | 4.7 | 5.5 | 6.4 |

| SPA | Rated Power (kW) per belt for small pulley of various pitch diameters (mm) | | | | | | SPB |
|---|---|---|---|---|---|---|---|
| **rpm** turbine shaft | **90** | **100** | **112** | **125** | **132** | **140** | **140** |
| **1000** | 1.4 | 1.8 | 2.3 | 2.9 | 3.2 | 3.5 | 4.1 |
| **1500** | 1.9 | 2.5 | 3.2 | 4.0 | 4.5 | 5.0 | 5.5 |
| **3000** | 2.9 | 4.0 | 4.7 | 6.7 | 7.4 | 8.2 | 8.5 |

**Table 13-6 Power per belt tables for Wedge belt drives**

**Single-belt drives or multiple-belt drives**

More than one wedge belt is often used to increase the power that can be transferred using a pulley of fixed diameter. However, for pico hydro applications it is recommended that only single-belt drives are used. This is for the following reasons:

- There is usually no cost saving with multiple belt systems at this power range.
- If more than one belt is required, then the belts must be very carefully 'matched' (i.e. be exactly the same size) If there is any difference in the size then this can cause one of the belts to fail more quickly.
- If one belt breaks, it is usually good practice to replace all the belts at the same time. A multiple belt system cannot be run if one or more or the belts is missing so multiple-belt systems have the same maintenance requirements and reliability as single-belts systems.
- Coupling and uncoupling of the turbine shaft from the mechanical load is more difficult with multiple belt systems.
- One belt simplifies the selection of the best pulley combination.

## *13.6 Procedure for choosing pulleys and belts:*

### STEP 1

Find the required pulley ratio:

**Speed ratio=** turbine shaft rpm / load shaft rpm

### STEP 2

Look at 'Power per Belt' tables (Table 13-5 and Table 13-6). Select the minimum pulley diameter and belt type suitable to deliver the required power. (Check Table 13-4 to make sure that at least the minimum pulley size for the generator is used) The belt tables include a service factor of 1.1 assuming that the load will be in use for 10 hours a day or less. For further information on sizing, consult Appendix C.

### STEP 3

Select another pulley from those available to give the speed ratio required to within ±10%. If it is not possible to obtain the correct ratio using the pulley sizes that are locally available, look at the power per belt tables again and make another selection, using the next pulley size up for the smallest pulley.

### STEP 4

Calculate the required belt length using the approximate centre distance (see Figure 13-7) and diameters of the two pulleys.

$$L = 2C + \frac{(D-d)^2}{4C} + 1.57(D+d)$$

where:

L= pitch length of belt in mm

C= centre distance in mm

D= pitch diameter of large pulley in mm

d= pitch diameter of small pulley in mm

In order to determine the centre distance required for, available belt lengths and pulley combinations, use the following formula:

$$CentreDist. = A + \sqrt{A^2 - B}$$

$$where$$

$$A = \frac{L}{4} - 0.3925(D+d)$$

$$and$$

$$B = \frac{(D-d)^2}{8}$$

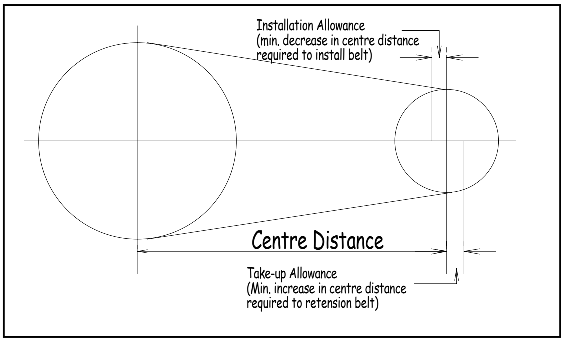



**Figure 13-7 Measurement of centre distance**

**Example** **Selection of suitable belt drives**

**1) What is a suitable pulley and belt combination if the following is known?**:

| | |
|---|---|
| Power to be transmitted | = **3.6 kW** |
| Speed of turbine shaft | = **1500 rpm** |
| Speed required by load shaft | = **550 rpm** |
| Approximate centre distance | = **800mm** |
| Maximum Usage | = **10 hrs per day** |

**Step 1** Pulley ratio = Turbine speed / load speed

= 1500 / 550

= 2.73:1

**Step 2** Design Power = Load power + 10%

= 3.6 kW + 0.36 kW

= 4.0 kW

**Step 3** Select belt and pulley from Table 13-5 and Table 13-6

The closest match to this power requirement is a SPA belt using a 125mm diameter pulley on the turbine shaft. The power per belt is 4.0 kW (at 1500 rpm ).

**Step 4** The diameter of the driven pulley can also be calculated: A ratio of 2.73 is required and the turbine shaft pulley is 125mm diameter

Pulley diameter required = 125 x 2.73 = 340mm

The nearest size to this is 315mm.

The ratio is now 315/125=2.52

This gives a load speed of 1500/2.52=595rpm

If this is acceptable then use this combination. If not then repeat the procedure using a different pulley size or different belt.

**Step 5** What belt length is required for a centre distance of approximately 800mm?

$$L = 2C + \frac{(D-d)^2}{4C} + 1.57(D+d)$$

L= 2*800+(315-125)$^2$/4*800 + 1.57(315+125)

L= 2302. A belt of 2300mm will be a suitable length.

The new centre distance can now be calculated using a belt of 2300mm

$$CentreDist. = A + \sqrt{A^2 - B}$$

where

$$A = \frac{L}{4} - 0.3925(D+d)$$

and

$$B = \frac{(D-d)^2}{8}$$

New Centre distance = 799mm (A=402.3, B=4512.5)

**2) What are the centre distance adjustments which are required for belt installation and re-tensioning?**

Consulting Table 13-7for an SPA belt of length 2300mm:

a) For installation : a reduction of centre distance by at least 25mm should be possible.

b) A minimum take-up allowance of 40mm in addition to centre distance will allow the belt to be re-tensioned if it stretches.

**Further Questions:**

1) What combination of pulleys and belt would be suitable to transmit 2kW between the following turbine and load shaft:

Turbine shaft speed = 1500rpm Load shaft speed = 2000 rpm Usage for a maximum of 3 hours per day.

2) A SPZ belt of length 1500mm. Is this suitable for transferring a mechanical load of 1kW? The centre distance is approximately 600mm.

### *13.7 Belt tensioning and supporting fixtures*

Correct tensioning of belt drive is important for reliability and efficiency. Under-tensioning creates slippage. This generates excessive heat that shortens the life of the belt. Over-tensioning also shortens belt life and increases the load on all the bearings. The life of the bearings will be reduced if the load on them is too high. Some means of adjusting the centre distance (the distance between centre of the two shafts) is required for installation of the belt and to adjust the tension. The tension can easily be measured using a spring balance. This procedure is described in Appendix C with methods for allowing the tension to be adjusted.

| Belt Pitch Length (mm) | Installation Allowance (mm) | | | Take-up Allowance (mm) |
|---|---|---|---|---|
| | Z SPZ | A SPA | B SPB | |
| **410 to 530** | 20 | | | 5 |
| **530 to 840** | 20 | 25 | 30 | 10 |
| **850 to 1160** | 20 | 25 | 30 | 15 |
| **1170 to 1500** | 20 | 25 | 30 | 20 |
| **1510 to 1830** | 20 | 25 | 30 | 25 |
| **1840 to 2170** | 20 | 25 | 30 | 30 |
| **2180 to 2830** | 20 | 25 | 30 | 40 |
| **2840 to 3500** | 20 | 25 | 30 | 50 |
| **3520 to 4160** | 20 | 25 | 30 | 60 |
| **4170 to 5140** | 20 | 25 | 30 | 70 |
| **5220 to 6150** | | 25 | 30 | 65 |

**Table 13-7 Installation and Take-up Allowances (see Figure 13-7)**

| Type of Machine | Speed (rpm) | Power required h.p. | kW |
|---|---|---|---|
| **Milling** | | | |
| 200mm | 600 | 3 | 2.2 |
| 225 | 550 | 4 | 3.0 |
| 280 | 550 | 6 | 4.2 |
| Thresher 450mm dia. drum | 1100 | 4-5 | 3.0-3.6 |
| **Woodworking** | | | |
| Circular Saw dia. 200mm | 2800 | 1 | 0.75 |
| Band saw wheel dia. 300mm | ------ | 1 | 0.75 |
| Hand Feed Planer (surfacing only 600mm width of blade) | 3000 | 1 | 0.75 |
| Centre Lathe ( Med. Duty, 160mm) | 500-2000 | 0.5 | 0.375 |

**Table 13-8 Examples of mechanical loads and their typical requirements**

# 14 THE DISTRIBUTION SYSTEM



**Figure 14-1 Installation of a village distribution system (Kushadevi, Nepal)**

## 14.1 Introduction

The distribution system is the name given to the cables, poles and associated equipment that deliver the electricity produced by the generator to the houses and other buildings where it is required.

The cost of a village distribution system is likely to be one of the largest costs of the whole pico hydro project. This cost can however, be minimised by careful design.

The methods described in this section are limited to the design and installation of single-phase AC distribution systems for village electrification. For further information about AC electricity, consult Appendix A.

For more detailed information on distribution systems consult the Mini-Grid Design Manual (ESMAP Technical Paper 007). This excellent reference is currently available free of cost from the World Bank.

The design of the distribution system needs to satisfy the following criteria:

- all the consumers who are to be included in the electrification scheme will receive a connection
- a voltage drop of 10 % or less will be maintained at the furthest point from the generator
- the distribution system will operate safely and reliably without presenting a danger to people.

### 14.2 Drawing a Plan

The first step in the design of the distribution system is to draw an accurate, scale plan of the area. The water source (stream) will be represented, in addition to the houses that will be connected to the generator.

It is important that this plan is drawn to scale. This means that the distances between each of the houses and the stream need to be measured accurately and drawn in the correct position. If this plan is wrong then it will be difficult to work out how much cable will be needed and where to route the cable.

The following steps enable the plan to be produced:

STEP 1

On a piece of paper, mark North, East, South and West.

STEP 2

Indicate with an arrow at the side of the paper the general direction uphill. If the village crosses a valley, draw two arrows pointing in different directions to show the opposite sides.

STEP 3

Draw the stream from which water for the hydro scheme will be taken.

STEP 4

Draw in carefully, any roads, footpaths, rivers, woods and other prominent landmarks.

STEP 5

Decide on the layout of the scheme (Page 6-1). Mark the proposed locations of the intake, the forebay or reservoir, penstock and the powerhouse. Write on the length of the penstock.

STEP 6

Mark the position of four houses that are going to be connected to the distribution system, choosing the ones that are furthest away from the generator. Choose one in each direction, North, East, South and West, if possible and use a compass. These are going to form the reference points for the system layout. Sometimes there are no houses in one or two directions from the generator. If this is the case, choose three or four houses that are both furthest away from the generator and from each other.

STEP 7

Number each of the reference houses 1,2,3,4. Then draw in all other houses that will be connected to the generator. Try and get their location on the plan as accurately as possible. Do not connect up the houses with lines representing cables at this stage.

STEP 8

Walk in as straight a line as possible from the proposed location of the powerhouse to each of the reference points in turn. Count the number of paces and calculate the exact distance in metres by first measuring the length of 20 normal paces. Mark these distances on the map and their compass bearings. Include the distance from the generator of any intermediate houses that lie on or very close to the path that is walked.

STEP 9

The map will be improved if the rough sketch is redrawn a couple of times. Try to get the relative positioning of the houses correct and estimate the distances between them. This map will be more valuable if care is taken to draw it accurately. Walk around the village several times, if necessary, and show your sketch to other people to get their opinion. Add as much detail as possible particularly about distances between the houses.

STEP 10

Draw the map out one more time, but this time draw it to scale. Spending time at this stage to plan carefully could save large amounts of money on cable. Draw in the penstock, powerhouse, and four reference houses.

STEP 11

Now add the other houses, carefully. Be sure to position each one in the correct position relative to the others.

STEP 12

Once the final copy of the map has been drawn in this way, it is time to consider the best method to connect the houses to the generator.
Note: Hand-held GPS (Global Positioning Systems) are becoming widely available at prices of about $200. These can make drawing the plan much easier.

### *14.3 Layout Patterns*

Look at the following examples of distribution layouts and consider which is most like the layout of houses on the plan which you have drawn.

**A: Houses grouped together with the generator some distance away**
This is a very common situation with hydro-power schemes. Consider if it is possible to reposition the powerhouse using the suggestions in Section 6 so that the long distance to the village is reduced. Obviously the cost saving in cable will need to be balanced against the additional expense of extending the penstock or the canal to the forebay.

**B Radial spread; central powerhouse with houses in all directions**

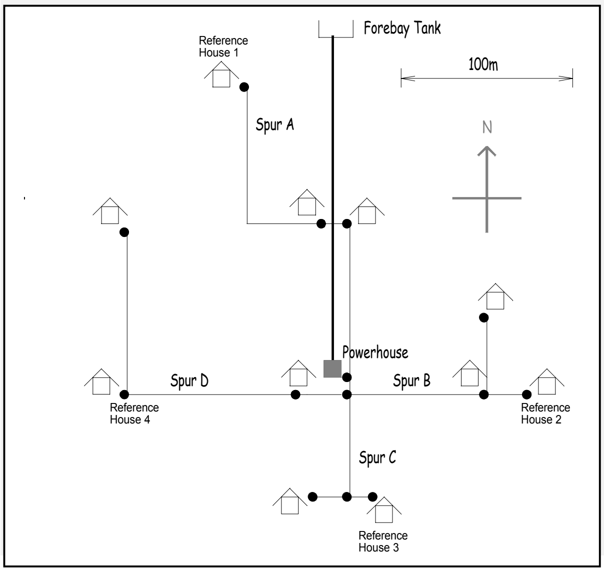



**Figure 14-2 Radial spread distribution system**

This is the most convenient arrangement. If the powerhouse is in the middle of the houses, then the distribution system can be kept as short as possible. Running cables to houses in different directions from the powerhouse also has the advantage that the network can be maintained and repaired more easily. Switches can be used to isolate the individual spurs. These can be located centrally in the powerhouse. MCB's are suitable for this purpose (see Section 0). The cable diameter required for the main distribution lines will be smaller because the total load current is divided amongst several spurs.

**C: Random distribution in one or two directions**

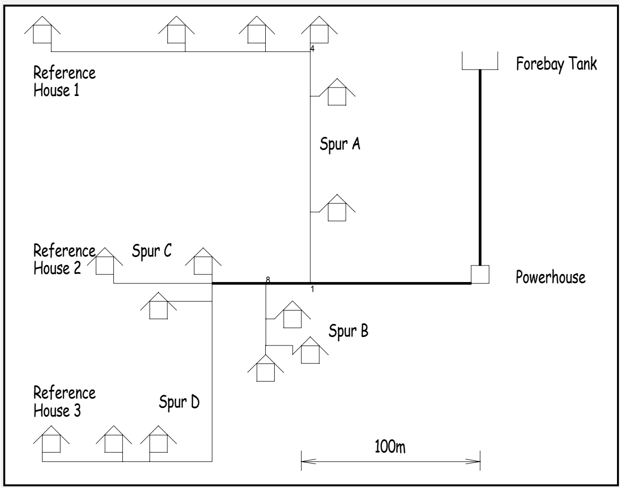



**Figure 14-3 Distribution system in two directions**

The shortest route to connect up all of the loads to the generator may be obvious on a small scheme. On larger schemes, carefully consider different routes for connecting the houses.

## *14.4 Selecting Cable for Village Electrification*

The cable required to supply the houses with electricity, will be a significant part of the total scheme cost. It is therefore important that the most cost-effective cable is chosen.

**Key issues**

When selecting cable for village electrification projects, the key issues can be summarised as follows:

- **Cost**: Both the direct cost of the cable and the indirect cost of poles and fittings need consideration. The indirect costs are usually greater if non-insulated cable is used because the conductors have to be held under the correct tension to keep them spaced apart and insulators used so that they do not contact with the poles.
- **Voltage drop**: The voltage at the end of the cable will be different from that at the generator. This is mainly because the cable has a resistance. The resistance depends on the cable thickness and the type of conducting material from which the cable is made (e.g. copper or aluminium).
- **Lifetime / reliability**: The cable will be exposed to the weather throughout the year. Some of the factors which affect the life and reliability are diameter, conductor material, type of insulation and the number of strands which are wound together to make the complete cable. Stranded cable should always be chosen, the more strands the better.
- **Safety**: The safety of local people can be affected by the choice of cable. Cable with a tough insulation such as cross-linked polyethylene is safest. Pole design and correct tensioning also affects safety particularly when using non-insulated cables.
- **Security**: It is easier for people to make illegal connections to non-insulated cable.

**Types of cable**

The conducting material that the cable is made from is likely to be either copper or aluminium.

**Copper Cable:**

Copper cable is made of separate strands of wire. The number of strands and the thickness of each, determine the overall resistivity and cost. The number of strands vary but typical values for small cables are 3,7,16,24,30,32 and 50 strands. Different copper cables are identified by a numbering system. The first is the number of wire strands in the cable and the second is the gauge which gives a measure of the thickness of each strand. Cable number 7,16 for example, has seven wires of 16 gauge.

There are two common gauge systems: SWG (Standard Wire Gauge) and AWG (American Wire Gauge). They use different gauge systems for particular cross-sectional areas (CSA), so care should be taken to ensure that the two systems are not confused.

Hand drawn copper is better than the annealed (flexible) copper found in most equipment wire because it has approximately 60% more strength.

However, insulated annealed copper equipment wire has been used on many pico hydro schemes in Nepal because it is widely available in convenient sizes. The only reported problem has been where a small, three-stranded cable broke inside the insulation which made the fault difficult to locate. Firstly, it is recommended that cables with a larger number of strands are used to minimise this risk. Equipment wire is not designed to support its own weight over long spans. To prevent the cable from stretching a galvanised steel or iron support wire should be used around which the cable is wrapped. Most insulated copper cable has PVC insulation which is less weatherproof than the XLPE (Cross-linked Polyethylene) insulation which is commonly found on cables intended for outdoor use.

**Note on PVC cable insulation**

Some types of PVC cable insulation degrade in sunlight. Also it becomes brittle at sub-zero temperatures. If PVC coated cable is used for the distribution system, the operator should periodically check the cable for signs of degradation such as cracks in the insulation. If necessary, sections of the cable should then be replaced. Dark-coloured insulation usually degrades less than lighter colours.

**Aluminium Cable:**

1. **ACSR** Aluminium cable is commonly reinforced with galvanised steel. This is referred to as ACSR (Aluminium Cable Steel Reinforced). It is popular because of its relatively low cost and high strength. The aluminium cables are given names that correspond to a particular equivalent CSA of copper. This allows different cables to be compared in terms of their resistance.
2. **ABC**. Aerial Bundle Conductor is aluminium alloy cable with XLPE insulation. This is recommended where available as it is strong, highly resistant to sunlight and usually very cost-effective.
3. **Aluminium equipment wire** is also available in some areas. This is low cost but is <u>not suitable</u> for use as distribution cable because of its low strength.

## *14.5 Distribution Poles*

**Key issues**

The important issues regarding selection of distribution poles are as follows:

- **Cost**: The cost of the poles may be quite substantial or very little and depends on whether local materials are suitable or if poles must be purchased and transported from further away.
- **Lifetime**: The materials used and how the poles are installed and maintained will affect how long they last.

- **Safety**: Safety depends on factors such as the material and method of installation as well as the pole height.
- **Weight**: Poles made from heavy materials such as concrete are difficult to transport and handle.

Poles can be a very expensive part of the distribution system, and as a consequence the cheapest option is often taken, even though this may prove to be more expensive in the long term due to the need for frequent replacement.
Wood is usually the preferred choice for poles, although reinforced concrete and steel are sometimes used where wood is scarce. Properly treated and maintained quality wood poles have a life of at least 40 years. However, poles made from unseasoned and untreated wood can fail in less than 12 months, particularly in hot and humid areas. Poles must be seasoned (dried) and treated. In dry climates, seasoning can be done by natural air circulation, but kiln drying or steam conditioning is required in humid climates. To properly treat poles, pressure or hot/cold soak methods are used to force creosote or other preservatives into the wood. Unfortunately these methods are not well suited for treating a small number of poles due their complexity and expense. A cheap approach is to paint or soak the lower portion of the pole using creosote or old engine oil, though this is much less effective than properly treating the complete pole.

An effective low-cost method with bamboo poles is to place the cut ends of freshly-felled bamboo in a container of preservative and to leave them in a sunny place for 4 – 5 days. Natural transpiration will cause the preservative to diffuse from the base of the bamboo to the leaves.For more information on poles and pole treatment consult the Mini-Grid Design Manual.

Sometimes, the main trunk of a living tree is used to support cables in rural areas. Only healthy, mature trees should be used and the foliage should be cleared to at least 1.5m in all directions around the cable. Also the lower branches should be removed to discourage children from climbing the tree. Regular checks should be made to ensure that further growth is not interfering with the cables. However, in lightning prone areas, live trees should not be used to support cables (see Section 16). A direct strike on a tree that has been used to support part of the distribution system will cause a large voltage to be conducted to the cables. This can result in significant damage to equipment and injury to people.

## 14.6 Installation of the Distribution System

### Pole Installation

Distribution poles should be spaced between 25 metres and 40 metres apart.

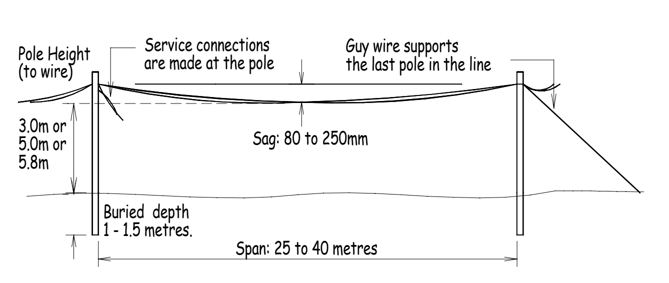



**Figure 14-4 Required installation practice for distribution poles**

The first and last poles in a line should be stayed with guy wire. Any poles on corners or bends should also be stayed. Minimum ground clearances should be according to national standards. If there are no standards available then the minimum ground clearance is 3.0m over open ground, 5.5m along motorable road and 5.8m across motorable road. The poles should be spaced approximately every 25m and at a maximum of 40m. Note different requirements for poles over 5 meters in Table 14-1. Since bamboo poles of appropriate diameter are unlikely to be available for poles which are 5 metres and above, hardwood poles should be used.

| **Ground clearance** | 3.0m | 5.0m | 5.8m |
|---|---|---|---|
| **Min. pole dia.** | 100mm | 125mm | 125mm |
| **Buried Length** | 1.0m | 1.5m | 1.5m |
| **Maximum span** | 40m | 35m | 35m |
| **Material options** | Bamboo or hardwood | hardwood | hardwood |

**Table 14-1 Requirements for distribution poles**

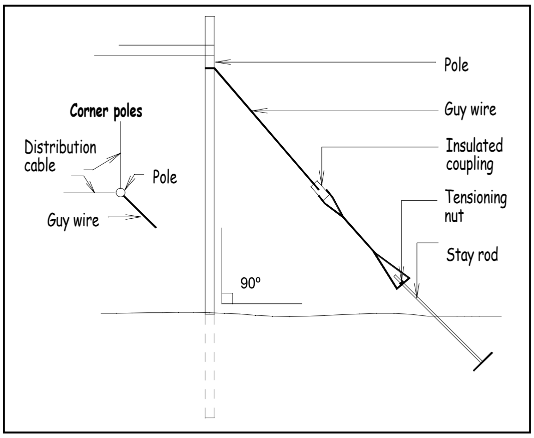



**Figure 14-5 Use of guy wires to support poles and help tension cables**

## Cable installation

**Sag**: The distance between the poles determines the amount of sag that is required. The sag is not critical for insulated cables providing that a minimum sag of 80mm is allowed to prevent excessive tensioning. The maximum sag for insulated cables is 250mm.

For non-insulated conductors, it is important to measure the sag more carefully in order to prevent the risk of conductors making contact with each other especially during windy conditions. The requirements for sag of ASCR cables with various pole spans are presented in Table 14-2.

Cables expand in hot weather and therefore the sag is greater. When installing cables in cold weather, aim to achieve close to the minimum sag, and in hot weather aim for close to the maximum sag.

| Span (m) | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|
| Min. sag (mm) | 20 | 30 | 45 | 50 | 75 |
| Max. sag (mm) | 70 | 100 | 150 | 200 | 250 |

**Table 14-2 Sag requirements for ACSR**

**Sighting method of sag measurement**

A method of measuring the cable sag is to using straight wooden boards nailed to the poles as shown in Figure 14-6. The boards are fixed at the correct height for the cable sag and sighted from another pole one span back. The cable is tensioned until the sag is aligned with the boards as shown. One advantage of this method is that if the wooden boards are left in place, it is easy to determine if the cable sag increases over time, indicating if adjustments are required. This is likely, as cables will stretch over time with their own weight.

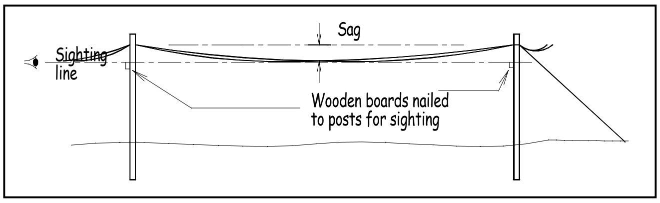



**Figure 14-6 Sighting method of sag measurement**

For long pole spans, a 'return wave' method can be used to obtain the correct sag. This is described in the Mini-Grid Design Manual (see Page 20-1).

## Lengthening cables

The cable lengths can be joined by using crimp-type cable connectors and by twisting stranded cables together (see Figure 14-7)

Crimp type cable connectors, consist of a compressible metal tube (or splice) that slides over the ends of the conductors and is compressed (crimped) using a special tool. It is essential to use connectors that are specified for the diameter of cable used and to use a crimping tool suitable for the size and type of connector. If the correct connector and the right tool are used the connector should be able to support the full tension of the cable. The connectors are cheap, though for cables above 6mm$^2$ the tools are quite expensive.

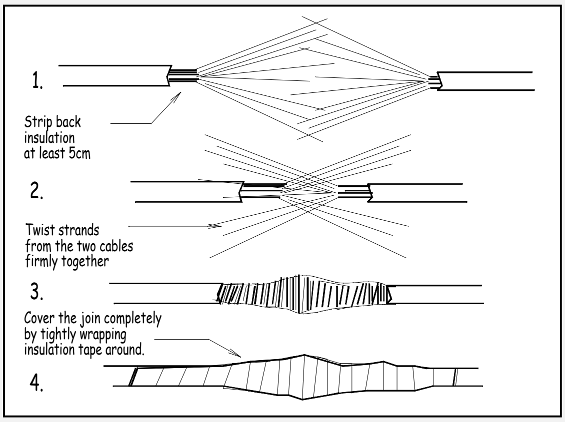



**Figure 14-7 Twisting stranded cable**

Insulated copper cables can be joined by twisting. However, the cable joins must never take the tension of the cable. Both cables should be wrapped around the pole or another fixture such as a bracket to prevent this. In this way, a loop of slack wire can be formed where a connection is made.

Identifying the live and the neutral can be a problem if conductor with the same colour insulation is used for both. If different coloured insulation is unavailable, use coloured insulating tape at the beginning and end of cable coils used for the live line. This will allow it to be easily identified during installation.

### Connecting spurs to the main conductor

If a copper cable is to be connected to an aluminium cable, special bimetallic connectors are required that separate the conductors to prevent electrolytic attack on the aluminium conductor.

An alternative method of joining the cables is shown in Figure 14-8. If the distribution cable is insulated then the insulation must be carefully stripped back. Solder should be applied to the join using a soldering iron (preferably gas powered) and then the join should be re-insulated with tape.

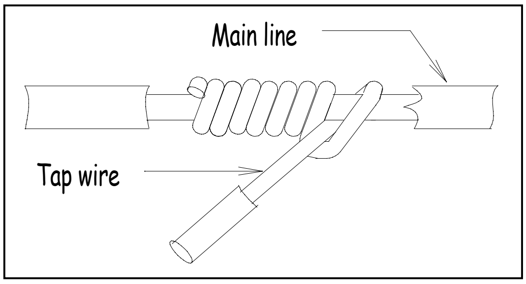



**Figure 14-8 Suitable method of connecting tap wires to distribution cables**

### Service Connections

The service cable runs from the house to the main distribution line. A good, weather-resistant, electrical connection is required, between the distribution system and the service cables. The methods described for connecting spurs to the main line can be used for connecting the service cables.

A convenient and more rapid method of connecting the copper service cable to insulated copper conductor is to use a small, plastic connecting device called a 'tap splice' shown in Figure 14-9. These are available in sizes for various cable diameters between 0.5mm$^2$ and 6mm$^2$. They provide a low cost and safe alternative to splicing cables. Insulated cable need not be stripped back as an electrical contact with the conductor is made when the tap splice is clamped shut with pliers. It is essential to use tap splices of the correct size to minimise damage to the cables and ensure a good connection.

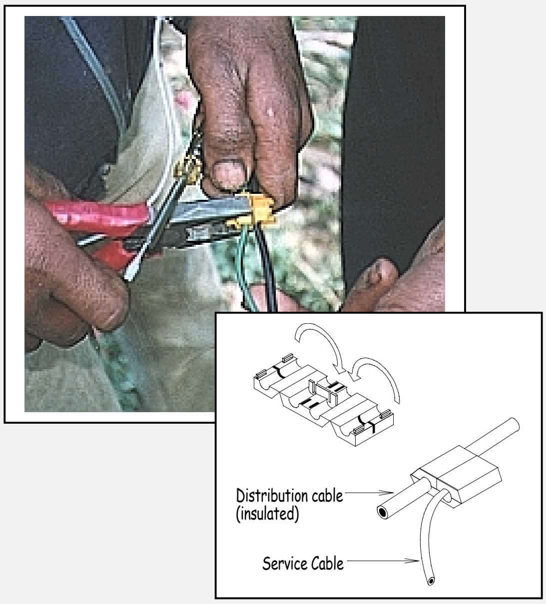



**Figure 14-9 and Figure 14-10: Use of a tap splice to connect the service cable to an insulated distribution cable**

## *14.7 Protection of the distribution system*

### Lightning

It is very important that consideration is given to protecting the distribution system from lightning. Even indirect strikes some distance away from the cables can cause very high voltages to be induced in the cable that can damage equipment. Consult Section 16.3 and incorporate the recommended measures at the initial stages of designing the distribution system.

### Excess Current

The cables are protected from high currents (these could be caused by a short circuit) by either a Motor Protection Switch or MCB inside the controller in the powerhouse. The minimum cable sizes are determined by the current rating of this protection although cable sizes will usually be larger to minimise the volt drop (see Section 14.8). If several spurs begin at the powerhouse, it is preferable to connect an MCB for each spur so that the individual sections can be isolated if necessary. Additional MCBs may be required if the current carrying capacity of the smallest cables used at the ends of the distribution system are less than that of the existing MCBs.

**Installation procedure for distribution system**

**Step 1**: Using the guidelines for pole spacing and the map of the distribution system, work out how many poles will be required and where they should be positioned.
**Step 2**: Calculate how many poles will require supporting with guy wires (including corner poles, see Figure 14-5).
**Step 3:** Avoid routing distribution cable along exposed ridges where the risk of damage from wind and lightning strikes is greatest.
**Step 4:** Dig holes and lay out poles along intended route
**Step 5:** Erect all poles along chosen route except for those that will be supported by guy wires.
**Step 6:** Beginning at the powerhouse, and installing the thickest first, suspend the cable from each pole in turn. If non-insulated cable is used, ensure that cables are correctly fitted to insulators.
**Step 7:** Use people to pull the cable taught, achieving approximately the correct tension while attaching the cable to each pole.
**Step 8**: At the end of a run of poles, dig a hole and fix the end pole in position with a guy wire to support it.
**Step 9**: Measure the sag and adjust tension as required in order to set within the correct limits.
**Step 10**: When distribution system is complete, connect service cables. Leave a loop of slack cable where the cables enter the building. This prevents rainwater from running down the cable into the building.

### *14.8 Sizing the cables*

The cables in a distribution system are likely to be different diameters in different places. This is because some parts of the system will carry more current than others parts and the cables will therefore need to be larger in diameter. It would be a waste of money to use large cables on branches of the distribution system where only a few houses with small loads are connected.

| CSA of copper cable | Current capacity (Amps) |
|---|---|
| 1.0 $mm^2$ | 17A |
| 1.5 $mm^2$ | 22A |
| 2.5 $mm^2$ | 30A |
| 4.0 $mm^2$ | 40A |
| 6.0 $mm^2$ | 51A |

**Table 14-3 Current carrying capacity of single core insulated copper cables in free air.**

By calculating the **voltage drops** across the distribution system, it is possible to find the best sizes of cable to use.

**Explanation of voltage drops:**
The consumer voltage drop is the difference in voltage between the generator voltage and the voltage in a consumers house. This difference is due to the resistance and inductance of the cable through which the electric current flows. The volt drop due to inductance is usually small and for simplicity can be neglected, enabling the volt drop to be calculated using Ohms Law:

**Volt (drop) = Current x Resistance (of cable)**

A small volt drop is acceptable. If the voltage in a house is too low however, electrical loads that are connected (e.g. tube lights) will not work properly. An acceptable minimum voltage is 6% below the national voltage. For example, if the national voltage is 220V, for a 6% volt drop the consumer voltage would be:

$$220 - (0.06 \times 220) = 206.8 \text{ V}$$

At 207 V, electrical loads designed for 220V will still function normally. Houses that are furthest from the generator will have the largest volt drop because the current has to flow through more cable to reach them. Choose cables that ensure a minimum voltage of 6% below national voltage at the furthest houses. This keeps the distribution system cost to a minimum and ensures that voltages in other parts of the system are acceptable.

Example: Calculating % volt drop:

Generator voltage = 220 Volts
Cable resistance = 0.0061 Ohms per metre
Length of distribution = 150 meters
Length of Cable = 300 metres
Load Current = 5 Amps

Volt drop = Current x Total resistance of cable
= 5 x (0.0061 x 300)
= 9.15 Volts
% volt drop
= 9.15/220 x 100
= 4.1%

Calculating the best size of cables for a distribution system increases in complexity, the more houses are connected. The best method is to treat each individual branch or spur separately. However, this is very time-consuming because of the number of separate calculations which must be made. Computer programmes allow this to be done much more rapidly.

**Note: Save Money on Cable by Raising the Generator Voltage**
If the voltage at the generator can be raised to the upper voltage limit (i.e. national voltage + 6%) then even greater savings in the cost of the distribution cable may be possible. The voltage range across the system is now +6% of the nominal value at the generator and -6% of the voltage at the terminals of the furthest house. A total volt drop across the cables of 12% is therefore possible. This means that a cable of smaller diameter can be used while still keeping the volt drop within acceptable limits.

Two manual approaches to sizing the distribution cable based on the volt drops are described below. Both methods make assumptions about the position of the loads. This helps to reduce the number of calculations that are necessary.

| **Cable type** | **CSA strand $mm^2$** | **CSAcable $mm^2$** | **Ohms / 1km** | **Cost: US$/m** |
|---|---|---|---|---|
| **Insulated Copper** | | | | |
| 3,20 | 0.6567 | 1.9701 | 8.63 | 0.09 |
| 7,22 | 0.397 | 2.779 | 6.12 | 0.15 |
| 7,20 | 0.6567 | 4.5969 | 3.70 | 0.19 |
| 7,18 | 1.1675 | 8.1725 | 2.08 | 0.33 |
| 7,16 | 2.0755 | 14.528 | 1.17 | 0.69 |
| **Aluminium (ACSR) CSA in $mm^2$ copper equivalent** | | | | |
| Squirrel | - | 13 | 1.31 | 0.16 |
| Gopher | - | 16 | 1.06 | 0.20 |
| Weasel | - | 20 | 0.85 | 0.24 |
| Rabbit | - | 30 | 0.57 | 0.37 |
| Dog | - | 55 | 0.31 | 0.67 |
| Add US $0.11 per metre to ASCR for average cost of D irons and insulators (not required for insulated cable) | | | | |

**Table 14-4 Sample of cable specification from Nepal**

**Method 1: Consumer loads clustered together at the end of the distribution cables**
This method will tend to oversize the cable because the current is slightly overestimated. The cable is therefore likely to be more expensive than necessary. However, it is the most straightforward method for a rapid design of distribution system.

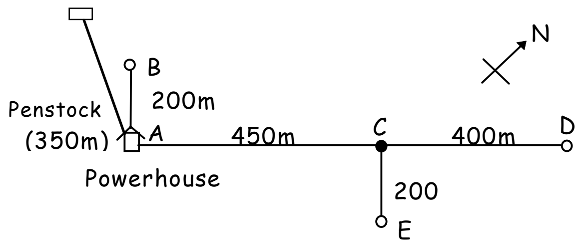



**Figure 14-11 Distribution system with load "clusters" at the end of spurs**

Consider the simple distribution system in Figure 14-11. The loads have been grouped together at B, D and E and the distances from the powerhouse A and from node C, have been carefully measured. All that remains is to size the cable for the distribution system to give the lowest acceptable voltage at B, D and E and therefore to minimise the cost.

What is the best cable to use if
- the load at each point (B,D and E) is 1kW single phase,
- the nominal voltage is 220V, and
- the power factor is 1 (for explanation of power factor, see Appendix A)

**A-B**
Current (I) flowing along A-B (using I=P/V)
1000/220 = 4.545Amps

**a) Try 7,16 insulated copper cable**. (see Table 14-4)
Total length of conductor required is 2 x 200m = 400m. Resistance (Ohms per metre) = 0.0012
Cable Resistance = length x resistance per metre
= 400 x 0.0012 = 0.48 Ohms
Cable Cost = 400 x 0.69 = US **$276**
Voltage Drop = I x R = 0.48 x 4.545 = **2.18V**
% Volt Drop = (2.18/220)*100 = 1%.

Since we are aiming for a total drop of 12% of the nominal value (see Note, P.14-8), this cable can clearly be reduced in diameter

**b) Try 7,22 insulated copper cable** (see Table 14-4)
Cable Resistance = 400 x 0.0061 = 2.44 Ohms
Cable Cost = 400 x 0.15 = US **$60**
Voltage Drop = 2.44 x 4.545 = 11.08V
Percentage volt drop is 5% which is still within the acceptable limits. Reducing the cable more than this becomes impractical because the cable strength will not normally be sufficient.

**A-C**

Although no load is directly attached to C the cable must be sized separately since the currents flowing are different from C-D and C-E. The voltage drop A-C must be added to the Voltage drop of C-D and C-E. The value at the end of the line must not exceed 12%.

**a) Try 7,22 insulated copper**
Cable Resistance = 900 x 0.0061 = **5.49 Ohms**
Cable Cost = 900 x 0.15 = US **$135**
Line Current = Load Connected / Nominal Voltage
= 2000 / 220 = **9.09 A**
Voltage Drop = 5.49 x 9.09 = **50 V**
Percentage voltage drop = 22.7% so cable diameter must be larger.

**b) Try Squirrel ACSR (see** Table 14-4)
Cable Resistance = 900 x 0.0013 = **1.17 Ohms**
Cable Cost = 900 x 0.16 = US **$144**
Line Current = Load Connected / Nominal Voltage
= 2000 / 220 = **9.09 A**
Voltage Drop = 1.17 x 9.09 = **10.63 V**
Percentage voltage drop = (17.2/220)*100 = 4.8 % must be added to voltage drop C-D and C-E

**C-D Try 7,20 insulated copper (see** Table 14-4)
Cable Resistance = 800 x 0.0037 = **2.96 Ohms**
Cable Cost = 800 x 0.19 = US **$152**
Line Current = Load Connected / Nominal Voltage
= 1000 / 220 = **4.54 A**
Voltage Drop = 2.96 x 4.545 = **13.45 V**
% voltage drop = (13.45/220)*100 = **6.1 %**
Total Voltage Drop A-D = 4.8 + 6.1 = **10.9 %**

**C-E Same as A-B (1kW load and 200m long)**
Voltage drop = **5%**
Cost of cable = US **$60**
Total Voltage Drop A-E = 5.0 + 6.1 = **11.1%**

**Cost Comparison**

The cost of this distribution system is compared.
**1) Using all 7,16 insulated copper = (**200 + 200 + 450 + 400)*2 = 2500 x 0.69
= US **$1725**
**2) Using all 'squirrel' ACSR=** 2500 x 0.16 + 1250 x 0.11 (0.11 = cost of D irons and insulator per meter along the section i.e. half the cable length)
= US **$537.50**
**3) Using mixed conductors as calculated above**:
A-B = US $60 (Cu)
A-C = US $144 + 450 x 0.11= US $193.50(ACSR)
C-D = US $152 (Cu)
C-E = US $60 (Cu)
Total for 3) = US **$465.50**

Clearly if the loads change, recalculation is required based on the new current value along each section. Although this process can be time consuming, particularly for more complex distribution systems, careful planning at an early stage will be rewarded with potentially significant savings in cost.

**Method 2: Equally Spaced Consumer Loads**

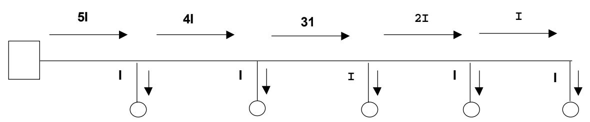



**Figure 14-12 Equally spaced consumers**

The second method of voltage drop calculation assumes that the loads connected to a particular branch of the distribution system are equally spaced along its length. This is slightly more complicated than the method shown above but is likely to give a more accurate picture of the expected voltage drop.

The current I, is assumed to be constant for each house. It is calculated by dividing the total available power (assuming a 6% power loss in the distribution system) by the nominal voltage and then by the total number of houses. Each house is assumed to have an identical load and to be spaced equally along a particular section of distribution line, as shown in Figure 14-12 The total voltage drop at the end of the line can be calculated as follows:

**Vdrop = (5+4+3+2+1) I.R1**

Where, R1 = cable length (i.e. 2 x distance between houses) x cable resistance per metre

Re-analysing the previous example in this way, and assuming that each 1kW load is actually 10 houses evenly spaced, and that the cable is used as calculated in Option 3 above (mixed conductors) then the voltage drops are as follows:

I= 100/220 = 0.4545

**A-B** : R1 = 2x200/10 x 0.0061 = 0.244

Vdrop = (10+9+8+...+1) x 0.4545 x 0.244
= 6.1V = **2.8%**

**A-C** : Same as before as no loads are connected in this section.
Vdrop = 1.17 x 9.09
= 10.63 V = **4.8 %**

**C-D** : R1 = 2x400/10 x 0.0037 = 0.296

Vdrop = (10+9+8+...+1) x 0.4545 x 0.296
= 7.4V = **3.3%**

**C-E** R1 = 2x200/10 x 0.0061 = 0.244

Vdrop = (10+9+8+...+1) x 0.4545 x 0.2.44
= 6.1V = **2.8%**

Reassessment of the cable requirements will be possible based on the above voltage drops which are much less than those calculated by the previous method.

Note: An Excel spreadsheet has been created to allow accurate design of village distribution systems with greater ease. Please contact the editorial address via email for a copy.
(Email address: phillip.maher@ntu.ac.uk )

## *14.9 Design of a distribution system to supply a workshop*

This section has been included to illustrate the approach to sizing and connecting motor loads to a small induction generator. The example used is for a workshop but the principles can be applied to other types of motor loads connected to a distribution system.

### Example

A particular village has a pico hydro site with the potential to produce 4.4kW of electrical power. The intention is to use the electricity for evening lighting. Some members of the community are also very interested in constructing a workshop to produce wooden furniture. This could potentially be very useful as it would provide a daytime load and add to the income generated from the pico hydro scheme.

The carpenters would ideally like to be able to use the following machines

- band saw
- plane
- lathe
- circular saw
- pillar drill
- hand drill
- grinding wheel

The community is aware that the mechanical power produced by the turbine is greater than the electrical power and it would be useful if the workshop machines could be driven directly using belt drives. Unfortunately the sides of the valley are steep and the flat area for building the powerhouse near the river is limited. In addition, access with timber for sawing into planks would be difficult if the workshop was in the same building. A flat area of land 200m uphill from the proposed generator site has been identified which would make a good location for the

workshop. However, this will mean using workshop machines that are driven by electric motors.
The carpenters would like to know the following:

1) Which of the machines listed above could be operated?
2) What would be the cost of a distribution cable from the generator to the workshop?
3) What other considerations are important?

**Answer**

**1) Which machines can be used?**

All the machines that are listed can be run using the power supplied by the pico hydro generator if they are selected carefully. Small, workshop tools are usually powered by single-phase motors. A single-phase supply is the simplest to generate and will therefore be the most appropriate to transmit the electricity from the generator to the workshop. Before sizing the supply cable, research the available workshop machines that run on single-phase power.
Electric motors up to a certain size only can be connected to small induction generators (see Section 13.3). It is important to know what the starting current requirements are for these machines so that the generator is not overloaded. Generally, non- of these machines are under load when first switched on. They will only be used when the normal operating speed has been reached. For this reason, they can be classed as low-starting torque loads and sized up to 20% of the supply capacity.

Supply capacity = generator capacity – power loss in distribution cable.

Assume that the power loss is 6% and then size the cable to deliver the power with no more than 6% volt drop.

Supply capacity = 4.4kW – 6% = 4.1kW

So, the largest motor which can be connected in to the workshop to power one of the machines listed is

20% x 4.1kW = 820W

For example, machines that have induction motors up to 1 horse power (750W) can be operated successfully using this generator.

Hand held power tools usually do not use induction motors and can often be sized up to 25% or more of the supply capacity. This would enable a 1kW hand-held drill for example, to be connected in the workshop.

**2) What is the cost of a suitable distribution cable?**

The distribution cable required is 200m in length. All of the load is at the end of the cable and a maximum voltage drop of 6% is permissible.

Assume that all the power produced by the generator, may be consumed by loads in the workshop. The motors are small in relation to the generator but their power factors are uncertain. Calculate the maximum current that the generator can supply at the rated voltage and use this to size the cable.

Maximum generator current (@240V)
= 4400 / 240 = 18.3Amps

The length of cable is 200m x 2 (phase and neutral) = 400m

From Table 14-4, and selecting Squirrel cable (smallest ASCR), calculate volt drop:

Cable Resistance = 400 x 0.0013 = 0.52 Ohms

Voltage Drop = 0.52 x 18,3 = 9.5 V

Percentage voltage drop = (9.5/240)*100 = 4 %

Cable Cost = 400 x 0.16 + 200 x 0.11
($0.11 = average cost of D-irons and insulators per metre of cable)
= US **$86**

**3) What additional considerations are there?**

Additional considerations are as follows:

- Do not purchase the workshop machines until the turbine and generator are installed and the electrical output is checked.
- Do not start the machines simultaneously as the combined power requirement may exceed the generator capacity and trip the overload protection in the powerhouse. The motors should be started on after another, waiting

for one motor to reach its running speed before starting the next.

- Power factor correct the motors as explained in Section 13.3.
- Each machine should be connected to the supply through a circuit breaker. This will protect the motor windings from high currents. Motor start MCB's should be specified and rated slightly higher than the normal rated current of the motor. Adjustable protective motor switches can also be used (see Figure 9-13). These allow the tripping current to be adjusted to the precise current rating of the motor for maximum overload protection. Use Table 14-5 as a guide for 240V supplies. Circuit breakers are not normally used for hand-held tools. These are protected by a consumer unit with a suitably rated MCB and a fused plug.

| Motor size | Amp range of MCB (240V) |
|---|---|
| 1/3 HP (250W) | 2 – 4 Amps |
| ½ HP (375W) | 2 – 4 Amps |
| 2/3 HP (500W) | 2 – 4 Amps |
| ¾ HP (560W) | 4 – 6 Amps |
| 1 HP (750W) | 4 – 6 Amps |

**Table 14-5 Protective motor switch ratings for different machine sizes**