5. MPPT ALGORITHMS & HYBRID SYSTEMS

5.1 Need of Maximum Power Point Tracking for PV systems

The environmental condition under which a solar power system operates can be wide, as shown in I-V curves in Figure 1. The current-voltage relation of a solar array is variable throughout the day, as it varies with environmental conditions such as irradiance and temperature. In terrestrial applications, Low Irradiance, Low Temperature (LILT) condition reflects morning condition where the sun just rises. A High Irradiance, High Temperature (HIHT) condition might represent a condition near high noon in a humid area. High Irradiance, Low Temperature (HILT) condition can represent a condition with healthy sunlight in the winter. Finally, condition near sunset can be described by Low Irradiance, High Temperature (LIHT) condition. For space application, LILT characterizes a deep space mission or aphelion period, while HIHT condition is when satellite orbits near the sun (perihelion).

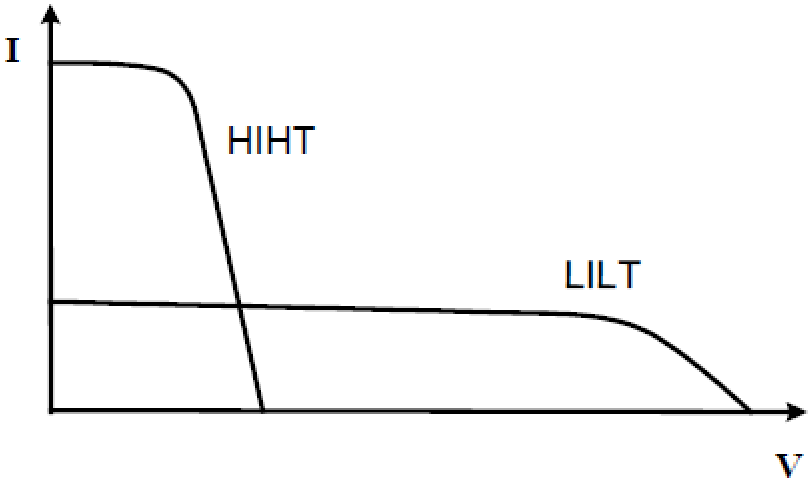


Figure 1: I-V characteristics under wide operating conditions

For a uniformly illuminated array, there is only one single point of operation that will extract maximum power from the array. In a battery charging system where the load seen by the solar modules is a battery connected directly across the solar array terminals, the operating point is determined by the battery’s potential. This operating point is typically not the ideal operating voltage at which the modules are able to produce their maximum available power.

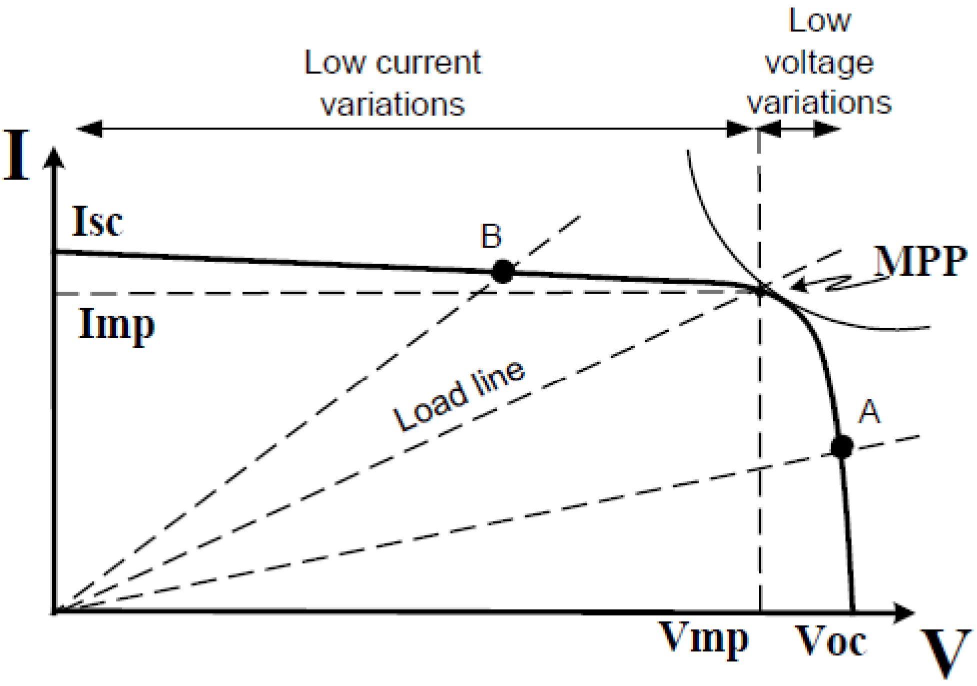


Figure 2: Direct coupled method

In the direct coupled method, in which the solar array output power is delivered directly to the loads, as shown in Figure 2. To match the MPPs of the solar array as closely as possible, it is important to choose the solar array I-V characteristic according to the I-V characteristics of the load. A general approach for the power feedback control is to measure and maximize the power at the load terminal, and it assumes that the solar array maximum power is equal to the maximum load power. However, this maximizes the power to the load not the power from the solar array. The direct-coupled method cannot automatically track the MPPs of the solar array when the insolation or temperature changes. The load parameters or solar array parameters must be carefully selected for the direct coupled method.

To be able to extract the maximum power from the solar array and to track the changes due to environment, therefore, a maximum power point tracking should be implemented. Devices that perform the desired function are known as Maximum Power Point Trackers, also called MPPTs or trackers. A tracker consists of two basic components, as shown in Figure 3: a switch-mode converter and a control with tracking capability. The switch-mode converter is the core of the entire supply. The converter allows energy at one potential to be drawn, stores as magnetic energy in an inductor, and then releases at a different potential. By setting up the switch-mode section in various topologies, either high-to-low (buck converter) or low-to-high (boost) voltage converters can be constructed. The goal of a switch-mode power supply is to provide a constant output voltage or current. In power trackers, the goal is to provide a fixed input voltage and/or current, such that the array is held at the maximum power point, while allowing the output to match the load voltage.

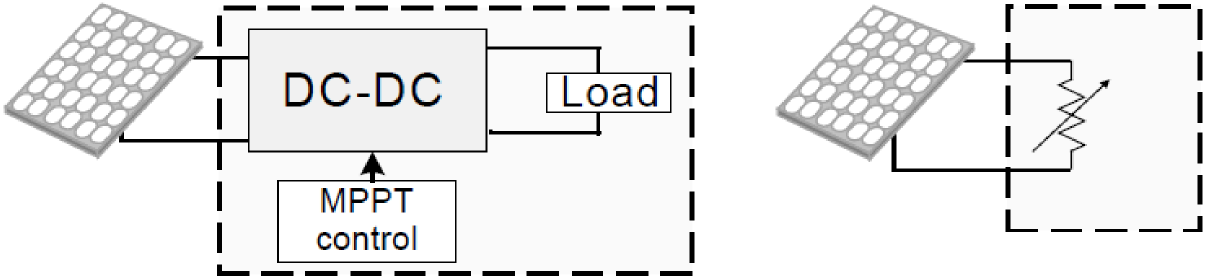


Figure 3: Basic components of a maximum power pointer tracker

When properly applied, a maximum power point tracking control can prevent the collapse of the array voltage under excessive load demand, particularly when supplying a constant-power type of load. One of the proper approaches is to operate the system in a solar array voltage regulation mode where the array voltage is clamped to a commanding set point, V_{mp}, which is dynamically updated by the MPPT control circuit. The control processes feedback signals, such as the array current and voltage, to determine a proper direction to move the operating point. Eventually, this continuously updated set point will fluctuate around the voltage corresponding to the array peak power point. By adjusting the operating point of the array to the point V_{mp}, power output of the array is maximized, and the most efficient use of the solar array may be realized.

For a system without MPPT, the voltage will quickly collapse to zero. This phenomenon can be understood from the I-V characteristic of a solar array. The flatness of the I-V curve on the left of the MPP implies that a small incremental increase in current demand leads to large voltage change. A system with MPPT avoids the voltage collapse by keeping the operating point near the MPP. On the I-V curve, the operating point corresponding to the maximum-power point is around the “knee” region. Therefore, unlike other power systems with stiff voltage sources, power conversion from solar array sources with MPPT requires more robust design due to risks of an array voltage collapse under peak load demand or severe changes in the array characteristics. The location of the MPP of an I-V characteristic is not known a priori, and must be located.

5.2 METHODS OF MPPT ALGORITHMS

1. Constant Voltage and Current.
2. Perturb-and-Observe.
3. Incremental Conductance.

5.3 Constant Voltage and Current Methods.

The constant voltage algorithm is based on the observation from I–V curves that the ratio of the array's maximum power voltage, V_{mp}, to its open-circuit voltage, V_{oc}, is approximately constant:

$$Vmp / Voc = K < 1 \tag{5.1}$$

The constant voltage algorithm can be implemented using the flowchart shown in Figure 4. The solar array is temporarily isolated from the MPPT, and a Voc measurement is taken. Next, the MPPT calculates the correct operating point using Equation (5.1) and the preset value of K, and adjusts the array's voltage until the calculated Vmp is reached. This operation is repeated periodically to track the position of the MPP. Although this method is extremely simple, it is difficult to choose the optimal value of the constant K. The literature reports success with K values ranging from 73 to 80%. Constant voltage control can be easily implemented with analog hardware. However, its MPPT tracking efficiency is low relative to those of other algorithms. Reasons for this include the aforementioned error in the value of K, and the fact that measuring the open-circuit voltage requires a momentary interruption of PV power.

It is also possible to use a constant current MPPT algorithm that approximates the MPP current as a constant percentage of the short-circuit current. To implement this algorithm, a switch is placed across the input terminals of the converter and switched on momentarily. The short-circuit current is measured and the MPP current is calculated, and the PV array output current is then adjusted by the MPPT until the calculated MPP current is reached. This operation is repeated periodically. However, constant voltage control is normally favored because of the relative ease of measuring voltages, and because open-circuiting the array is simple to accomplish, but it is not practically possible to short-circuit the array (i.e., to establish zero resistance across the array terminals) and still make a current measurement.

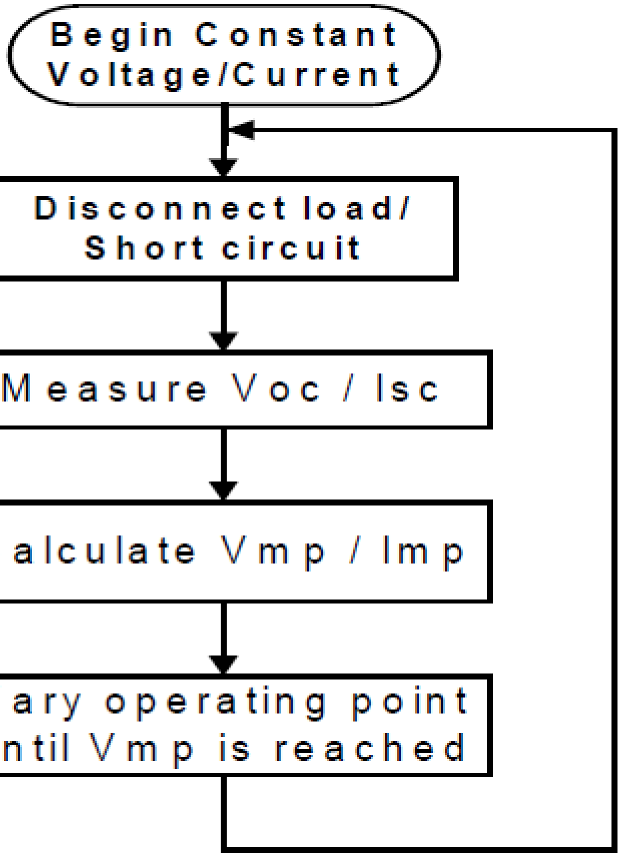
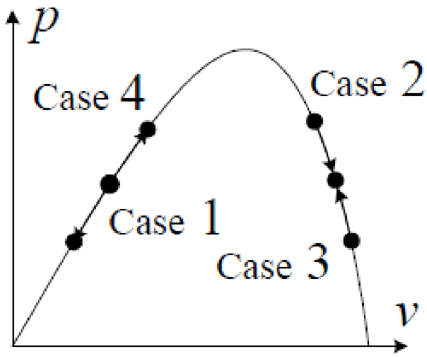


Figure 4: Constant voltage/current algorithm flowchart

5.4 **Perturb-and-Observe**

As the name of the perturb-and-observe (P&O) states, this process works by perturbing the system by increasing or decreasing the array operating voltage and observing its impact on the array output power. The operating voltage is perturbed with every MPPT cycle. As soon as the MPP is reached, V will oscillate around the ideal operating voltage Vmp. Figure 5 summarized the control action of the P&O method. The value of the reference voltage, Vref, will be changed according to the current operating point. For example, for when the controller senses that the power from solar array increases ($dP > 0$) and voltage decreases ($dV < 0$), it will decrease (-) V_{ref} by a step size C1, so V_{ref} is closer to the MPP. The MPP represents the point where V_{ref} and scaled down V_{sa} become equal.

The oscillation around a maximum power point causes a power loss that depends on the step width of a single perturbation. The value for the ideal step width is system dependent and needs to be determined experimentally to pursue the tradeoff of increased losses under stable or slowly changing conditions. In fact, since the AC component of the output power signal is much smaller than the DC component and will contain a high noise level due to the switching DC-DC converter, an increase in the amplitude of the modulating signal had to be implemented to improve the signal to noise ratio (SNR), however, this will lead to higher oscillations at the MPP and therefore increase power losses even under stable environmental conditions.



Case	dP	dV	Action
1	< 0	< 0	+
2	< 0	> 0	-
3	> 0	< 0	-
4	> 0	> 0	+

Figure 5: Perturb & Observe (P&O) control action

Several improvements of the P&O algorithm have been proposed. One of the simplest entails the addition of a ‘waiting’ function that causes a momentary cessation of perturbations if the algebraic sign of the perturbation is reversed several times in a row, indicating that the MPP has been reached. This reduces the oscillation about the MPP in the steady state and improves the algorithm’s efficiency under constant irradiance conditions. However, it also makes the MPPT slower to respond to changing atmospheric conditions, worsening the erratic behavior on partly cloudy days. Another modification involves measuring the array’s power P1 at array voltage V1, perturbing the voltage and again measuring the array’s power, P2, at the new array voltage V2, and then changing the voltage back to its previous value and re measuring the array’s power, P1, at V1. From the two measurements at V1, the algorithm can determine whether the irradiance is changing. Again, as with the previous modifications, increasing the number of samples of the array’s power slows the algorithm down. Also, it is possible to use the two measurements at V1 to make an estimate of how much the irradiance has changed between sampling periods, and to use this estimate in deciding how to perturb the operating point. This, however, increases the complexity of the algorithm, and also slows the operation of the MPPT. The flowchart for P&O algorithm is shown below.

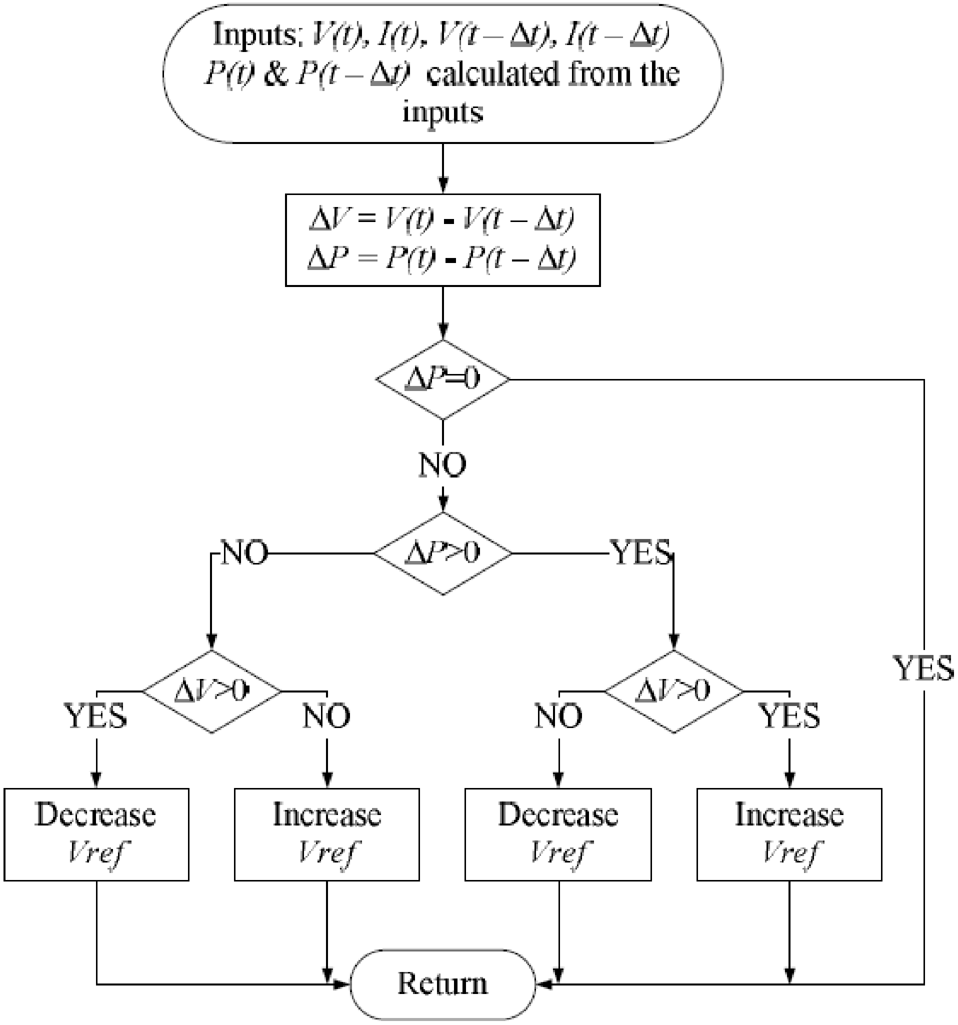


Figure - The flowchart of the P&O Algorithm.

5.5 Incremental Conductance

The incremental conductance (IncCond) method is based on comparing the instantaneous panel conductance with the incremental panel conductance. The input impedance of the DC-DC converter is matched with optimum impedance of PV panel. As noted in literatures, this method has a good performance under rapidly changing conditions. The algorithm uses the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point:

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} = 0 \qquad (5.2)$$

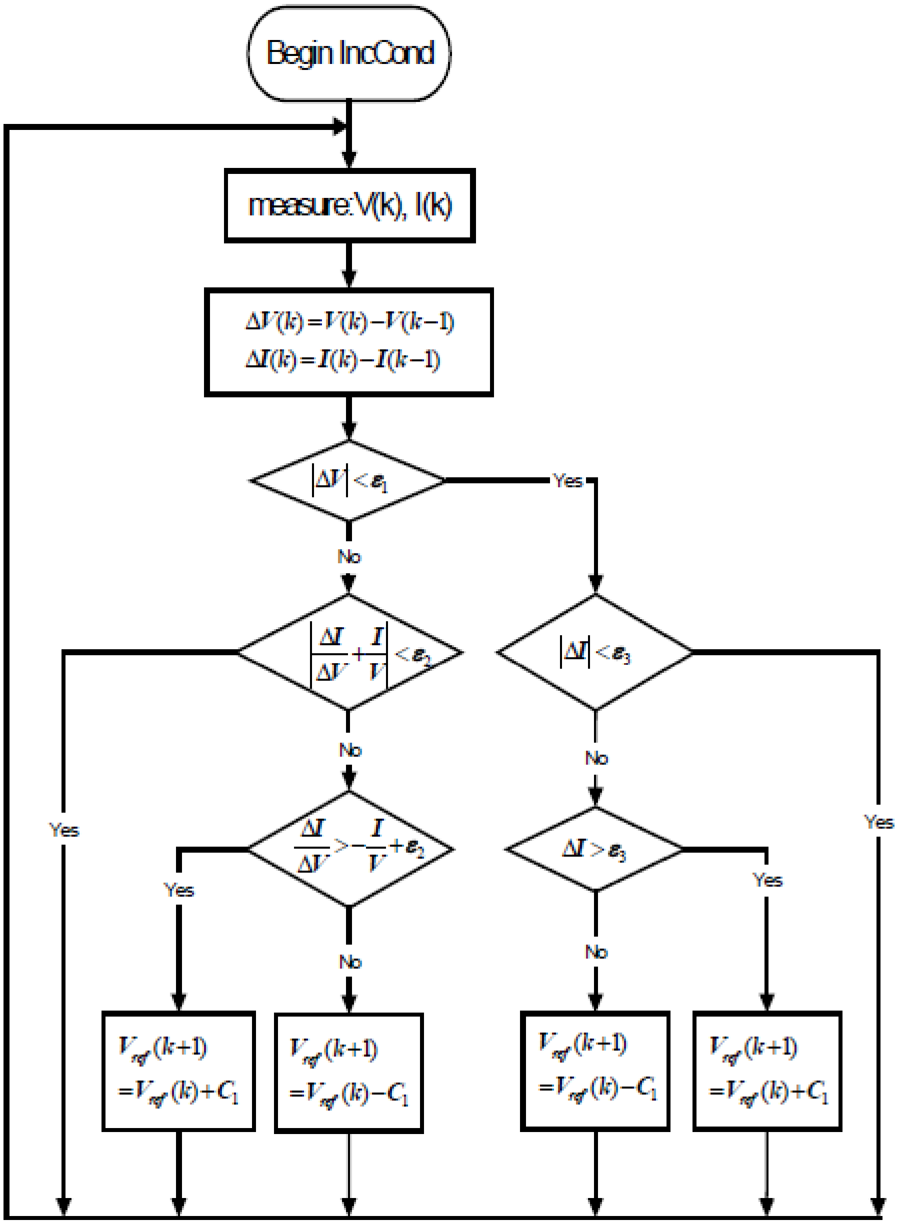


Figure 6: Incremental conductance algorithm flow chart

One of the advantages of the IncCond algorithm is that it does not oscillate around the MPP. The check of condition (1) and dI = 0 allows it to bypass the perturbation step and therefore maintain a constant operating voltage V once the MPP is found. Furthermore, conditions $\left|\frac{dI}{dV}+\frac{I}{V}\right| > 0$ and dI > 0 make it possible to determine the relative location of the MPP. This leads to the advantage that an initial adjustment in the wrong direction, as with the "trial and error" P&O method, does not occur. A fast and correct system response to changing operating conditions should be the result – yielding high system efficiency. A small marginal error could be added to the maximum power condition (1) such that the MPP is assumed to be found if $\left|\frac{dI}{dV}+\frac{I}{V}\right| < €_2$. The value of $€_2$ was determined with consideration of the tradeoff between the problem of not operating exactly at the MPP and the possibility of oscillating around it. It will also depend on the chosen perturbation step size C1.

5.6 Need of MPPT for Wind Energy Conversion Systems

The typical turbine torque vs. rotor speed is plotted in Figure 7. It shows a small torque at zero speed, rising to a maximum value before falling to nearly zero when the rotor just floats with the wind. Two such curves are plotted for different wind speeds V_1 and V_2, with V_2 being higher than $V1$. The corresponding power vs. rotor speed at the two wind speeds are plotted in Figure 8. As the mechanical power converted into the electric power is given by the product of the torque T and the angular speed, the power is zero at zero speed and again at high speed with zero torque. The maximum power is generated at a rotor speed somewhere in between, as marked by $P_{1\max}$ and $P_{2\max}$ for speeds V_1 and V_2, respectively. The speed at the maximum power is not the same speed at which the torque is maximum. The operating strategy of a well-designed wind power system is to match the rotor speed to generate power continuously close to the $P_{\max}$ points. Because the $P_{\max}$ point changes with the wind speed, the rotor speed must, therefore, be adjusted in accordance with the wind speed to force the rotor to work continuously at $P_{\max}$. This can be done with a variable-speed system design and operation.

At a given site, the wind speed varies over a wide range from zero to high gust. We define tip speed ratio (TSR) as follows:

$$\boldsymbol{TSR} = \frac{\text{Linear speed of the blade's outermost tip}}{\text{Free upstream wind velocity}} = \frac{\omega R}{V} - - - - - - - - -(5.3)$$

Where *R* and *ω* are the rotor radius and the angular speed, respectively

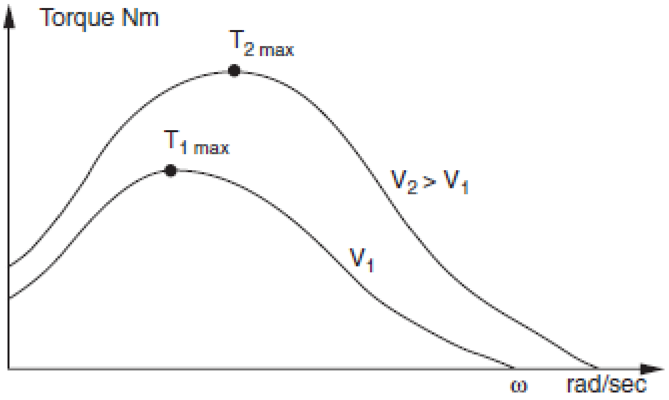


FIGURE 7 Wind turbine torque vs. rotor speed characteristic at two wind speeds, V_1 and V_2.

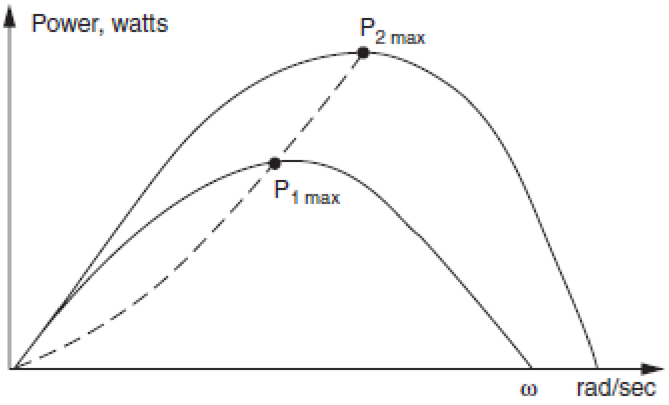


FIGURE 8 Wind turbine power vs. rotor speed characteristic at two wind speeds, V_1 and V_2.

For a given wind speed, the rotor efficiency *C*p varies with TSR as shown in Figure 9. The maximum value of *C*p occurs approximately at the same wind speed that gives peak power in the power distribution curve of Figure 8. To capture high power at high wind, the rotor must also turn at high speed, keeping TSR constant at the optimum level. However, the following three system performance attributes are related to TSR:

1. The maximum rotor efficiency *C*p is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine. As was seen in Figure 3.4, the TSR needed for maximum power extraction ranges from nearly one for multiple-blade, slow-speed machines to nearly six for modern high-speed, two-blade machines.

2. The centrifugal mechanical stress in the blade material is proportional to the TSR. The machine working at a higher TSR is necessarily stressed more. Therefore, if designed for the same power in the same wind speed, the machine operating at a higher TSR would have slimmer rotor blades.
3. The ability of a wind turbine to start under load is inversely proportional to the design TSR. As this ratio increases, the starting torque produced by the blade decreases.

A variable-speed control is needed to maintain a constant TSR to keep the rotor efficiency at its maximum. At the optimum TSR, the blades are oriented to maximize the lift and minimize the drag on the rotor. The turbine selected for a constant TSR operation allows the rotational speed of both the rotor and generator to vary up to 60% by varying the pitch of the blades.

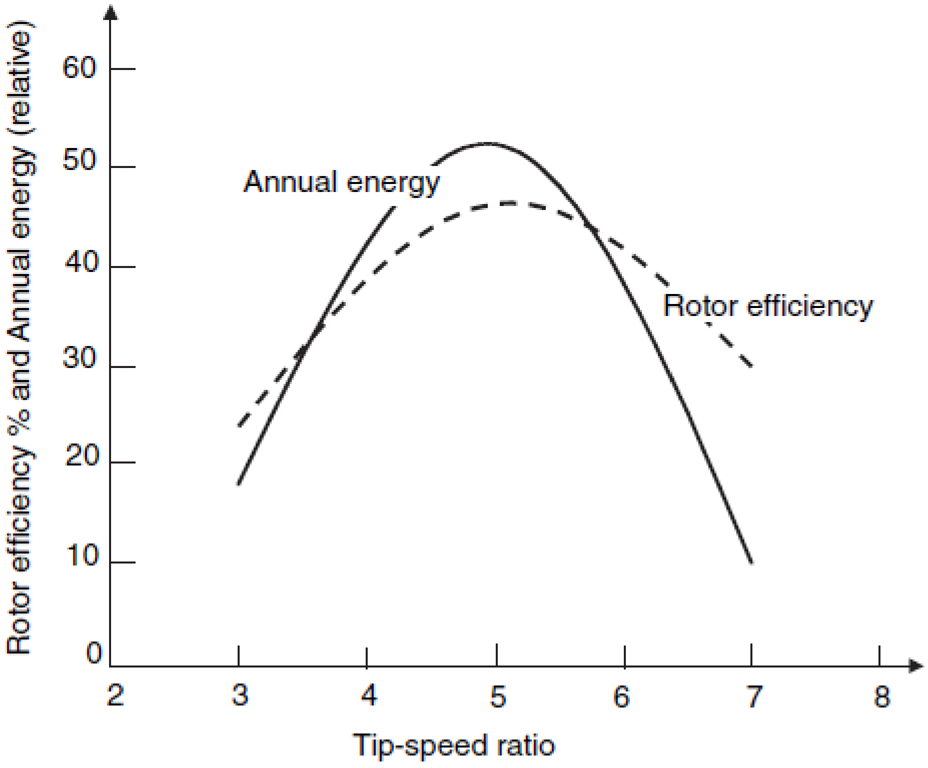


FIGURE 9 Rotor efficiency and annual energy production vs. rotor TSR.

5.7 MAXIMUM ENERGY CAPTURE

The wind power system design must optimize the annual energy capture at a given site. The only operating mode for extracting the maximum energy is to vary the turbine speed with varying wind speed such that at all times the TSR is continuously equal to that required for the maximum power coefficient *C*p. The theory and field experience indicate that the variable-speed operation yields 20 to 30% more power than with the fixed-speed operation. Nevertheless, the cost of variable-speed control is added. In the system design, this trade-off between energy increase and cost increase has to be optimized. In the past, the added costs of designing the variable pitch rotor, or the speed control with power electronics, outweighed the benefit of the increased energy capture. However, the falling prices of power electronics for speed control and the availability of high-strength fiber composites for constructing high-speed rotors have made it economical to capture more energy when the speed is high. The variable-speed operation has an indirect advantage. It allows controlling the active and reactive powers separately in the process of automatic generation control. In fixed-speed operation, on the other hand, the rotor is shut off during high wind speeds, losing significant energy. The pros and cons of fixed- and variable speed operations are listed in Table 1.

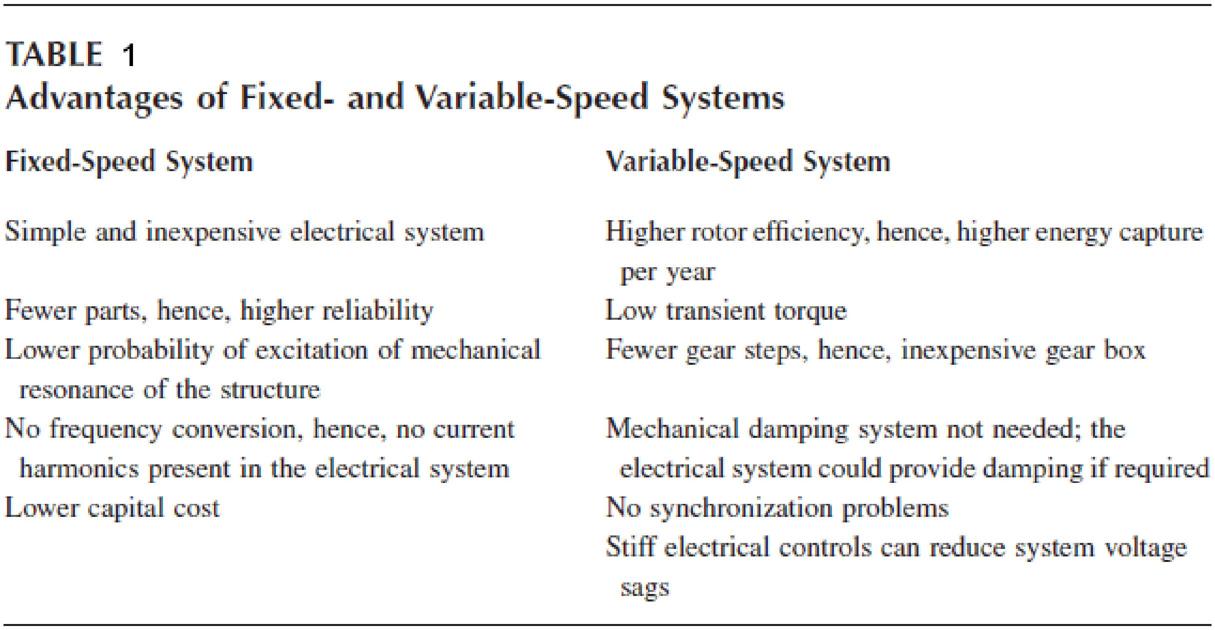


TABLE 1
Advantages of Fixed- and Variable-Speed Systems

Fixed-Speed System	Variable-Speed System
Simple and inexpensive electrical system	Higher rotor efficiency, hence, higher energy capture per year
Fewer parts, hence, higher reliability	Low transient torque
Lower probability of excitation of mechanical resonance of the structure	Fewer gear steps, hence, inexpensive gear box
No frequency conversion, hence, no current harmonics present in the electrical system	Mechanical damping system not needed; the electrical system could provide damping if required
Lower capital cost	No synchronization problems
	Stiff electrical controls can reduce system voltage sags

Almost all major suppliers now offer variable-speed systems in combination with pitch regulation. Potential advantages of the variable-speed system include active grid support, peak-power-tracking operation, and cheaper offshore foundation structure.

5.8 MAXIMUM POWER OPERATION

As seen earlier, operating the wind turbine at a constant TSR corresponding to the maximum power point at all times can generate 20 to 30% more electricity per year. However, this requires a control scheme to operate with a variable speed to continuously generate the maximum power. Two possible schemes for such an operation are as follows:

5.8.1 CONSTANT-TSR SCHEME

In this scheme the machine is continuously operated at its optimum TSR, which is a characteristic of the given wind turbine. This optimum value is stored as the reference TSR in the control computer. The wind speed is continuously measured and compared with the blade tip speed. The error signal is then fed to the control system, which changes the turbine speed to minimize the error (Figure 10). At this time the rotor must be operating at the reference TSR, generating the maximum power. This scheme has the disadvantage of requiring the local wind speed measurements, which could have a significant error, particularly in a large wind farm with shadow effects. Being sensitive to the changes in the blade surface, the optimum TSR gradually changes with age and environment. The computer reference TSR must be changed accordingly many times, which is expensive. Besides, it is difficult to determine the new optimum TSR with changes that are not fully understood or easily measured.

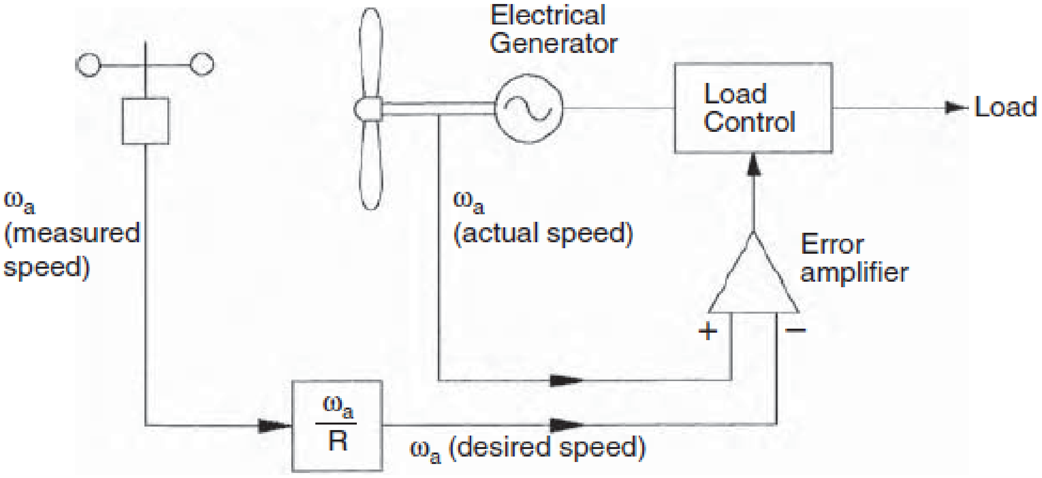


FIGURE 10 Maximum power operation using rotor tip speed control scheme.

5.8.2 PEAK-POWER-TRACKING SCHEME

The power vs. speed curve has a single well-defined peak. If we operate at the peak point, a small increase or decrease in the turbine speed would result in no change in the power output, as the peak point locally lies in a flat neighborhood. In other words, a necessary condition for the speed to be at the maximum power point is as follows:

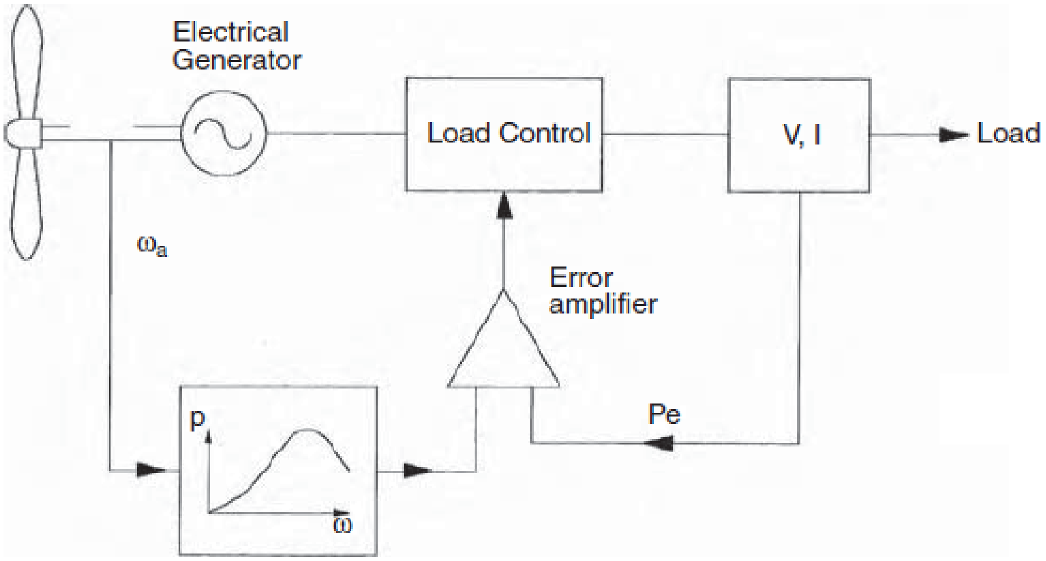


FIGURE 11 Maximum power operation using power control scheme.

$$\frac{dP}{d\omega} = 0 \qquad (5.4)$$

This principle is used in the control scheme (Figure 11). The speed is increased or decreased in small increments, the power is continuously measured, and $\Delta P/\Delta\omega$ is continuously evaluated. If this ratio is positive — meaning we get more power by increasing the speed — the speed is further increased. On the other hand, if the ratio is negative, the power generation will reduce if we change the speed any further. The speed is maintained at the level where $\Delta P/\Delta\omega$ is close to zero. This method is insensitive to errors in local wind speed measurement, and also to wind turbine design. It is, therefore, the preferred method. In a multiple-machine wind farm, each turbine must be controlled by its own control loop with operational and safety functions incorporated.

5.9 Wind Turbine Generators in Hybrid Power Systems

Two main types of hybrid generation structures embedding WECS can be found in insulated grid utilities. Typically, the generators feed energy into a common AC bus, as Figure 12 depicts. An alternative solution envisages the power sources coupling on a common DC-bus, the electrical power being further transformed by an inverter in order to feed AC loads.

In Figure 12 the example of two sources is taken, namely a wind turbine and a diesel generator feed common AC bus. This structure presents two kinds of energy storage. The first, envisaging the long-term electro-chemical energy storage, is realised by the accumulator battery. The second, acting in the short term, stores kinetic energy by means of a high-speed flywheel. These two storage elements allow bidirectional power flow.

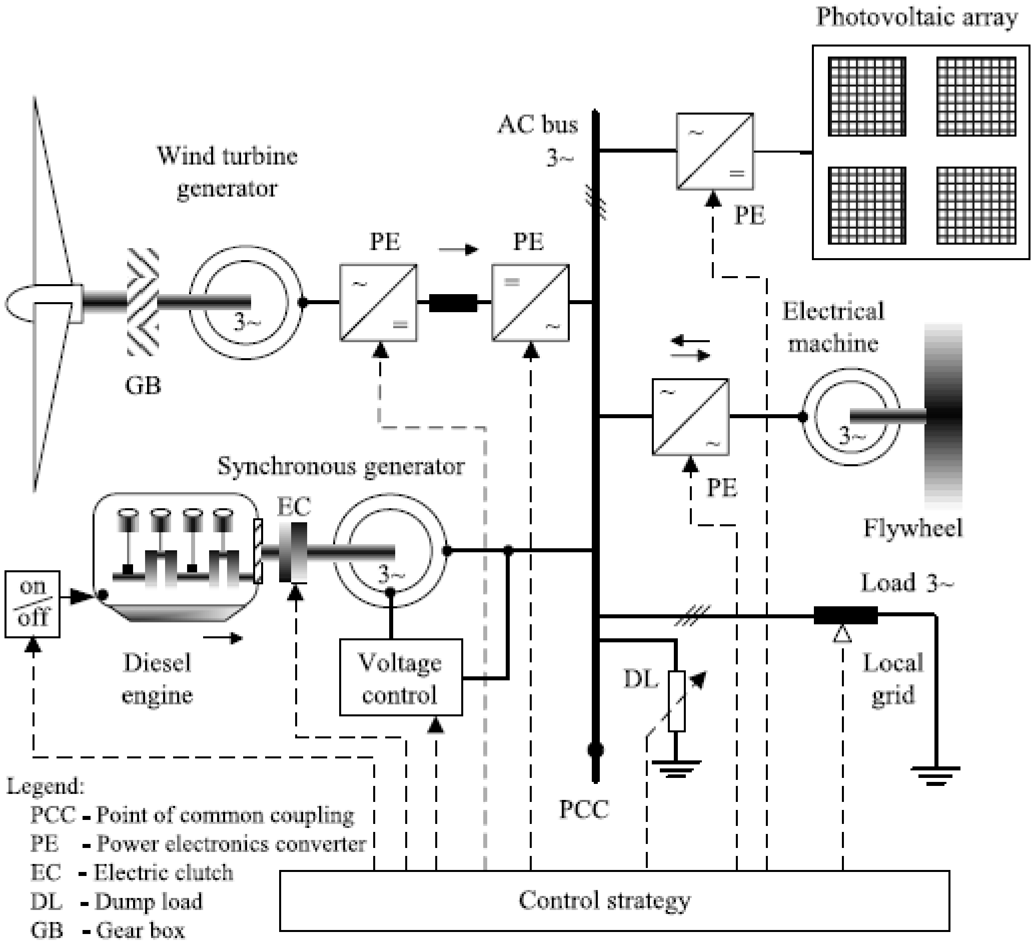


Figure 12. AC-coupled hybrid generation system

Here are the guidelines of how the system in Figure 12 operates. When the wind speed is low, WECS generates less power than the load (local utilities) needs, and the diesel engine is turned on, compensating the active power imbalance. When the wind velocity is sufficiently high, the diesel engine is shut down, and the synchronous generator acts as reactive power compensator. Concerning the flywheel, it accumulates kinetic energy when the high winds induce energy in excess. In case of short wind gaps the flywheel delivers power to the AC bus. The photovoltaic system represents the emergency solution. Concerning the DC-connected generation system, an example is given in Figure 13. In this configuration some short-term energy storage units can be supplementary introduced (*e.g.*, the flywheel device driven by a switched reluctance machine).

Figure 13 is self-explanatory; each moment the power fed into the DC-bus is the result of the wind turbine, diesel-generator, and photovoltaic array and accumulator power contributions, depending on their operating regimes. The control objective aims at the AC load being continuously supplied with energy. Depending on the operating regime the turbine can be controlled either for maximum power point tracking or for power limiting. The reliability requirements are important in these structures.

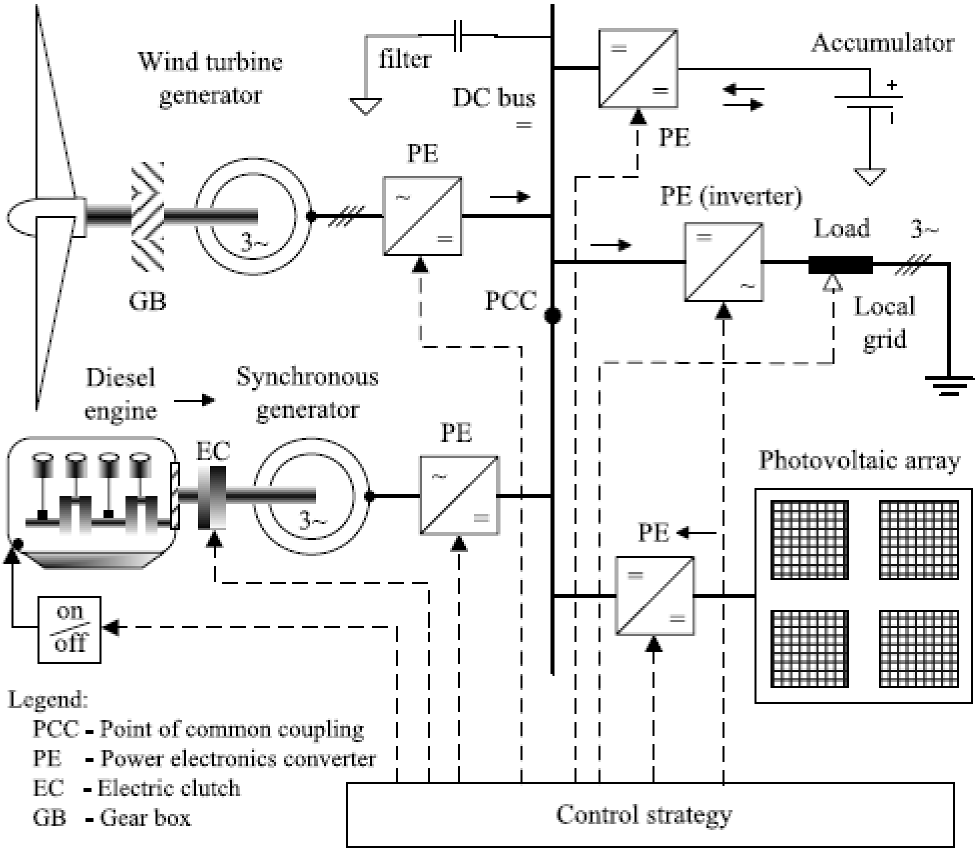


Figure 13. DC-coupled hybrid generation system