MPPT for Hybrid Energy System Using Gradient Approximation and Matlab Simulink Approach

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Abstract: This paper applies new maximum-power-point tracking (MPPT) algorithm to a hybrid renewable energy system that combines both Wind-Turbine Generator (WTG) and Solar Photovoltaic (PV) Module (SPVM). In this paper, the WTG is a direct-drive system and includes wind turbine, three-phase permanent magnet synchronous generator, three-phase full bridge rectifier, and buck-bust converter, while the SPVM consist of solar PV modules, buck converter, maximum power tracking system for both systems, and load. Several methods are applied to obtain maximum performances, the appropriate and most effective method is called gradient-approximation method for WTG approach, because it enables the generator to operate at variable wind speeds. Furthermore MPPT also is used to optimized the achieved energy generated by solar PV modules. Matlab/Simulink approach is used to simulate, discuss, and optimized the generated power by varying the duty cycle of the converters, and tip speed ratio of the WTG system.

Key words: Matlab simulation, renewable energy, solar energy, wind energy, hybrid energy, gradient approximation, synchronous motors and PWM.

1. Introduction

Existing traditional energy resources are consumed extremely fast because of industrial growth and consumer behaviors. Therefore looking for another resources (renewable energy resources) presents high priority for large number of industrial countries suffers from energy shortages and working on enhancing the surrounding environment. The use of renewable energies can mitigate the use of traditional resources and reduce significantly emission to meet the strict requirements stated in the Kyoto protocol [1], which is an agreement under which industrialized countries will reduce their collective emissions of greenhouse gases including CO₂ in 2012 by 5.2% compared to year 1990.

Several studies describing Hybrid Energy systems has been conducted in the past decade [2, 3], where the design is based on particular scenario with a certain set of design values yielding the optimum design solution only. Because of that, these systems have been widely used for electricity supply in isolated locations far from the distribution network. Well design of such systems leads to providing a reliable service and operation in an unattended manner for extended period of time. At the same time hybrid system suffer from the fluctuating characteristics of available solar and wind energy sources, which must be addressed in the design stages. Ekren [4] states that, the degree of desired reliability from a solar and wind process so as to meet a particular load can be fulfilled by a combination of properly sized wind turbine, PV panel, storage unit and auxiliary energy source. Fig. 1 illustrates a schematic diagram of a basic hybrid energy system, where it seen that, the electricity produced via PV array and wind turbine are regulated by voltage regulator components and the excess electricity produced by this system is stored by the battery banks to be used for later lacking loads.

This paper discusses the wind and solar power gene-
ration. Especially, the variable speed and solar radiations control are addressed. Ying-yi Hong and another researchers [5-7] stated that variable-speed system is better than constant-speed because of the variable-speed control include: the maximum power extraction, improvement the dynamic behaviors of the turbine, and noise reduction at low speed levels. According to these research studies, realizing successful variable-speed control, two control sensors are required for MPPT, they are the wind-speed sensor (Anemometer) and rotor-velocity encoder (Tachometer).

On the other hand SPVM consists of cells, modules, and arrays that must operates at maximum power level by applying MPPT system[8-10]. MPPT system operates successfully by existing radiation and temperature sensors. These sensors realized system operation at maximum power at variable radiations and surrounding temperature.

Eliminating all of the above mentioned sensors and additional control modules such as PID [11] can be achieved by applying adaptive duty cycle method with Gradient Approximated (GA). Several research approaches were conducted in order to analyze the behaviors of wind turbine performances, and solar cell performances. Various conclusions and recommendations were proposed with respect to achieve maximum power ratings. Very efficient control algorithm was proposed by Datta and Ranganathan, where a generator velocity reference being dynamically modified in accordance with the magnitude and direction of change of active power [12]. The peak power points in the P-ω mechanical curve corresponds to dP / dω =0. The duty cycle is adjusted by the steepest ascent algorithm in which a derivative of electric power (Pe) with respect to (D) equals zero for various speed or irradiation levels.

2. Wind-Turbine Generation System

The wind turbines has various designed modification depending on the output parameters, generated power, reliability and cost reduction. The proposed wind-turbine design circuit is shown on Fig. 2, where regulating the operation time of the chopper switching devices is achieved by regulating the duty cycle D, which is in turn is regulated by applying the gradient approximation approach. Fig. 3 illustrates the power versus the rotor angular velocity at various wind speed.

2.1 Characteristics of Wind-Turbine

The mechanical power of a wind-turbine is a function of the power coefficient Cp. furthermore, Cp is a function of the Tip Speed Ratio (TSR) λ can be formulated as follows[6]:

\[
C_p = a + b \lambda + c \lambda^2 + d \lambda^3 + e \lambda^4 + f \lambda^5 \tag{1}
\]

Where \(a, b, c, d, e\) and \(f\), are constants depending on the turbine performances and can be obtained by polynomial regression [13, 14]. Fig. 4 illustrates the relation between \(C_p\) and \(\lambda\) with respect to the speed torque ratio TSR.

2.2 Mathematical Modeling

Way out from the dynamic equation of the generator system is:

\[
\frac{d \omega_m}{dt} = \frac{1}{j} (T_e - T_m) = \frac{1}{j} \left( \frac{P_m}{\omega_m} - P_e \right) \tag{2}
\]

Where: \(T_e\) and \(T_m\) are the electromagnetic and mechanical torque respectively; \(j\) is the generator inertia; \(\omega_m\) and \(\omega_e\) are the mechanical and electrical angular frequency respectively.

![Fig. 1 Schematic diagram of a basic hybrid energy system.](image-url)
The static relation of the Buck-Boost converter can be expressed as follows:

\[
V_o = V_r \cdot \frac{D}{1 - D}; \quad P_e = V_o \cdot I_o
\]

The above equations Eq.(2), and Eq.(3) will be used for the simulating the dynamic behaviors of a WTG.

Furthermore there is no need to solve these equations. One only needs several measured signals of \( P_e \) and \( \omega_e \).

2.2.1 The Concept of Gradient Approximation Method (GA)

The main reason for applying the Gradient Approximation is that the maximum power curve cannot be formulated as a function of \( \omega_m \) and wind speed, therefore sensor less control is applied based on changing the duty cycle. GA is an optimization method by using Newton’s method form maximum power optimization based on solving the nonlinear equation as follows:

\[
\frac{dF(x)}{dx} = 0; \Rightarrow \quad X_{k+1} = X_k - F(X_k) \frac{dF(X_k)}{dX_k}
\]

(4)

Where \( k \) is the iteration index.

Achieving optimization condition can be realized by applying Lagrangian method denoted by \( L \) for solving unknown parameter \( \mu \). The necessary condition for obtaining the optimality is as follows:

\[
g(\mu) = \frac{\partial L(\mu)}{\partial \mu} = 0
\]

(5)

Solving \( g(\mu) = 0 \) in Eq.(5) is the same as solving \( F(X) = 0 \). Taking into account Lagrangian approach the GA optimization is expressed as follows:

\[
\mu_{k+1} = \mu_k - \alpha_k g_k(\mu_k)
\]

(6)

Where,

\[
\alpha_k = F^+(X_k)^{-1}; \quad g_k = \left[ \frac{Y_k - Y_k^*}{2C_k} \right]
\]

(7)

\[ Y_k = L(\mu_i + C_k) + \varepsilon_k \]

\[ Y_k^* = L(\mu_i - C_k) + \varepsilon_k^* \]

\( C_k \) is a sequence of positive scalars such that \( C_k \) approaches zero, and the symbols \( \varepsilon_k^\pm \) and \( \varepsilon_k^\pm \) represent measurement noise terms.
Taking into account the proposed Lagrangian approach for achieving optimized power generation, several methods are applied, but most applied one due to its simplicity and less required preconditions is “Adaptive Duty Cycle method wit GA” illustrated by Ying-Yi [6].

2.2.2 Adaptive Duty Cycle method with GA

The proposed adaptive duty cycle method with GA does not require parameter setting, sensors, characteristics of the turbine-generator. Because $P_e(n)=V_o(n), I_o(n)$ is expected to be maximized and GA is used for minimization, as well illustrated on Fig.5, the control variable is also the duty cycle of the DC / DC converter with the following expression at $k^{th}$ iteration:

$$D_{k+1} = D_k + \alpha_k \left[ \frac{P_e(D_k + C_k) - P_e(D_k - C_k)}{2C_k} \right] = D_k + \alpha_k g_k$$

(8)

The duty cycle will be sent to the DC / DC converter through Pulse Width Modulation Controller as will shown on Fig. 2.

3. Characteristics of PV Panel

The simplest equivalent circuit of a solar cell is a current source in parallel with diode [14-16]. The output of current source is directly proportional to the light falling on the cell; this current is called photocurrent $I_{ph}$. During darkness, the solar cell is not an active device; it works as a diode as well shown on Fig. 6a, where the flows current is called dark current $I_D$. While, Fig. 6b illustrates the output characteristic of one solar cell, called I-V curve.

Increasing accuracy and complexity can be introduced to the model according to M. Francisco [8] taking into account:

Temperature dependence of the diode saturation current $I_0$;

Temperature dependence of the photo current $I_{ph}$;

Series resistance $R_s$, which gives more accuracy in shaping of maximum power point and MPPT. This resistance represent the internal losses due to current flow.

3.1 Mathematical Modeling

In an ideal cell $R_s=0$; which is a relatively common assumption. The net current of the cell is the difference of the photocurrent $I_{ph}$ and the normal diode current $I_d$:

$$I = I_{ph} - I_d$$

$$I_d = I_o e^{\frac{q(V + IR)}{nKT} - 1}$$

(9)

The Current-Voltage I-V Curve for a typical solar cell at a certain ambient irradiation $G$ and a certain fixed temperature $T$, is shown in Fig. 6 for resistive load $R$. The load characteristic is a straight line with slope $I/V=1/R$. It should be pointed out that the power delivered to the load depends on the value of the resistance only.
Fig. 6  a) A typical PV model, and b) current-voltage I-V curve for a solar cell.

Depending on the load R value, the cell operates as current source or voltage source mode, therefore short circuit current $I_{SC}$ will be at small R, while open-circuit voltage $V_{OC}$ will be at large R [17].

3.2 Maximum Power Point Tracking of Solar Cells

A real solar cell can be characterized by short circuit current, open-circuit voltage, maximum power point operation, maximum efficiency, and filling factor. Hereinafter a few short description about these parameters:

Maximum power point: is the operating point $A(V_{max}, I_{max})$ illustrates in Fig.6, at which the power dissipated in the resistive load is maximum $P_{max} = V_{max} \cdot I_{max}$.

Maximum efficiency: is the ratio between the maximum power and the incident light power:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{max} \cdot I_{max}}{A \cdot Ga}$$  \hspace{1cm} (10)

Where $Ga$ is the ambient irradiation; and $A$ is cell area.

Fill factor: is the ratio of the maximum power that can be delivered to the load and the product of $V_{oc}$ and $I_{sc}$:

$$FF = \frac{P_{max}}{V_{oc} \cdot I_{sc}} = \frac{V_{max} \cdot I_{max}}{V_{oc} \cdot I_{sc}}$$  \hspace{1cm} (11)

The fill factor is a measure of real I-V characteristic. Its valued is higher than 0.7 for good designed cells. Furthermore the fill factor diminishes as the cell temperature is increased.

3.2.1 Maximum Power Point Tracker of Solar Cells (MPPT)

MPPT for prediction the maximum power point occurrence by using perturb and observation algorithm in looking for maximum output parameters in terms of voltage and current, therefore increasing the fill factor . According to [7,18], the proposed algorithm reads the value from the solar PV module. The value of the pow-
er for two adjacent iteration points $k^{th}$ and $(k+1)^{th}$ where $(dP / dV)<0$ at the right hand side of the curve, where as $(dP / dV>0)$ at the left hand side. This means that the right side curve is for lower duty cycle ($D\rightarrow D_{\text{min}}$), where as the left side is for the higher duty cycle ($D\rightarrow D_{\text{max}}$).

Correcting the duty cycle can be realized as follows:

\[
\begin{align*}
    dP &= P(k+1) - P(k); \\
    dV &= V(k+1) - V(k);
\end{align*}
\]  \hspace{1cm} (12)

According to $(dP / dV)$ the algorithm decides whether to increase the duty cycle or to reduce it. The proposed algorithm flow chart is illustrated on Fig. 7.

4. Storage Model

In practice there are many different options to store the produced energy of both WT and PV model, but in practice the commercially and affordable options are limited batteries [17, 18]. Lead Acid batteries are suitable for storing the energy for medium term energy storage. Different ways are used to modeled the battery storage taking into account the complexity of their behaviors. According to Hraman and Kacholdt [19], two methods are used to analyze the storage model:

4.1 Energy Transfer Model
Fig. 8 Hybrid system flowchart.

Table 1 System data parameters.

**WT data:**

<table>
<thead>
<tr>
<th>Number of Gen. unit</th>
<th>Gen. rating, VA</th>
<th>Generator speed, rpm</th>
<th>Max. wind speed, m/s</th>
<th>Min. wind speed, m/s</th>
<th>Blade length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>330</td>
<td>12</td>
<td>2.5 m/s</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**PV data:**

<table>
<thead>
<tr>
<th>Number PV Panels</th>
<th>Rated voltage of panel, V</th>
<th>Open Circuit voltage, V</th>
<th>Rated Power of panel, W</th>
<th>Peak ampere, A</th>
<th>Total amperes, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>12</td>
<td>17</td>
<td>60</td>
<td>3.3</td>
<td>13.3A</td>
</tr>
</tbody>
</table>

**Battery bank:**

<table>
<thead>
<tr>
<th>Number of parallel batteries, Np</th>
<th>Number of series batteries, Ns</th>
<th>Battery capacity, Ah</th>
<th>Battery voltage, V</th>
<th>Minimum state of charge, %</th>
<th>Discharging efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>24</td>
<td>12</td>
<td>30%</td>
<td>80%</td>
</tr>
</tbody>
</table>
4.2 Simulation Model.

To avoid complexity, Energy Transfer Model is used in this paper, which gives the gross energy flow by using the information provided in the manufacturer’s data sheets. This approach is concerned primarily with the summation of energy transfer to and from the battery.

During charging the resulting State of Charge SOC for acceptance of an amount of energy $W_{\text{inp}}$ for a charging efficiency $\eta_{\text{ch}}$ and rated battery capacity $C_{\text{rated}}$ can be calculated as follows:

$$\text{SOC} = \text{SOC} + \frac{W_{\text{inp}} \eta_{\text{ch}}}{C_{\text{rated}}}$$  \hspace{1cm} (13)

When discharging an amount of energy $W_{\text{out}}$, the resulting SOC is given by,

$$\text{SOC} = \text{SOC} - \frac{W_{\text{out}}}{C_{\text{rated}} \eta_{\text{disch}}}$$  \hspace{1cm} (14)

Where $\eta_{\text{disch}}$ is the discharging efficiency.

The amount of energy transferred can be calculated using,

$$W_{\text{transfer}} = P_{\text{av}} \Delta t$$  \hspace{1cm} (15)

Where $W_{\text{transfer}}$ is energy transferred form the source to the load in kWh, $P_{\text{av}}$ is the average power applied during energy transfer over the time interval in kW, $\Delta t$ is the time interval in hours.

The input, output energy $W_{\text{inp}}$, $W_{\text{out}}$ can be calculated as:

$$W_{\text{out}} = W_{\text{transfer}} - \Delta P_{\text{loss}} \Delta t$$

$$\Delta P_{\text{loss}} = I^2 \cdot R_{\text{tot}}$$

$$R_{\text{out}} = R_{\text{in}} \frac{N_s}{N_p}$$  \hspace{1cm} (16)

Where, $\Delta P_{\text{loss}}$--charging and discharging loss in watts, $I$ - charging and discharging current in amps, $R_{\text{tot}}$, $R_{\text{in}}$--the total and internal battery in ohms respectively, $N_s$--number of series battery cells, and $N_p$--number of parallel cells.

The minimum state of charge $SOC_{\text{min}}$ is usually set at around of 30% with purpose to avoid excessive damage to the battery.

5. Hybrid Model

The hybrid model is controlled in such a way that the power output from the Wind turbine and PV panels is used for directly meeting the consumer demand.

Excess power, if available, is stored in the battery, and energy taken from the battery is used to meet any shortfall. The control model is based on the state of charge of the battery bank. Depending on the current SOC decision has been made whether if would charge the battery or discharge from the battery depending on the availability of power. Flowchart of the control model is shown in Fig. 8.

6. Simulation Results.

Taking into account the proposed mathematical models, there are three applied simulation models using Matlab\ Simulink and system data given in Table 1.

6.1 Simulation of WT Model

A simulation model of WT system is build in Matlab / Simulink environment, where four main units are designed and linked together to form the WT model, as well shown on Fig. 9a, the main generating model, and Fig. 9b the wind turbine model. The wind turbine speed is assumed to vary in wide range with purpose to predict the changes in the turbine power, voltage and current. Fig. 10 illustrates the results of such variation respectively. It clearly seen that the circuit parameters varies consequently as varying the wind speed.

6.1.1 Simulation of PV Model

A simulation model of PV model is build in Matlab / Simulink environment, where a set of PV arrays were connected with DC charging system and MPPT system that energized a DC buck-Boost chopper with appropriate gate pulses having variable time duration. Fig.11 illustrates the model subsystems, while Fig.12 presents the obtained simulation results demonstrates that as the duty cycle decreases the output voltage and power raises, which means that the power will perturb at its maximum value as a result of MPPT subsystem.
Ref Voltage, pu

Wre

f

Pe

Speed

Wturb

Pturb

Cont

W. turbine unit

VLL-gen

Load

000VA

Ia,A

(a) Main model

Fig. 9  Matlab / simulink of WT model.

(b) Wind turbine model

Raw

1.05

Area

2.22

Product1

Pwind=Raw.Area.Velocity3/2

Product

Pwind

1/2

Product4

Pturbine=Cp.Pwind

1

Pturbine

2

Taeord

3

W

Velocity

Radius, m

0.227

V=W.R

Vwind

fcn

Cp

Cp calculation

(a) Velocity

(to be continued)
6.1.2 Simulation of Battery Model

A simulation model of Battery charging-discharging process is illustrated on Fig. 13, where the main model, generated power, consumed power and charging-discharging diagram are displayed, taking into account Eq.(13), Eq.(16) and the battery data sheet. From this model it's shown that the battery will start to discharge into the load when deficit in generated WT and PV power modules are incapable to meet the required consumed power.

7. Conclusions

In this work, three main components Wind Turbine with ac to dc converter, PV panel with dc chopper and battery charging system were studied. According to the consumer needs the battery will charge or discharge the required amount of power aiming at meeting the power shortage mainly at peak loading intervals.

Gradient Approximation method with adaptive duty cycle approach is applied at almost optimal value of power coefficient. This method is efficient when looking for optimum MPPT operation of the wind turbine and PV photovoltaic modules.
MPPT for Hybrid Energy System Using Gradient Approximation and Matlab Simulink Approach

(a) Main model

(b) PV model

(c) DC chopper

Fig. 11  Matlab / simulink of PV model.
Matlab / simulink environment is applied to simulate the proposed mathematical models starting from power generation to power consuming, where the effect of velocity variation, temperature change, and irradiations levels in additional to loading diagram are discussed. This paper is the first step to develop a complete Wind-Solar power generation unit with the needed power conversion subsystem. Prototype modules have been designed for three subsystems. Labview software is applied to control the generating and consuming process of the designed units.

**Acknowledgments**

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![Diagram](image_url)

**Fig. 12** Simulink results of output DC power at given variations of duty cycle.

(a) Main Battery Charging model

(to be continued)
Fig. 13 Matlab/simulink of battery model.

References


