Modelling and Simulation of Wind Energy using SEIG and Solar PV System for Electrical Power Generation

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Abstract:
Due to ever increasing energy consumption, rising public awareness of environmental protection, and steady progress in power deregulation, alternative i.e., renewable distributed generation (DG) systems have attracted increased interest. Wind and photovoltaic (PV) power generation are two of the most promising renewable energy technologies. PV systems also show great potential in DG applications of the future due to their fast technology development and many merits they have, such as high efficiency, zero or low emission (of pollutant gases) and flexible modular structure. The modeling and control of a hybrid wind/PV/FC DG system is addressed in this paper. Different energy sources in the system are integrated through DC bus. Dynamic models for the main system components, namely, wind energy conversion system (WECS), PV energy conversion system (PVECS) and power electronic interfacing circuits are developed. Power control of a grid-connected PV and wind energy conversion system as well as load mitigation control of a stand-alone system is investigated. The pitch angle control for WECS and the maximum power point tracking (MPPT) control for PVECS are also addressed in the paper. Based on the dynamic component models, a simulation model for the proposed hybrid energy system has been developed using MATLAB/Simulink.

Keywords: Photovoltaic system, converter (AC-DC) and MPPT technology

1 INTRODUCTION

We all know that the world is facing a major threat of fast depletion of the fossil fuel reserves. Most of the present energy demand is met by fossil and nuclear power plants. A small part is met by renewable energy technologies such as the wind, solar, biomass, geothermal etc. There will soon be a time when we will face a severe fuel shortage. As per the law of conservation of energy, “Energy can neither be created, nor be destroyed, but it can only be converted from one form to another”. Most of the research now is about how to conserve the energy and how to utilize the energy in a better way. Research has also been into the development of reliable and robust systems to harness energy from nonconventional energy resources. Among them, the wind and solar power sources have experienced a remarkably rapid growth in the past 10 years. Both are pollution free sources of abundant power. With high economic growth rates and over 17 percent of the world’s population, India is a significant consumer of energy resources. Despite the global financial crisis, India’s energy demand continues to rise. India consumes its maximum energy in Residential, commercial and agricultural purposes in comparison to China, Japan, and Russia.[1] Solar energy is energy from the Sun. It is renewable, inexhaustible and environmental pollution free. Solar charged battery systems provide power supply for complete 24 hours a day irrespective of bad weather. By adopting the appropriate technology for the concerned geographical location, we can extract a large amount of power from solar radiations. More over solar energy is expected to be the most promising alternate source of energy. The global search and the rise in the cost of conventional fossil fuel is making supply-demand of electricity product almost impossible especially in some remote areas. Generators which are often used as an alternative to conventional power supply systems are known to be run only during certain hours of the day, and the cost of fueling them is increasingly becoming difficult if they are to be used for commercial purposes. Wind energy is the kinetic energy associated with the movement of atmospheric air. It has been used for hundreds of years for sailing, grinding grain and for irrigation. Wind energy systems convert this kinetic energy to more useful forms of power. Wind energy systems for irrigation and milling have been in use since ancient times and at the beginning of the 20th century it is being used to generate electric power. Windmills for water pumping have been installed in many countries particularly in the rural areas. Wind turbines transform the energy in the wind into mechanical power, which can then be used directly for grinding etc. or further converting to electric power to generate electricity. Wind turbines can be used singly or in clusters called ‘wind farms.’

II SYSTEM DESCRIPTION AND MODELING
A) SOLAR CELL MODEL
a) Equivalent circuit of a solar cell
In order to analyze the electronic behaviour of a solar cell, an electrical equivalent model is considered. An ideal PV cell may be considered as a current source in parallel with a diode. In practice a PV cell is not ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit is shown in the Figure 1,
Photovoltaic (PV) System
The most commonly used model for a PV cell is the one-diode equivalent circuit as shown in Figure 2. Since the shunt resistance $R_s$ is large, it normally can be neglected. The five parameters model shown in Figure 2 (a) can therefore be simplified into that shown in Figure 2 (b). This simplified equivalent circuit model is used in this study.

![Fig. 1: Equivalent circuit](image)

Figure 2. One-diode equivalent circuit model for a PV cell (a) Five parameters model; (b) Simplified four parameters model

The relationship between the output voltage $V$ and the load current $I$ can be expressed as:

$$I = I_L - I_D = I_L - I_0 \left[ \exp \left( \frac{U + IR_s}{\alpha} \right) - 1 \right]$$

(1)

Where $I_L$ = light current (A);
$I_0$ = saturation current (A);
$I$ = load current (A);
$V$ = output voltage (V);
$R_s$ = series resistance (r);
$W$ = thermal voltage timing completion factor (V)

There are four parameters ($I_L$, $I_0$, $R_s$, and $W$) that need to be determined before the $I$-$V$ relationship can be obtained. That is why the model is called a four-parameter model. Both the equivalent circuit shown in Figure 2(b) and the equation 1 look simple. However, the actual model is more complicated than it looks because the above four parameters are functions of temperature, load current and/or solar irradiance.

Characteristics of PV model

![Fig. 3: I-V characteristic curves of the PV mode under different irradiances](image)

Temperature Effect on the Model Performance
The effect of the temperature on the PV model performance is illustrated in Figures 4 and 5. From these two figures, it is noted that the lower the temperature, the higher is the maximum power and the larger the open circuit voltage. On the other hand, a lower temperature gives a slightly lower short circuit current.

![Fig. 4: P-V characteristic curves of the PV model under different irradiances](image)

![Fig. 5: I-V characteristic curves of the PV model under different temperatures](image)

Wind Energy System

Energy in Wind
Wind energy systems harness the kinetic energy of wind and convert it into electrical energy or use it to do other work, such as pump water, grains, etc. The kinetic energy of air of mass $m$ moving at speed $v$ can be expressed as,

$$E_k = \frac{1}{2}mv^2$$

(2)

During a time period $t$, the mass ($m$) of air passing through a given area $A$ at speed $v$ is:
\[ m = \rho A v t \]  
(3)

where \( \rho \) is the density of air (kg/m\(^3\)).

\[ P = \frac{1}{2} \rho A v^3 \]  
(4)

The specific power or power density of a wind site is given as

\[ P_{\text{den}} = \frac{P}{A} = \frac{1}{2} \rho v^3 \]  
(5)

It is seen that the specific power of a wind site is proportional to the cube of the wind speed.

**Power Extracted from Wind**

The actual power extracted by the rotor blades from the wind is the difference between the upstream and the downstream wind powers

\[ P = \frac{1}{2} k_m (v^2 - v_0^2) \]  
(6)

where \( v \) is the upstream wind velocity at the entrance of the rotor blades, \( v_0 \) is the downstream wind velocity at the exit of the rotor blades and \( k_m \) is the mass flow rate, which can be expressed as

\[ k_m = \rho A \frac{v + v_0}{2} \]  
(7)

Where \( A \) is the area swept by the rotor blades.

From (6) and (7), the mechanical power extracted by the rotor is given by:

\[ P = \frac{1}{2} \rho A \frac{v + v_0}{2} (v^2 - v_0^2) \]  
(8)

Let

\[ C_p = \frac{1}{2} \left[ 1 + \frac{v_0}{v} \right] \left[ 1 - \left( 1 - \frac{v_0}{v} \right)^2 \right] \]  
(9)

and rearrange the terms in (9), we have

\[ P = \frac{1}{2} \rho A v^3 C_p \]  
(10)

\( C_p \) is called the power coefficient of the rotor or the rotor efficiency. It is the fraction of the upstream wind power, which is captured by the rotor blades and has a theoretical maximum value of 0.59, shown in Figure 6. It is noted from (6) that the output power of a turbine is determined by the effective area of the rotor blades \( (A) \), wind speed \( (v) \), and wind flow conditions at the rotor \( (C_p) \). Thus, the output power of the turbine can be varied by changing the effective area and/or by changing the flow conditions at the rotor system. Control of these quantities forms the basis of control of wind energy systems.

**Tip Speed Ratio**

The tip speed ratio (TSR), defined as the ratio of the linear speed at the tip of the blade to the free stream wind speed, is given as follows

\[ \lambda = \frac{\omega R}{v} \]  
(11)

where \( R \) is the rotor blade radius and \( \omega \) is the rotor angular speed. TSR is related to the wind turbine operating point for extracting maximum power. The maximum rotor efficiency \( C_p \) is achieved at a particular TSR, which is specific to the aerodynamic design of a given wind turbine. For variable TSR turbines, the rotor speed will change as wind speed changes to keep TSR at some optimum level. Variable TSR turbines can produce more power than fixed TSR turbines.

**Wind Turbine Characteristics**

The power \( P_{\text{wind}} \) (in watts) extracted from the wind is given in equation 10. It is rewritten here as:

\[ P_{\text{wind}} = \frac{1}{2} \rho A v^3 C_p (\lambda, \theta) \]  
(12)

where \( T \) is the air density in kg/m\(^3\), \( A \) is the area swept by the rotor blades in m\(^2\), \( v \) is the wind velocity in m/s. \( C_p \) is called the power coefficient or the rotor efficiency and is a function of tip speed ratio \( \lambda \) and pitch angle \( \theta \). The maximum rotor efficiency \( C_p \) is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine. The rotor must turn at high speed at high wind, and at low speed at low wind, to keep TSR constant at the optimum level at all times. For operation over a wide range of wind speeds, wind turbines with high tip speed ratios are preferred. In the case of the variable speed pitch-regulated wind turbines considered in this dissertation, the pitch angle controller plays an important role. The following function is used.

\[ C_p = C_1 (C_2 - C_3 \theta - C_4) \exp(-C_5) \]  
(13)

Where \( \theta \) is the pitch angle.

Proper adjustment of the coefficients \( C_1-C_5 \) would result in a close simulation of a specific turbine under consideration.
The values for C1-C5 used in this study are listed in Table 1. The $C_p\cdot u$ characteristic curves at different pitch angles are plotted in Figure 10. From the set of curves in Figure 10, we can observe that when pitch angle is equal to 2 degrees, the tip speed ratio has a wide range and a maximum $C_p$ value of 0.35, suitable for wind turbines designed to operate over a wide range of wind speeds. With an increase in the pitch angle, the range of TSR and the maximum value of power coefficient decrease considerably.

Table 1 PARAMETER VALUES FOR C1-C5

<table>
<thead>
<tr>
<th>$C_1$</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_2$</td>
<td>116/2η</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0.4</td>
</tr>
<tr>
<td>$C_4$</td>
<td>5</td>
</tr>
<tr>
<td>$C_5$</td>
<td>21/2η</td>
</tr>
</tbody>
</table>

The pitch angle controller used in this study employs PI controllers as shown in Figures. These controllers control the wind flow around the wind turbine blade, thereby controlling the torque exerted on the turbine shaft. If the wind speed is less than the rated wind speed, the pitch angle is kept constant at an optimum value. If the wind speed exceeds the rated wind speed, the controller calculates the power error (between the reference power and the output power of the wind turbine) and the frequency error (between the measured stator electrical frequency of the SEIG and the rated frequency). The output of the controllers gives the required pitch angle. In this figure, the Pitch Angle Rate Limiter block limits the rate of change of pitch angle as most modern wind turbines consist of huge rotor blades. The maximum rate of change of the pitch angle is usually in the order of 3o to 10o/second.

$k_\phi$ in Table 1 used to calculate $C_2$ and $C_5$ is determined by $u$ and $\theta$ as:

$$k_\phi = \left[ \frac{1}{\lambda + 0.08\theta} \right]^{-\frac{0.035}{\theta^3 + 1}}$$

(14)

For variable speed pitch-regulated wind turbines, two variables have direct effect on their operation, namely rotor speed and blade pitch angle. Power optimization strategy is employed when wind speed is below the turbine rated wind speed, to optimize the energy capture by maintaining the optimum TSR. Power limitation strategy is used above the rated wind speed of the turbine to limit the output power to the rated power. This is achieved by employing a pitch angle controller which changes the blade pitch to reduce the aerodynamic efficiency, thereby reducing the wind turbine power to acceptable levels, as discussed. The different regions of the above-mentioned control strategies of a variable speed wind turbine system are as shown.

Variable-speed Wind Turbine Model

The dynamic model of the variable speed wind turbine are developed in MATLAB/Simulink. Figure 13 shows the block diagram of the wind turbine model. The inputs for the wind turbine model are, wind speed, air density, radius of the wind turbine, mechanical speed of the rotor referred to the wind turbine side and power reference for the pitch angle controller. The output is the drive torque $T_{drive}$ which drives the electrical generator. The wind turbine calculates the tip speed ratio from the input values and estimates the value of the power coefficient from the performance curves. The pitch angle controller maintains the value of the blade pitch at optimum value until the power output of the wind turbine exceeds the reference power input.

Dynamic Model for SEIG

There are two fundamental circuit models employed for examining the characteristics of a SEIG. One is the per-phase equivalent circuit which includes the loop-impedance method adapted by Murthy et al and Malik and Al-Bahran and Ouazene and McPherson and Chan. These methods are suitable for studying the machine’s steady-state characteristics. Another
method is the dq-axis model based on the generalized machine theory proposed by Elder et al and Grantham et al, and is employed to analyze both the machine’s transient as well as steady-state.

**Steady-state Model**

Steady-state analysis of induction generators is of interest both from the design and operational points of view. By knowing the parameters of the machine, it is possible to determine its performance at a given speed, capacitance and load conditions. Loop impedance and nodal admittance methods used for the analysis of SEIG are both based on per-phase steady-state equivalent circuit of the induction machine, modified for the self-excitation case. They make use of the principle of conservation of active and reactive powers, by writing proper loop equations or nodal equations, for the equivalent circuit. These methods are very effective in calculating the minimum value of capacitance needed for guaranteeing self-excitation of the induction generator. For stable operation, excitation Capacitance must be slightly higher than the minimum value. Also, there is a speed threshold, the cutoff speed of the machine, below which no excitation is possible. In the following paragraph, a brief description of the loop impedance method is given for better understanding. The per-unit (p.u.) per-phase steady-state circuit of a self-excited induction generator under lagging (RL) load is shown in Figures. In the analysis of SEIG, the following assumptions were made:

1. Only the magnetizing reactance $X_m$ is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant. Self-excitation results in the saturation of the main flux and the value of $X_m$ reflect the magnitude of the main flux. Leakage flux passes mainly in the air, and thus these fluxes are not affected to any large extent by saturation of the main flux.

2. Per unit values of the stator and rotor leakage reactance (referred to stator side) are assumed to be equal ($X_{ls} = X_{lr} = X_p$). This assumption is normally valid in induction machine analysis.

3. Core loss in the machine is neglected.

**Fig 12 Equivalent T circuit of self-excited induction generator with R-L Load**

In the figure, the symbols are: $R_s$, $R_r$, $R$ : p.u. per-phase stator, rotor (referred to stator) and load resistance respectively.

$X_l$, $X_r$, $X_m$ : p.u. per-phase stator/rotor leakage, load and magnetizing reactances (at base frequency), respectively.

$X_c$ : p.u. per-phase capacitive reactance (at base frequency) of the terminal excitation Capacitor.

$f$, $v$ : p.u. frequency and speed, respectively.

Vg, V0 : p.u. per-phase air gap and output voltages, respectively. For the circuit shown in Figure 4.36, the loop equation for the current can be written as:

$$I Z = 0$$

Where $Z$ is the net loop impedance given by

$$Z = \left( \frac{R}{f - v} + jX \right)$$

For equations to hold true for any current $I$, the loop impedance ($Z$) should be zero. This implies that both the real and imaginary parts of $Z$ are zero. These two equations can be solved simultaneously for any two unknowns, such as $f$ and $X_c$.

**Simulation result**

**Responses of the Model for the Variable Speed WECS**

The model of a 550 W variable speed wind energy conversion system consisting of a pitch-regulated wind turbine and self excited induction generator is developed in MATLAB/Simulink environment using SimPowersystems block-set.

1. **Wind Turbine Output Power Characteristic**

Figure 15 shows the wind turbine output power of the simulated model for different wind velocities. It can be observed that the output power is kept constant at higher wind velocities even though the wind turbine has the potential to produce more power. This is done to protect the electrical system and to prevent the over speeding of the rotor.

**Fig 13 Wind turbine output power characteristic**

2. **Process of Self-excitation in SEIG**

The process of self-excitation can occur only if there is some residual magnetism. For numerical method of integration, residual magnetism cannot be zero at the beginning of the simulation. Therefore, non-zero initial values are set for $K_q$ and/or $K_d$, and the rotor speed. The process of voltage build up continues, starting with the help of the residual magnetism, until the iron circuit saturates and therefore the voltage stabilizes. In other terms, the effect of this saturation is to modify the magnetization inductance $L_m$, such that it reaches a saturated value; the transient then neither increases nor decreases and becomes a steady state quantity giving continuous self-excitation. The energy for the above process is provided by the kinetic energy of the wind turbine rotor. Figure shows the process of a successful self excitation in an induction machine under no load condition with wind speed at 10m/s. The value of the excitation capacitor is given in the figure. An unsuccessful self excitation process under the same condition (except a smaller capacitor bank) is shown in Figure.
Final Result Of Hybrid DC System

Final result obtained after simulation on matlab simulink 2013 environment is shown below. When solar PV cell and wind turbine combine then 150 V DC is obtained after this by using SVPWM inverter this DC power is converted into AC power. Simulation is carried out for 2 sec.

The wave forms show the output voltage and output current its peak value magnitude is 80 V and 20 amp. When the one more load is connected the value of current is increases while at that time voltage magnitude decreases.

References


