

# CONTROL OF WIND TURBINES

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## INTRODUCTION

Wind turbines are optimized to produce maximum power output at the most probable wind speeds around 15 m/s, 33 mph, or 33 knots. It would be uneconomical to design them for operation at the improbable higher wind speeds.

It is necessary to limit the power output in high wind conditions on all wind turbines; otherwise a runaway turbine will be overloading its rotors, mechanical power train, as well as its electrical generator leading to catastrophic failure.

It is unavoidable, in order to protect the structural integrity of the wind turbine, to ignore the energy production potential of these improbable wind gusts and to provide power controls in modern wind turbines to stop the turbine when these occur.

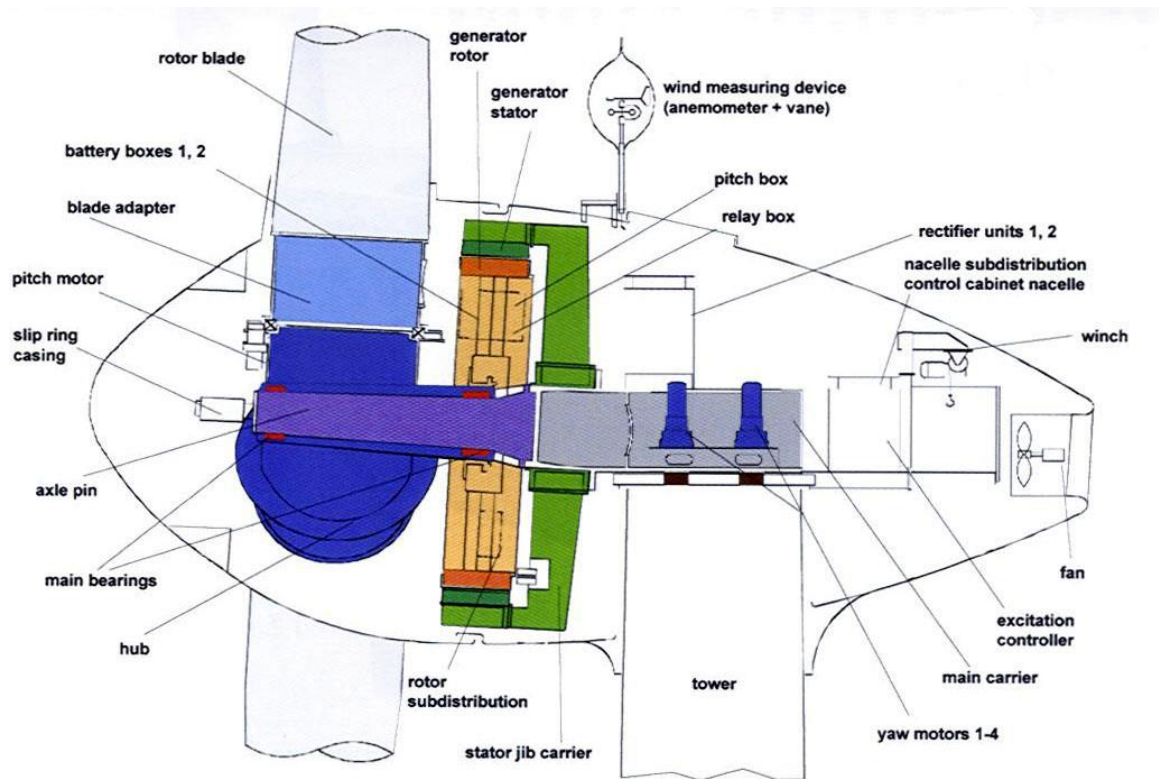


Figure 1. Electronic orientation yaw drive and pitch control mechanism in the direct drive Enercon E66 1.5 MW wind turbine. Notice the absence of a gear box in this design.

Wind turbines have to also be oriented perpendicular to the wind stream using wind orientation mechanism or yaw control. In addition their brakes must be applied under unfavorable high wind conditions. Some of these controls are performed mechanically in older wind machines, but in newer machines they are performed

hydraulically, and in the most recent designs they are done electrically using stepped up motors.

This is similar to the evolution in aircraft from manual controls to hydraulic controls to fly by wire controls.

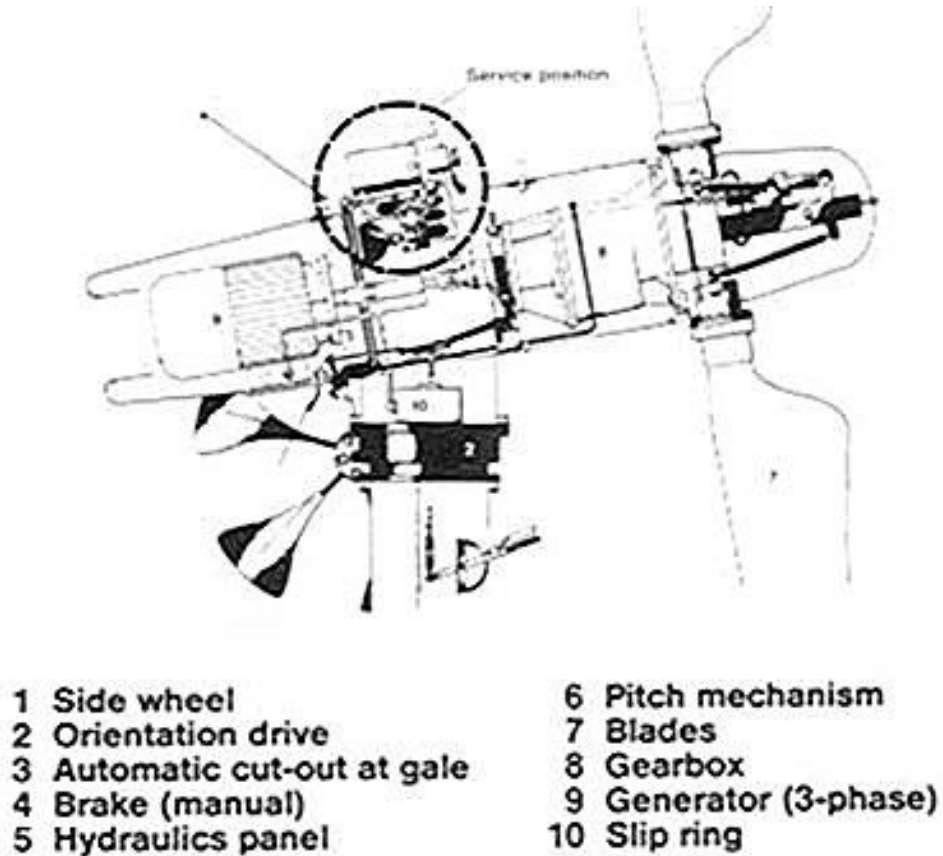


Figure 2. Mechanical orientation drive, brake and pitch control mechanism in an earlier design wind turbine.

## **MECHANICAL PITCH CONTROL**

Ingenious methods were developed to control the pitch or the angle of attack that a rotor airfoil presents to the wind stream. In a spring operated mechanism, the higher rotational speed of the rotor generates a centrifugal force on a regulating balancing weight which compresses a spring. The force of the weight rotates the blade about a pivot decreasing the angle of attack of the airfoil to the wind stream and reducing its rotational speed. The compressed spring tends to restore the airfoil to its original angle of attack once the wind speed decreases.

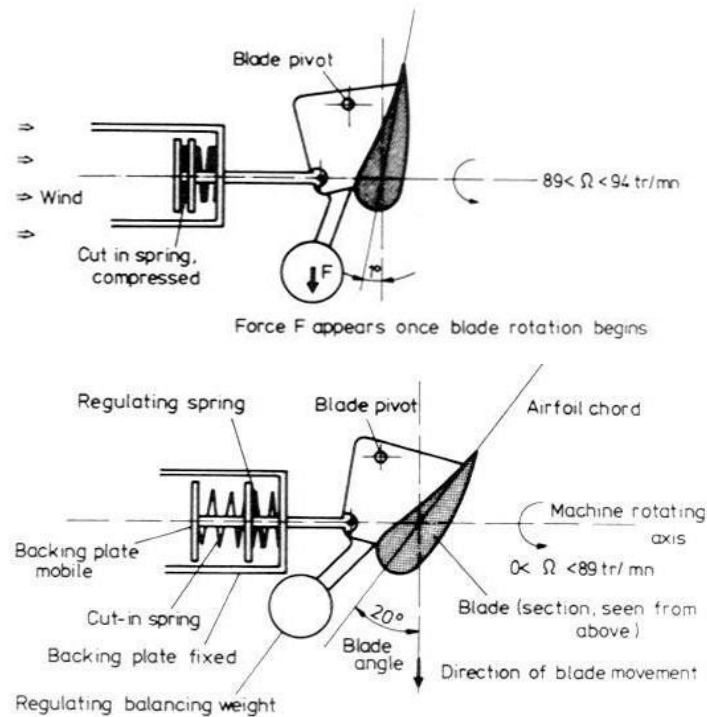


Figure 3. Mechanical spring loaded pitch control of rotor blades.

In modern wind generators the mechanical spring loaded pitch control was replaced by power operated controls.

## PITCH POWER CONTROL

In pitch power controlled wind turbines an electronic controller senses the power output of the turbine several times per second. If the power level exceeds a prescribed safe level, an electronic signal is generated which turns or pitches the blades out of the wind. When the power level is lower, they are pitched back to catch the wind at the optimal angle of attack of the blade's airfoil.

In pitch control the rotor blades are rotated around their longitudinal axis a fraction of a degree at a time while the rotor continues its normal rotation.

Clever design is needed to pitch the rotor blades the optimal amount so as to maximize the power output at all wind speeds.

The pitch control mechanisms are hydraulically controlled, even though electrical controls using stepped electrical motors are replacing them much the same as fly by wire is replacing the hydraulics in airplane controls.

About one third of the installed wind machines use pitch control mechanisms

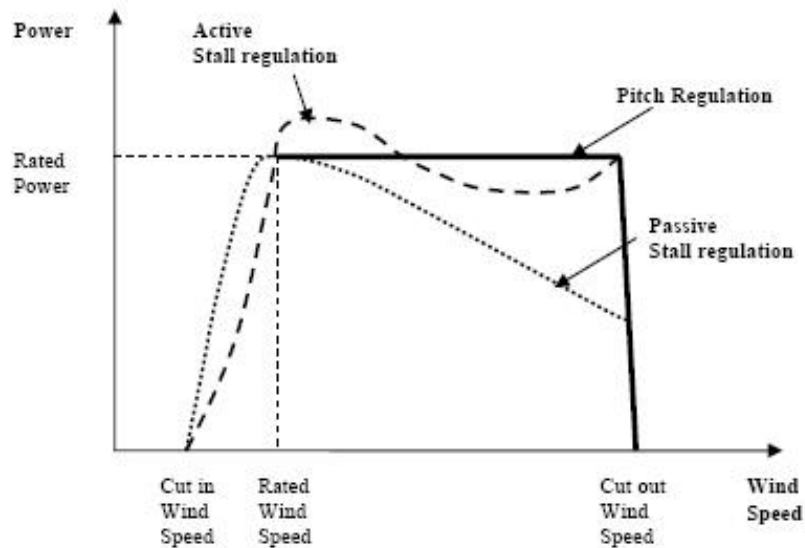


Figure 4. Passive and active stall regulation and pitch power control.

## PASSIVE STALL POWER CONTROL

Passive stall power controlled wind turbines use a simpler form of blades that are attached to the hub at a fixed angle. The rotor airfoil profile is aerodynamically designed such as when the wind speed exceeds a safe limit, the angle of attack of the airfoil to the wind stream is increased, and laminar flow stops and is replaced by turbulence on the top side of the airfoil. The lift force on the blade stops acting stalling its rotation.

In stall controlled wind turbines the blade is slightly twisted along its longitudinal axis. This ensures that the blade stalls gradually rather than abruptly as the wind speed reaches its critical stall value.

The advantage of stall control in wind turbines is that it avoids the introduction of moving parts into the rotor. This advantage is obtained as interplay between the aerodynamic design and the structural dynamic design of the rotor airfoil so as to avoid stall induced vibrations. Two third of the installed wind turbines are stall controlled.

## ACTIVE STALL POWER CONTROL

Larger wind turbines with larger than 1 MW rated capacity are equipped with active stall power control mechanisms. In this case they use pitchable blades resembling the pitch controlled machines.

To get a large torque or turning force at low wind speeds, the control system pitches the blades in steps like the pitched control machines at low wind speeds.

The situation is different when the turbine reaches its design rated power level, at that point the stall controlled machines operate differently than pitch controlled machines. If the electrical generator is going to be overloaded, the control system pitches the blades in the opposite direction of what a pitch controlled machine would do. In this case it

increases the angle of attack of the airfoil leading to a stall condition, rather than decreasing the angle of attack to reduce the lift and the rotational speed of the blades.

An advantage of active stall control is that the power output can be controlled so as to avoid overshooting the generator's rated power at the start of wind gusts. A second advantage is that the machine would deliver its rated power at high wind speeds, in contrast to a passive stall controlled machine which will normally experience a drop in its electrical power output level at high wind speeds since its rotor blades experience a deeper stall.

## **COMBINATION PITCH AND STALL CONTROL**

### **CONSTANT SPEED TURBINES: STALL-PITCH REGULATION**

Combined stall-pitch regulation was used on constant-speed turbines such as the Siemens SWT-1.3-62 and SWT-2.3-82 turbines. At low and medium wind speeds, the blade pitch setting is slowly adjusted to provide maximum power output at any given wind speed. When the rated wind speed is reached, the blades are adjusted to a more *negative* pitch setting, tripping aerodynamic stall and thereby spilling the excess power. At higher wind speeds, the pitch angle is adjusted continuously to maintain the maximum power specified.

The advantage of such regulation is that it is very simple and efficient, working well with constant speed operation. The disadvantages are that the noise level and blade deflection in high wind are somewhat higher than with pitch-stall regulation. These disadvantages are of minor importance for smaller turbines, but for very large turbines they tend to outweigh the benefits of the robust constant speed operation.

### **VARIABLE SPEED TURBINES: PITCH-STALL REGULATION**

Combined pitch-stall regulation was used on variable speed turbines such as the Siemens SWT-2.3-82 VS, SWT-2.3-93 and SWT-3.6-107 turbines. At low and medium wind speeds the blade pitch setting is slowly adjusted to provide maximum power output at any given wind speed. When the rated wind speed is reached, the blades are adjusted to a more *positive* pitch setting, thereby reducing the aerodynamic forces and maintaining the power level programmed into the turbine controller. At higher wind speeds, the pitch angle is adjusted continuously to maintain the maximum power specified.

The advantage of pitch-stall regulation is that it provides low aerodynamic noise and moderate blade deflections. Lower noise can be obtained by special operation. The disadvantage is that variable speed operation is required to provide the necessary flexibility in regulation. This disadvantage is of minor importance for large turbines, where the benefits of pitch-stall regulation outweigh the added complexity of variable speed operation.

## **FLAP POWER CONTROL**

Some wind machines have their rotors equipped with ailerons or flaps like aircraft. In this case the geometry of the wing airfoil is altered to provide increased or decreased air lift.

## **YAW POWER CONTROL**

It is possible to yaw or rotate the whole rotor mechanism out of the wind to decrease its rotational speed and power output. This technique is used for small wind turbines of 1 kW rated power or less. It would subject large wind turbines to cyclic stresses that could lead to the fatigue failure of the entire structure.

## **ORIENTATION YAW CONTROL**

The yaw position control mechanism is used to orient the wind turbine rotor in such a way that it perpendicularly faces the wind stream.

The wind turbine undergoes a yaw error, if the rotor is not perpendicular to the wind. The existence of a yaw error suggests that a lower fraction of the energy in the wind will be flowing through the rotor area and available for extraction. The lost power fraction is proportional to the cosine of the yaw error angle:

$$\Delta P \propto \cos(\varepsilon) \quad (1)$$

where:  $\varepsilon$  is the yaw error angle,

$\Delta P$  is the power loss caused by the yaw error.

If the yaw error would only lead to a decrease in the power output, it would be an acceptable method of power control. However this is not the case since a side effect occurs.

The part of the rotor that is closer to the wind becomes subject to a larger bending torque than the rest of the rotor. This means that the rotor has a propensity to automatically yaw against the wind and this applies to either upwind or downwind machine designs. The rotor blades under a yaw error would be bending back and forth in a flap-wise fashion for each turn of the rotor. Running a wind turbine with a yaw error subjects it to a large fatigue load that could lead to its eventual fatigue failure. It becomes necessary to equip wind machines with yaw mechanism placing them in a direction that is perpendicular to the wind direction.

Forced yawing is used in most horizontal axis wind turbines. The mechanism uses electric motors and gear boxes to keep the turbine yawed perpendicularly to the wind stream.



Figure 5. Wind generator yaw mechanism.

The yaw mechanism under the nacelle of a 750 kW machine looking from the bottom is shown in Fig. 5. The yaw bearing is situated around its outer edge, and the gears of the yaw motors and the yaw brakes are placed on the inside. Manufacturers of upwind machines include provisions for braking the yaw mechanism whenever it is not used. The yaw mechanism is activated by the electronic controller which interrogates the position of the wind vane on the turbine, several times per second.

### **SAFETY FEATURE: CABLE TWIST COUNTER**

A wind turbine accident situation is that it could continue yawing continuously in the same direction. Electrical cables carry the current from the wind turbine generator down through the structural tower. These cables could become twisted if the turbine accidentally keeps yawing in the same direction more than one rotation.

Wind turbines are equipped with an engineered safety feature consisting of a cable twist counter which informs the controller when it becomes necessary to untwist the power cables. It is connected to a circuit breaker which is activated if the cables become too twisted and brakes the yaw rotation mechanism. No more than five full twist rotations are allowed.

### **BLOCKING DIODES**

A diode is an electronic component which allows the current to flow in just one direction, and not in reverse.

They are essential in a small wind power installation that charges batteries. In periods of low or no wind, the turbine generator could use the power stored in the batteries to turn in reverse like a motor.

A power rectifier diode is used in typical domestic wind power applications. The 1N1190A power rectifier diode can manage a current of 40 Amps and a voltage of up to 600 Volts.



Figure 6. Power rectifier diode 1N1190 rated for 40 Amps and 600 Volts loads.

The power rectifier diode could be connected to the live positive cable and the battery bank. The threaded end of the diode can be clamped to the positive terminal of the battery, and the looped end is connected to the live cable with a nut and a bolt or it could be soldered to it.

Large currents flowing through the diode can heat it necessitating the attachment of a heat sink to the threaded end of the diode to dissipate the heat.



Figure 7. Power diode is connected to a heat sink.

For low voltage systems a Schottky diode rated at 30 Amps with a forward voltage drop of 310 mV but a maximum rated voltage rating of 40 volts can be used.

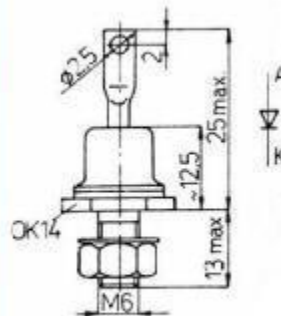


Figure 8. Schottky diode rated at 30 Amps and maximum voltage rating of 40 volts.



## **CHARGE CONTROLLER, REGULATOR, TURBINE BRAKING**

A charge controller or regulator is necessary for any wind turbine installation used to charge a battery bank. Continuous overcharging of the batteries would boil the electrolyte dry and ruin the expensive battery bank.

Charge controllers used in conjunction with solar panels are unsuitable for wind power applications. They function by monitoring the battery voltage, and once it reaches its full charge, the controller shorts the solar panel leads together. This does not harm the solar panels, even though it wastes the power they are generating. The energy ends up heating the transistors in the controller.

Shorting the output of the wind energy generator while it is spinning at high speed will generate a large current spike, possibly destroying the controller and perhaps even the generator in the process. Simply unhooking the generator from the batteries is not a good idea either, since with no load on it, the generator might overspeed in a strong wind and self destruct.

The solution for wind power applications is to charge the batteries until they reach a full charge, then switch to an alternate load where the energy can be safely handled. This dumped energy should be used for some useful purpose, such as supplementing a water heater or powering a Peltier-junction refrigerator. Lighting a bank of 12 volt light bulbs will also do.

The wind turbine controller is used to prevent the batteries from overcharging. A more important function is that it ensures that the wind turbine is constantly under load to prevent it from spinning out of control or overspeeding leading to its catastrophic damage or destruction in high winds.

A typical wind turbine charge controller constantly monitors the battery charge. When the voltage approaches the set maximum or float voltage; then the controller turns on a dump load or shunt which would dissipate the excess power to prevent it from charging the batteries.

When the battery voltage is measured to have fallen below a set threshold of 0.2-0.5 Volt below the float voltage, the dump load is turned off and the battery charging process restarted. Dump loads could be a low voltage electric heater, an immersion heater element for water heating, a high wattage 500 Watts car headlight lamp.



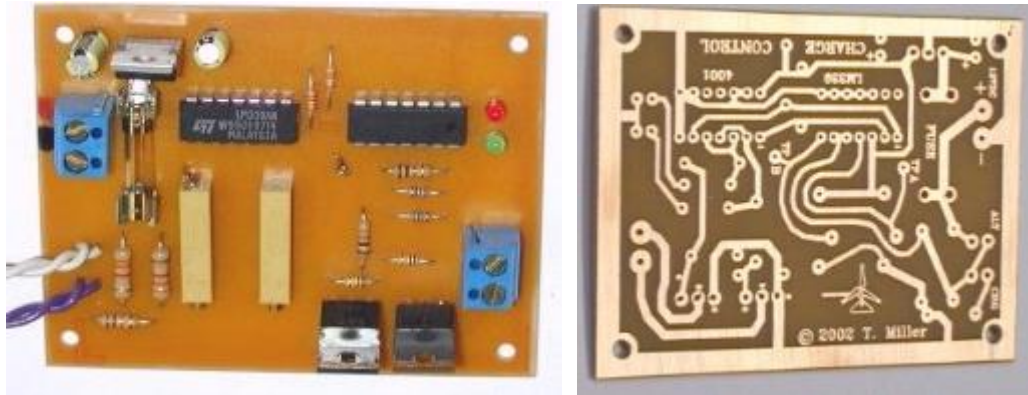


Fig. 11: Top and bottom of circuit board for charge controller.

A schematic of a charge controller circuit is described. The incoming battery voltage is divided in half by a pair of 3.3 K $\Omega$  resistors, so the trip points are adjusted to one half of the desired levels.

The actual trip points will depend on the particular batteries used. A good starting point is 14.5 volts for the full charge state and 11.8 volts for the discharged state. In this case, the trim pots should be adjusted to read 7.25 volts at test point TP-A and 5.9 volts at test point TP-B. The battery voltage should be monitored through several charge and discharge cycles to determine the perfect trip points for a particular system.

The outputs of the controller are latched, and drive a pair of IFR510 power FETs, which serve as relay drivers. If a double throw relay is used, only one output is necessary, since the relay can switch the incoming power to either the batteries or the alternate load as required.

The second output can be used to switch a small 12 volt DC muffin fan to vent hydrogen gas from the battery enclosure to avoid the danger of explosion when charging the batteries.

The two push buttons provide a way to toggle the output manually when the battery voltage lies in the null zone between the trip points. By momentarily pressing one of the buttons, the output state will reverse and latch. A 1K $\Omega$  resistor prevents a dead short, in case someone decides to press both buttons at once.

The charge controller is built on a small printed circuit board with Integrated circuits (ICs)s and capacitors. Terminal blocks are soldered to the board for the incoming 12 volts and for connections to the relay coil.

If the incoming power is produced by several different types of solar panels and wind generators each producing different voltages, they cannot all be hooked together, and each will need its own blocking diode in series with the positive lead.

When the battery is charging, each source is pulled down to the battery terminal voltage, so each source contributes whatever current it is capable of producing. Each blocking diode has to be sized for the current that source can generate. The negative lead from each source is connected to ground.

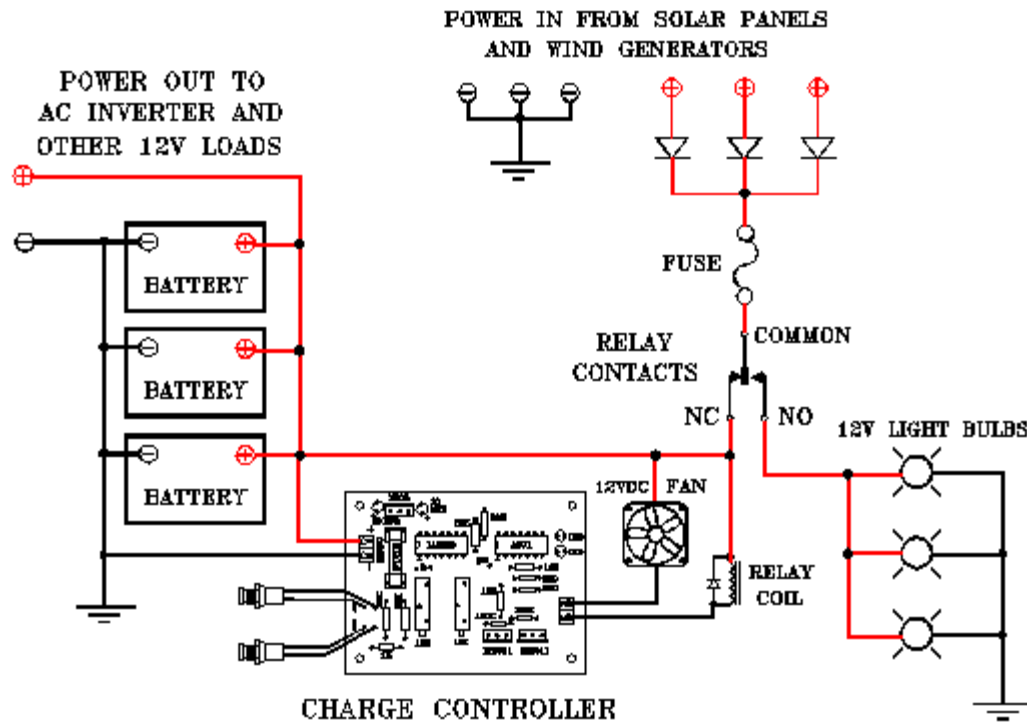


Figure 12. Charge controller connections to a combined wind turbine and solar panel and peripheral devices.

As long as the batteries are charging, the red LED light would be glowing. As soon as the trip voltage is reached, the red LED goes out and the green one comes on, and the power is shunted to the alternate load and no power is wasted.



Figure 13. DC on the left, and three phase with a built in three phase bridge rectifier, on the right, AC charge controllers. The regulators are rated at a current handling capacity of 20 Amps AC and 23 Amps DC. They can be configured for either 12 V or 24 volts battery charging.

A switched output allows the use of a dump load cooling fan. This switched output turns on when the dump load is switched on and remains on for a minute after the load is switched off to cool it down. High current rated MOSFETs are used instead of relays making them highly reliable and robust. Light emitting diodes (LEDs) are used to

indicate the current charging status: Green LED when the battery is fully charged and the dump load is ON, and red LED when the batteries are ready to be charged.

The regulators can be configured in two different configurations:

1. A simple battery shunt dump load, with the dump load directly powered from the battery bringing down the battery's level of stored charge and preventing it from getting overcharged.
2. The diversion mode for back electro motive (emf) braking, with the dump load powered only by the instantaneous power generated by the generator, with the battery retaining whatever charge it holds, but all power from the generator is diverted to the dump load. This results in its functioning as turbine brake controller.

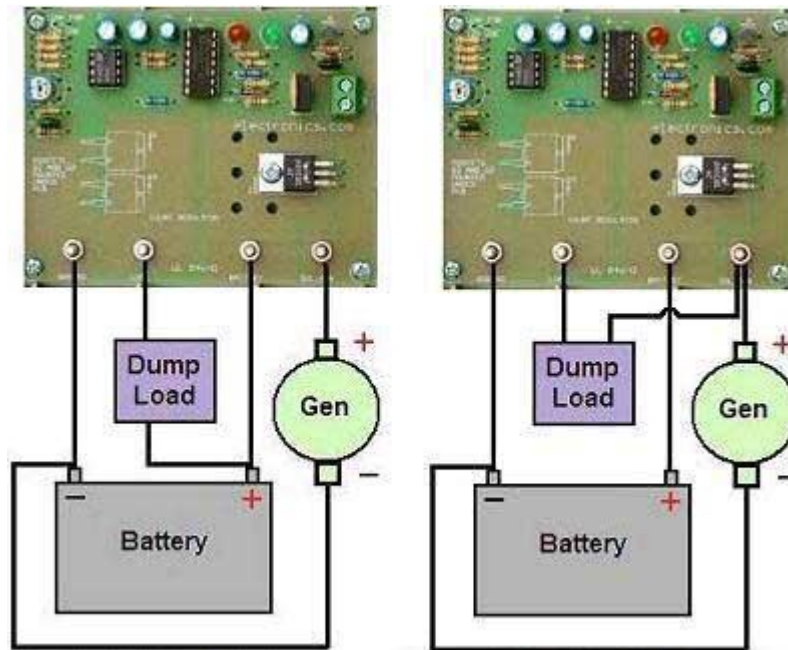


Figure 14. Configuration of controller for load dump, left and for diversion mode or back electro-motive-force, emf turbine braking.

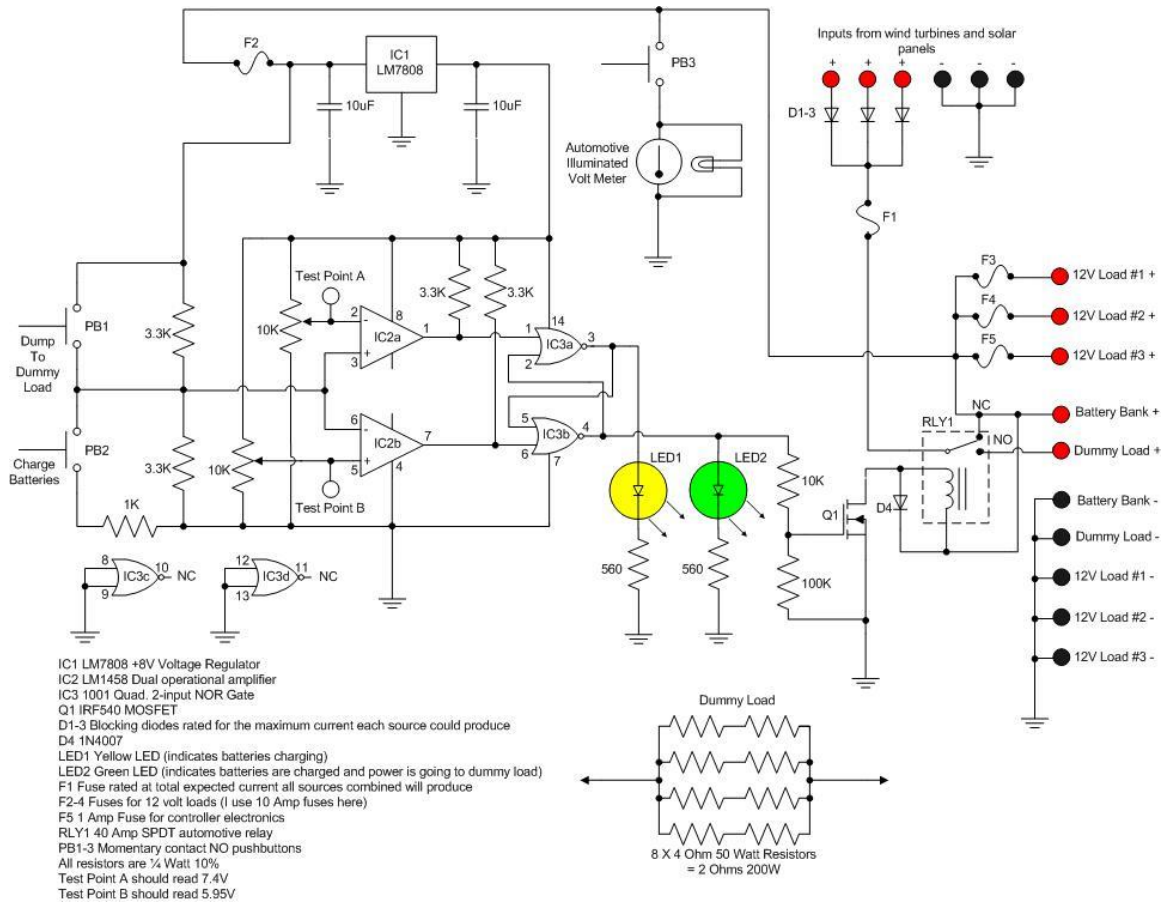


Figure 15. Electronic circuit for a battery charge controller equipped with a voltmeter.