Control Logic Algorithm for Medium Scale Wind Turbines

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Abstract

Recently, sustainable attention has been drawn to renewable energy sources. Wind energy systems as renewable source of energy have been extensively studied because of its benefits as an environmentally friendly clean energy, inexhaustible, safe and a low-cost for long term. Because of its unpredictable availability, power management control algorithms are essential to extract as much power as possible from the wind during its availability durations. This paper is motivated for proposing the main control algorithm for wind turbines each incorporating two generators. The proposed main algorithm contains several sub algorithm models (strategies) for power control, pitch control, status checking, starting, grid connection, normal and emergency shutdown that are studied, designed and also, tested under operation. The testing phase shows that in the high wind speed range, the pitch control seems the most relevant to release a power margin. While in the low wind speed range, the increase of the rotation speed is more convenient.

Keywords: *wind turbine, control logic algorithm, pitch control, status checking, starting, grid connection, normal shut down, and emergency shutdown*

1. Introduction

Wind energy has been harnessed by many generations for thousands of years to mill grain, pump water and sailing [5]. Just in last decade, the wind energy industry has experienced a growth of almost 30 percent each year [1]. Due to the increasing concern about the environment and the depletion of natural resources such as fossil fuels, much research is now focused on obtaining new environmentally friendly sources of power. The lack of accurate models must be countered by robust control strategies capable of securing stability and some performance features despite model uncertainties. The controller measures the following parameters as analogue signals Voltage on all three phases, Current on all three phases, Frequency on one phase, Temperature inside the nacelle, Generator temperature, Gear oil temperature, Gear bearing temperature, Wind speed, The direction of yawing, Low-speed shaft rotational speed and High-speed shaft rotational speed. The controller also measures the following parameters as digital signals Wind direction, Over-heating of the generator, Hydraulic pressure level, Correct valve function, Vibration level, Twisting of the power cable, Emergency brake circuit, Brake-caliper adjustment, Overheating of small electric motors for the yawing, hydraulic pumps, etc. by several sensors[21]. The control problems are even more challenging when turbines are able to operate at variable speed and variable pitch. The best use of this type of turbine can only be achieved by means of multivariable controllers. However, due to wind's erratic nature, intelligent control strategies must be implemented to harvest as much potential wind energy as possible while it is available. Because of its advantages, erratic nature, and recent technological advancements in wind turbine aerodynamics and power electronic interfaces, wind energy is considered to be an excellent supplementary energy source. Research to extract the maximum power out of wind energy is an essential part of making wind energy much more viable and attractive. In addition to increasing the energy capture, wind turbines can be controlled to reduce the loading on the drive-train and tower structure, leading to potentially longer installation life. Increasingly, modern wind turbines include mechanical actuators with the aim of having control of the blade pitch angle [16]. Pitch control is commonly meant to limit the captured power above rated wind speed, bringing about more cost-effective designs.

2. Background

The equations of kinetic energy is given by Eq. (1) and power describe the potential energy that can be harnessed from the wind is described by Eq. (2) [6].

$$EK = 0.5mv_m = 0.5\rho AdV^2_w \qquad (1)$$

$$P_w = 0.5mv_m / t = 0.5\rho AdV^2_w / t = 0.5\rho AV^3_w \qquad (2)$$

A turbine's efficiency, and thus power coefficient (C_p) curve, is what differentiates one turbine from another. By taking the efficiency of the turbine into account, Eq. (3) represents the mechanical power captured by the wind by any turbine. The power coefficient can be evaluated by Eq. (4). From equation (3), it can be observed that the

$$P_w = 0.5\rho A\, C_p(\beta , \lambda)\, V^3_w \qquad (3)$$

power available in the wind is proportional to the cube of the wind speed. This means that there is much more energy in high speed winds than in slow winds.

$$C_p(\beta , \lambda) = \text{actual turbine power} / \text{theoretical turbine power} = P_m / P_w = P_m / 0.5\rho AV^3_w \qquad (4)$$

The mathematical representation of the tip speed ratio is given to be as follows in Eq. (5) [6].

$$\lambda = R\, \omega_b / V_w \qquad (5)$$

Where ρ = air density, A = rotor swept area, d = distance, m = mass of air =air density * volume = ρ*A*d, V_w = distance/time, $C_p(\beta , \lambda)$ = power coefficient function, λ = the tip speed ratio, and β = pitch angle.
To maximize the amount of power captured by the turbine, variable-speed wind turbine systems are used because they allow turbine speed variation ([2],[3],[4],[7],[8],[9],[10],[11]).

2.1 Control Strategy

The primary challenge of wind energy systems is to be able to capture as much energy as possible from the wind in the shortest time. From the electronics point of view, this goal can be achieved through different converter topologies and maximum power. The main control goals were the limitation of power and speed below some specified values to prevent the turbine from unsafe operation under high wind conditions. The control systems have been expected not merely to keep the turbine within its safe operating region but also to improve efficiency and quality of power conversion. The development of a wind turbine control system can be divided into several tasks. The first task is to define clearly the control objectives. The second task is the selection of a suitable control strategy, which settles the operating point of the turbine for each wind speed. The third task is to decide how the control strategy will be realized. It encompasses the selection of the control schemes, the controlled variables, the reference signals, the switching procedure between different controllers, etc. This step is usually referred to as controller setup. Finally the last task previous to the implementation is the design of the input-output map, i.e., the dynamic characteristics of the controller according to the specifications.

2.2 Controller Objectives

A wind turbine is essentially a device that captures part of the wind energy and converts it into useful work. In particular, Wind Energy Conversion System (WECS) connected to electric power networks must be designed to minimise the cost of supplied energy ensuring safe operation as well as acoustic emission and power quality standards [12]. The minimisation of the energy cost involves a series of partial objectives (Energy capture, Mechanical loads, Power quality).These primary objectives (partial goals) of wind turbine control systems can be arranged in the following topics.

2.2.1 Energy capture

Maximisation of energy capture taking account of safe operation restrictions such as rated power, rated speed and cut-out wind speed, etc. For a wind turbine, the generation capacity specifies how much power can be extracted from the wind taking into consideration both physical and economic constraints. It is usually represented as a curve on the generated power – wind speed plane, the so-called ideal power curve. The ideal power curve for a typical wind turbine is sketched in Figure 1. The range of operational wind speeds is delimited by the cut-in (V_{min}) and cut-out (V_{max}) wind speeds. The turbine remains stopped beyond these limits. Below cut-in wind speed, the available wind energy is too low to compensate for the operation costs and losses. Above cut-out wind speed, the turbine is shut down to prevent from structural overload. Even though wind speeds above V_{max} contain huge energy, their contribution to the annual average energy is negligible.

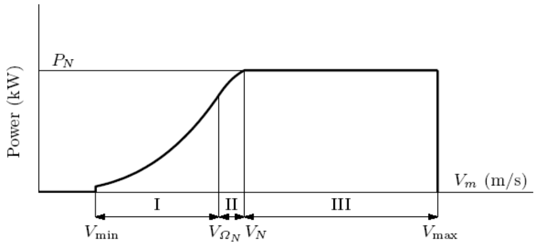

Fig. 1: Ideal power curve

This is corroborated by Figure 2 where a typical power density function at a given site is outlined. It is observed there that the energy left to be captured because of keeping the turbine stopped beyond the wind speed limits V_{min} and V_{max} is comparatively low. It can also be noted in Figure 1 that the ideal power curve remains constant at rated power

P_N above wind speed V_N named rated wind speed V_N. For instance, designing the turbine to extract all the available energy up to cut-out wind speed would lead to an increment in the cost per kW. The ideal power curve exhibits three different regions with distinctive generation objectives. At low wind speeds (region I), the available power is lower than rated power. The available power is defined as the power in the wind passing through the rotor area multiplied by the maximum power coefficient C_{Pmax}, that is So, the generation objective in region I is to extract all the available power. Therefore, the ideal power curve in this region follows a cubic parabola defined by Eq. (6). On

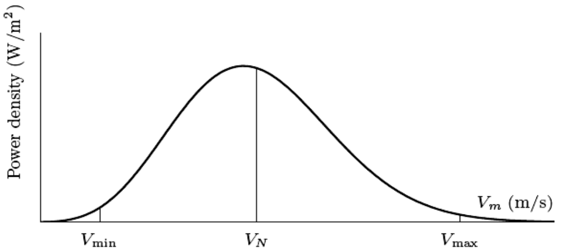

Fig. 2: Power density vs. wind speed

$$P_{av} = C_{Pmax}P_w = 0.5\rho\pi R^2 C_{Pmax}V^3 \qquad (6)$$

the other side, the generation goal in the high wind speed region (region III) is to limit the generated power below its rated value to avoid over loading. In this region the available power exceeds rated power; therefore the turbine must be operated with efficiency lower than C_{Pmax}. Finally, there is region II, which is actually a transition between the optimum power curve of region I and the constant power line of region III. In this region, rotor speed is limited to maintain acoustic noise emission within admissible levels and to keep centrifugal forces below values tolerated by the rotor. Eventually, in the case that such a speed limit is not reached, region II may not exist and the optimum power curve (i.e., region I) may continue until getting to rated power. So the control strategy settles the steady-state values of torque (or power) and rotor speed for each wind speed within the range of turbine operation. The control strategy affects the controller setup and design. In fact, the control schemes may differ from one region of operation to another.

2.3.2 Mechanical loads

Mechanical loads preventing the WECS from excessive dynamic mechanical loads. This general goal encompasses transient loads alleviation, high frequency loads mitigation and resonance avoidance. Considering the minimisation of the energy cost, the control system should not merely design to track as tightly as possible the ideal power curve. The mechanical loads wind turbines are exposed to must also be considered [13] because it may cause fatigue damage on several devices, thereby reducing the useful life of the system. The transition between maximum power tracking (region I) and power regulation (region III) and the way power is limited in above rated wind speeds have a direct impact on transient loads. Unsuitable control strategies may inevitably lead to strong transient loads. Cyclic loads are highly influenced by the control strategy as well as by the controller setup and design. The control of the electric generator affects the propagation of drive-train loads whereas the pitch control impacts directly on the structural loads. Therefore, inappropriate control designs might accentuate the vibration modes, potentially leading to the destruction of some mechanical devices such as gearbox or blades. The controller must provide damping at the vibration modes whenever possible in order to mitigate high frequency loads and reduce the risk of fatigue breakdown. So, the control strategy must avoid operation at points where those vibration modes that cannot be damped by the controller are likely to be excited ([14], [12]).

2.2.3 Power quality

Power quality conditioning the generated power to comply with interconnection standards to smooth the power supplied to the grid. It affects the cost of energy in several ways. Poor power quality may demand additional investments in power lines, or may impose limits to the power supplied to the grid. The control system design must also take power conditioning into account. This control requirement is more and more relevant as the power scale of wind generation facilities approaches the output rating of conventional power plants [34]. Power quality is mainly assessed by the stability of frequency and voltage at the point of connection to the grid and by the emission of flicker [15].The interaction of wind turbines with the power network affects the voltages at the grid terminals. On the one hand, slow voltage excursions take place when the power extracted by the WECS changes with mean wind speed. The amplitude of these variations closely depends on the impedance of the grid at the connecting point and on the active and reactive power flow. Reactive power, power factor or, directly, voltage regulation can be accomplished by an adequate control of the electronic converters ([16],[17]). The voltage fluctuations and flicker can be attenuated by including passive or active filters, or by controlling the reactive power handled by the electronic converters ([18],[19],[20]). Also, they can be smoothed indirectly by tackling the propagation of the cyclic loads. This is achieved incorporating dynamic damping to the drive-train by means of a suitable control of the generator torque characteristic [12]. These objectives are actually closely related and sometimes conflicting. Therefore, they should not be pursued separately. Conversely, the control target is to find a well balanced compromise among them. Some control strategies are designed to maximize the energy extraction; others accept a reduced energy capture in order to avoid operating regions where heavy mechanical loads are being inevitable.

3. The Proposed Control Logic Algorithm

The proposed algorithms, depicted in figure (3), comprise several modules .Those modules are hydraulic pump, tip brake, disc brake, generator etc. All these modules are controlled by main control. Main control manages when to apply the disc brake, pull in the tip brake or connect the generator to the grid.

3.1 Main control module

The main control module is divided into four main states as described in figure (3). Each state indicates generally what the turbine is doing. Each main state contains several sub states. The sub states describe more specifically what the turbine is doing. It could either produce on generator 1(G1), change from (G1) to generator 2(G2) or using emergency Brake programme to stop the turbine.

3.2 Main states

Figure (3) shows the four main states. The arrow shows how the proposed programme goes from one main state to another. One thing special is that from Start to Operate, the proposed programme can go directly to Braking. If a stop condition becomes active it can interrupt any running sub state, No matter which sub state is running. The stop main state (Stopped) contains all the sub stop states which handle all stop conditions as Emergency stop, grid failure etc. Start of wind turbine (Start state). Self tests and start sequence are performed. Brakes down the wind turbine (Braking state) by applying the mechanical disc brake or releases the tip brakes. The rotor speed will decrease and when the rotor reaches zero rpm, the programme will continue to main state Stopped. The wind turbine is producing power on either the G2 or G1 (Operate state).

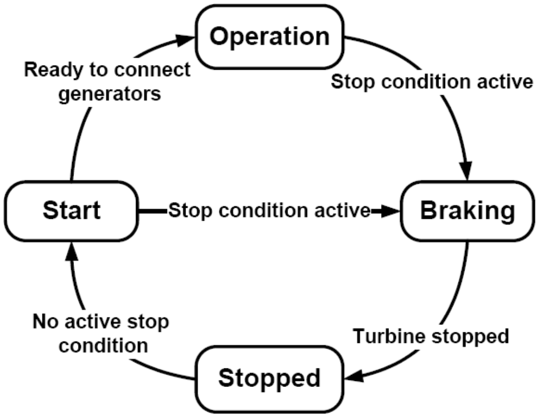

Fig. 3: The main control module

4. Control logic general description

Figure (4) describes the developed state diagram for the control logic of the proposed wind turbine controller. The Protection functions related to grid errors, temperatures and over speed are implemented to ensure protection of the turbine mechanical and electrical system. The normal operation of the wind turbine will be discussed including normal start up and shut down. Then the emergency situations will be described and finally wind turbine reactions to previously stated models will be described. The off operation can be generally classified into temporary and stationary. In Temporary modes the wind turbine is meant to be on them for a limited period of time. These modes are status checking, starting, grid connection, normal shut down and emergency shutdown. In The Stationary modes the wind turbine can be on for an unlimited period of time. The Stationary modes include stop and normal operation (partial load and full load). In the following, subsections the state diagram mode are described.

4.1 Stop mode

In this mode the generator is disconnected from the grid, the blades are 90 degrees to the rotor plane (pitch control) and mechanical brake on. This status can be achieve as a normal stop for example when there is no wind, after manual stop (by the operator), or after an emergency stop. In the last two cases the wind turbine will not change its mode until is reset by operator.

4.2 Status checking

After the turbine has been order to start, the controllers checks the status of all subsystem and reads all measurable variables, and then check that this values are within the acceptable range. During this process if any error sign appears, the preposed controller invalidates any other mode.

4.3 Starting

After the status has been checked and no error sign appears and the average wind speed match the desired one, the mechanical brake is released and the blades are pitched the rotor will start turning and when the connection conditions are achieve (normally it means a certain rotor speed), the grid connection process start

4.4 Grid connection

The grid connection has normally two steps soft connection and normal connection. The soft connection is used for few seconds just to avoid the high current and high mechanical loads. Then after the equilibrium condition is reached the connection shift to the normal connection.

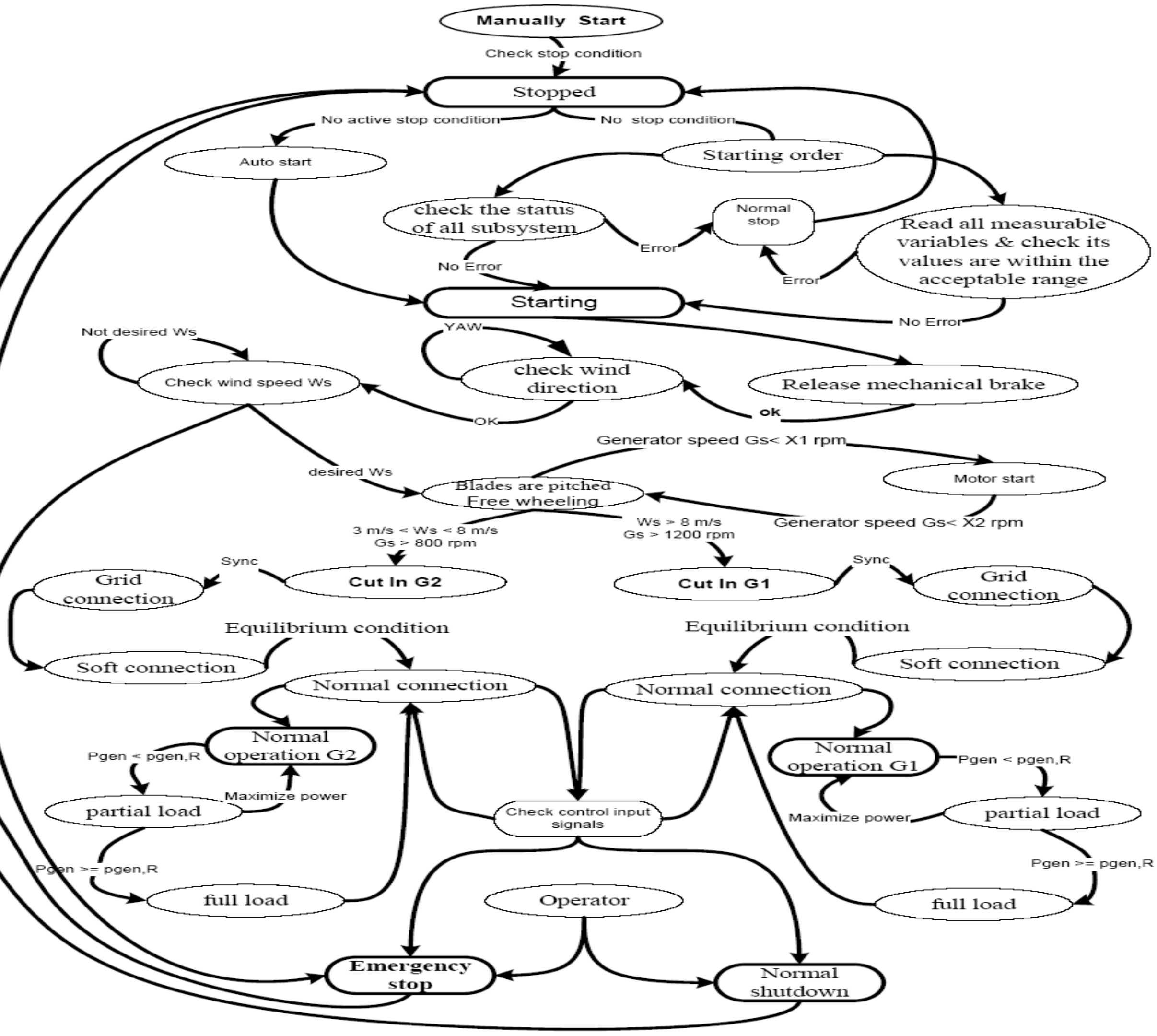

Fig. 4: The state diagram control logic

4.5 Normal operation

As discussed previously the turbine operation include two main power areas (partial load and full load).each power area has a distinct objective to be fulfilled by the control. In the pre rated power area the main objective is to maximize power production. While the post rated power area the main objective turn as into keeping the power under control as well as the loads on the machinery and the electrical part.

4.6 Normal shutdown

Depending on the design there could be several reason for a normal shutdown one of the most common are the low wind condition, by operator, and some control variable that is out of limit like oil temperature, excessive wind, etc. If one of the above mentioned conditions in detected by the controller the blades pitch start normal stop mode.

4.7 Emergency stop

Emergency stop occurs in the same way as the normal shutdown but faster. Some examples of event that can result in this kind of stop are big vibrations, over speed of the generator.

5. Main Control algorithm

The required algorithm can then be formulated according to the developed state diagram into the following main algorithm, Figure (4). This subsection considers an illustration to describe the operation of the proposed controller. The main control algorithm for the wind turbine is sketched in Figure (5).The control proposed algorithm designed through understanding how all operation state of wind turbine system is combined. an imaginary situation is consider where the wind will rise from 0 till 25 m/s in steady steps longer that 10 min. and try to follow the control procedures by using the ideal power curve sketched in Figure (1)..While the wind speed is below V_{min} (3) m/s the system will not issue any order. When V_{min} (3) m/s is reached then the status checking is performed. If there is an error sign the stop order will be issue. If all parameter are ok the yaw system is activated and the wind turbine start to keep tracking of the wind direction but the brake is still on because there is not enough wind to produce power effectively. When the wind gets to 4 m/s the mechanical brake is release and the blades are Pitch to the right angle (pitch controlled) so the rotor start turning by itself and accelerates until it reaches the synchronous condition then the grid connection mode takes over and the soft connection is activated first and after few seconds the main contactor for the grid connection is activated. In cases of a wind turbine with a two generators, the small generator will be trigger first. This generator is slower than the bigger one (2/3) and the power is also smaller (8/27).In other cases will result in a set of control parameters for the pitch angle and maximum torque. The turbine is now connected to the grid in the normal operation mode Figure (6) and in the partial load area. In the case of variable pitch and variable speed turbine adjustment of parameter (pitch angle, rotor speed) will be needed to maximize power production. When the power reaches to a value over 80 % of the nominal power of the small generator the conditions are given to trigger the bigger generator. This process cannot be done directly because the speed of the two generator are different and the second ones in higher than the first one so if we connected directly it will implicated a big consumption of energy and big loads in the mechanical parts and the blades. So the normal procedure will be to set the rotor free and allowed to accelerate by itself and when we reach the new synchronous conditions the grid connection process starts again. Any ways the control box will keep the surveillance of the operation and safety parameter. This last mode will continue as long as the wind speed is below V_{max} 25 m/s. when the wind speed goes over 25 m/s the turbine receive the order to change to normal shutdown modes. Then blades are pitch at (3-6) degree per second toward the wind and the generator is disconnected from the grid after the rotor have reduced the speed to zero the mechanical brake is applied.

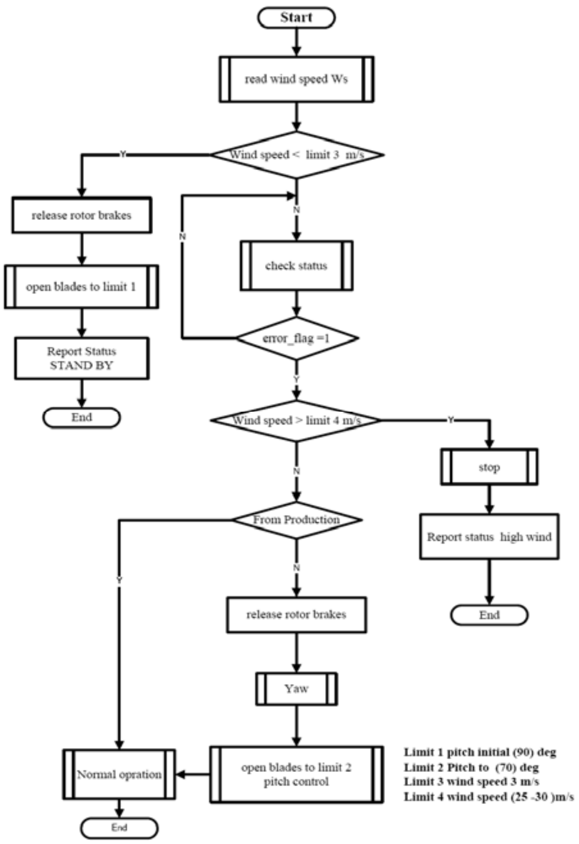

Fig. 5 The main control algorithm for wind turbine

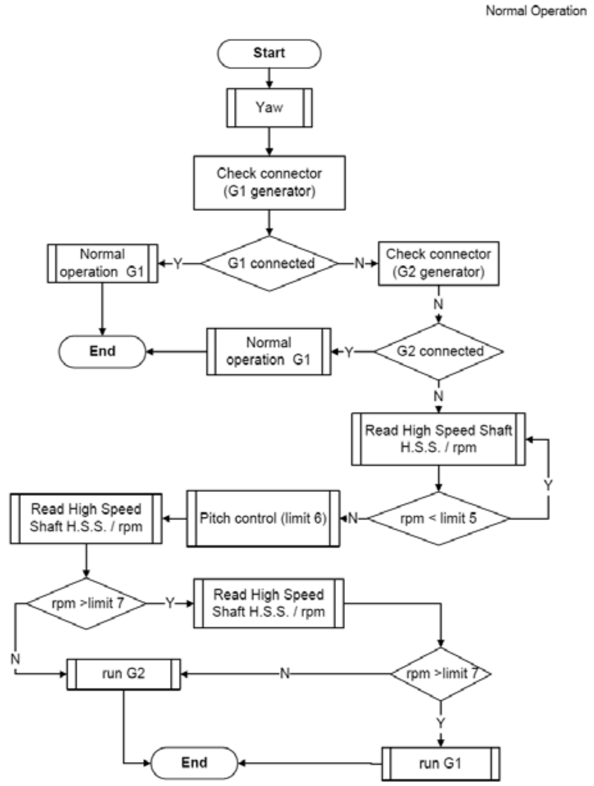

Fig. 6 The normal operation algorithm

6. Results

The control Algorithm was tested on a wind turbine through separate stages for the following functions: automatically directing the wind turbine in wind direction (yawing), Removing the era of automatic cable (cable twist), the normal stop and emergency shutdown of the turbine, and other jobs done manually, such as, Guide the turbine to the right and left, Control the opening angle of blade (from angle 2 ° to 90 ° angle), Stop the turbine and run manually, response of the turbine failures. All the previous functions successfully tested individually and then collected together, Nacelle is automatically directed to face the wind according to wind direction sensor signal, and also manually through the unit of the (hand held). The wind turbine is automatically stopped at the arrival of signal cables to the era then the controller directs the Nacelle automatically (YAW) in the opposite direction to lift the age of the cables. Finally the normal operation algorithm tested successfully and the turbine produced power and changing from generator 1(G1) to generator 2(G2) according to wind speed.

7. Conclusion

Due to wind's unpredictable nature, power management concepts are necessary to extract as much power as possible from the wind when it becomes available. The proposed algorithm has been developed to maintain the system at its highest possible efficiency by using its memory feature to infer the optimum parameters for wind turbine that have not occurred before. Another feature of the proposed algorithm is that it can be easily customized for various wind turbines since it is independent of turbine characteristics. The proposed algorithm uses a modified version of an algorithm that tested on 20 / 100 kW wind turbine in Hurghada area . This algorithm is characterized as the most appropriate for isolated electrical network (small and medium-sized wind power with or without battery) or for the electrical network connected to the network. The proposed algorithm has gleaned insight into the practical considerations of design control systems for wind turbines. A distinction has been made between supervisory and safety control and separate control issues identified. Common control systems and methods for implementation of these systems in modern wind turbines have been examined. The approach to controlling a wind turbine may vary but the primary objectives remain the same.

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