

Novel Algorithm of Maximum Power Point Tracking (MPPT) for Variable Speed PMSG Wind Generation Systems Through Model Predictive Control

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Abstract

In this paper, a novel maximum power point tracking (MPPT) algorithm for variable speed wind systems is presented. In this approach variable step second method is applied to improve the dynamic response of wind turbine MPPT which is based on incremental conductance (INC) algorithm. This method is also independent of specifications of turbine and generator. For lowering costs and improving reliability of system, the proposed maximum power track6er does not have any mechanical sensors. MPPT tracker forces the system to operate at maximum power point by appropriate control of a boost DC/DC converter. Model predictive control is used to control the boost converter. In the final stage a simple model predictive control method is employed for two-level three-phase inverter to deliver power to a load. Simulation results in MATLAB/SIMULINK validate feasibility of the proposed algorithm.

1. Introduction

Nowadays, wind power generation resources have found vast applications both in electricity supply of distant locations and also in the form of connection to electrical network. Wind system requires lower installation expenditures by using suitable power converters in a way that the acquired power is optimal for changes in weather conditions [1].

Major advantage of variable-speed wind turbines is their ability to achieve maximum power available in wind energy supply. For producing maximum wind power, the use of a maximum power point tracking (MPPT) system is vital. MPPT controller changes speed of turbine rotor according to wind velocity variations so that tip speed ratio (TPS) is kept fixed in its optimum value [2].

Generally, MPPT methods can be broadly classified into sensorless and those need mechanical sensors. The methods without sensors track the MPP by monitoring the power variation. This method is widely divided into perturbation and observation (P&O) and incremental conductance (IncCond) methods [3]. Neither P&O nor IncCond methods require any additional sensors to measure wind or rotor speed. Concerning power efficiency, theoretically, INC method could provide a better tracking of MPP than P&O algorithm [4].

Both control technique features advantages of simplicity and high flexibility, but fluctuates around the maximum power point reduces efficiency of the wind system. In order to improve MPPT performance and also to enhance convergence speed and system precision, incremental conductance (INC) algorithm is

modified. Variable steps based on second method is used for determining reference signal in this method.

Model predictive control (MPC) is an attractive alternative to the classical control methods, due to its fast dynamic response, simple concept, and ability to include nonlinearities and constraints in the design of a controller [5, 6].

In this paper, a modified variable step size INC MPPT algorithm is proposed, which automatically adjusts the step size to track the wind power system maximum power point. The implementation of a wind turbine MPPT using MPC combines two keys of vital importance, speed and reliability, avoiding unacceptable oscillations around MPP. Simulation results confirm that the proposed method can effectively improve the dynamic and steady state performance.

2. Wind Turbine Characteristics and Modeling

If rotor's friction is neglected, mechanical specifications of wind turbine can be described via the following formula:

$$T_m - T_{load} = J \frac{d\omega}{dt} \quad (1)$$

$$P_m = 0.5 * C_p * \rho * A * v_w^3 \quad (2)$$

Where T_m (N.m): mechanical torque of turbine, T_{load} (N.m): load torque, J : inertia of total wind system, ω (rad/s): angular velocity of rotor, A (m²): sweeping area of turbine blade, v_w (m/s): wind velocity, C_p : turbine power coefficient, ρ (kg/m³): air density, and P_m : rotor power. The turbine power coefficient is also defined as a function of blade tip speed (λ) and blade pitch angle (θ):

$$C_p(\lambda, \theta) = C_1(C_2 \frac{1}{\lambda} - C_3\theta - C_4\theta^X - C_5)e^{-C_6 \frac{1}{\lambda}} \quad (3)$$

$$\frac{1}{\lambda} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1 + \theta^3} \quad (4)$$

The coefficients C_1 – C_6 and X might differ for different turbines. Tip speed ratio of wind turbine (λ) is defined as below:

$$\lambda = \frac{R\omega}{v_w} \quad (5)$$

Where R is the radius of the rotor. Power coefficient in terms of blade tip speed for a typical wind turbine is shown in Fig. 1.

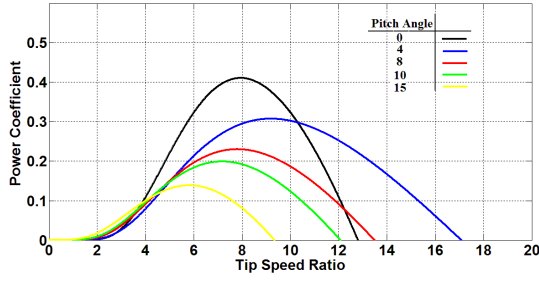


Fig. 1. $C_p - \lambda$ characteristics of wind turbine for different values of blade pitch angle

Output power of wind turbine would be maximized when C_p is maximal. This optimal value of C_p occurs in different values of λ . For a given wind velocity, there is an optimal value for rotor speed which maximizes the power supplied by the wind. Hence, if wind velocity is assumed constant, C_p value will be dependent on rotor speed of the wind turbine. Accordingly, output power of wind turbine is controlled by adjusting rotor speed. As observed in Fig. 2 and Fig. 3, maximum power point of wind turbine is different from maximum torque point.

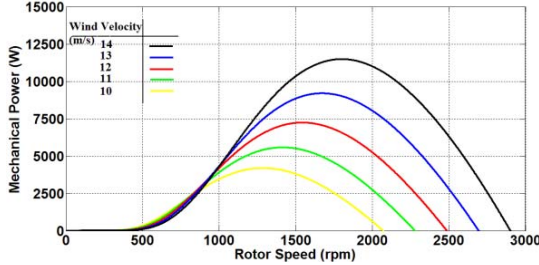


Fig. 2. Power-speed specification of a typical wind turbine for different wind velocities

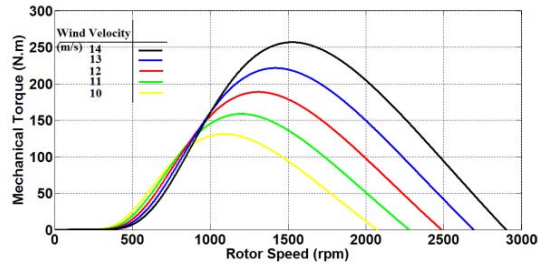


Fig. 3. Torque-speed specification of typical wind turbine for different wind velocities

3. Proposed MPPT Control Strategy

3.1. System Configuration

In wind generation systems, the power of wind varies proportional to the wind velocity. Thus, the wind turbine is supposed to operate in variable-speed state in order to maximize the power obtained from the wind. To allow performance of the turbine in variable-speed state, it is required to separate stages of electrical power generation from electricity consumption procedures. To do so, three-phase voltage of permanent magnetic synchronous machine generator is rectified and DC-

bus voltage needs to be adjusted. Also, it is necessary to use inverter as a link between generation and consumption. In order to supply load demand, power shall be fed in a proper manner (at suitable voltage and frequency). This is possible thanks to capability of power electronic converters for operation at different voltages and frequencies.

Fig. 4 shows the total scheme of wind generation system. Wind power is converted into mechanical power on the rotor shaft through wind turbine. This power is turned into electrical power by a permanent magnetic synchronous machine (PMSG) generator. The generated 3-phase voltage is rectified using an uncontrollable diode rectifier. Main purpose of using rectifier is to separate variable frequency voltage generated by the machine from the load which should operate at fixed frequency. DC/DC boost converter is used for controlling the output voltage of the rectifier (V_{dc}) (the voltage in capacitor C_1). Controller of maximum power tracker generates a reference voltage for the capacitor C_1 . MPC is used to control the boost converter. Wind turbine assumes an optimal speed for a given wind velocity, which enables achieving maximum power of wind. Therefore, by controlling V_{dc} voltage, it would be possible to control the current coming from generator, which in turn enables adjustment of turbine speed for gaining maximum power. Elaborate details of maximum power control using DC/DC converter will be presented in subsequent sections.

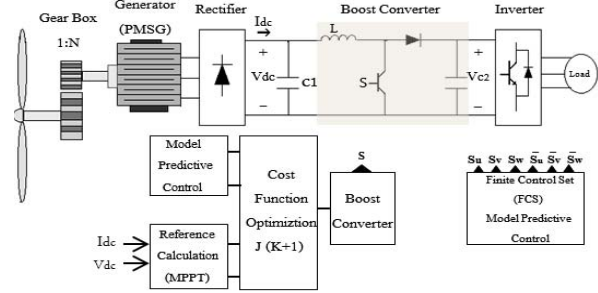


Fig. 4. Wind turbine system with maximum power point tracker (MPPT)

3.2. Optimal Search for V_{dc} Reference

Using $C_p - \lambda$ specification of wind turbine for a given wind velocity, mechanical power of turbine can be expressed as a function of DC link voltage (V_{dc}). There exists also an optimum V_{dc} which maximizes output power of PMSG generator [7]. To get maximum wind power, optimal value of V_{dc} is immediately probed using incremental conductance technique. In order to detect the position of the actual operating point in relation to MPP, this algorithm uses the derivative of the conductance di/dv . It is based on the fact that the slope tangent of the characteristic $P-V$ is zero in MPP, positive on the MPP left side, and negative on the MPP right side. As the power is equal to the product of current (i_{dc}) and voltage (V_{dc}), the calculation of this slope is given by:

$$\frac{dP_{dc}}{dv_{dc}} = \frac{d(vi)_{dc}}{dv_{dc}} = i_{dc} + v_{dc} \frac{di_{dc}}{dv_{dc}} \quad (6)$$

The development of this derivative in MPP is given by:

$$\frac{i_{dc}}{v_{dc}} + \frac{di_{dc}}{dv_{dc}} = 0 \quad (7)$$

The above equation implies that maximum power point can be tracked by searching for output power of rectifier instead of looking for ambient parameters such as wind velocity and direction. When the operating point is located on the left side of the MPP, $(i/v + di/dv)$ will be positive, whereas $(i/v + di/dv)$ will be negative when the operating point is on the other side. From the instantaneous measurement of i_{dc} and V_{dc} , the following approximations can be done:

$$\begin{aligned} di &\approx \Delta i = i(k) - i(k-1) \\ dv &\approx \Delta v = v(k) - v(k-1) \end{aligned} \quad (8)$$

So, the algorithm can instantly calculate i/v and di/dv to find the direction of the perturbation leading to the MPP. Search process initially starts with selection of an arbitrary value for reference DC voltage (V_{ref}) for the voltage of the capacitor C_l (V_{dc}). The reference voltage will then increase as much as ΔV_{dc} like below:

$$V_{ref}(k) = V_{ref}(k-1) + \Delta V_{dc} \quad (9)$$

It must be noted that V_{dc} variations are imposed with constant fixed steps.

For improving performance of the algorithm shown in Fig. 5, a variable step for V_{dc} variations is assumed in modified incremental conductance method. This leads to improvement of convergence speed and system accuracy. Variable step technique operates according to Secant Method. The secant method (SM) is in many ways similar to the Newton-Raphson Method (NRM) [8]. The SM is another iterative algorithm in which the fundamental equation is given by:

$$x_{n+1} = x_n - F(x_n) \cdot \frac{x_n - x_{n-1}}{F(x_n) - F(x_{n-1})} \quad (10)$$

x_n is initial value of X , $F(x_n)$ is value of function in point x_n . The function $F(x_n)$ can be written as below:

$$\begin{aligned} F(x_n) &= F(V_{dc}(n)) = \frac{dP}{dV_{dc}} \\ &= \frac{P(n) - P(n-1)}{V_{dc}(n) - V_{dc}(n-1)} = \text{grad}(n) \end{aligned} \quad (11)$$

Using the previous equations, step of V_{dc} variations (ΔV_{dc}) is expressed as:

$$\Delta V_{dc} = \text{grad}(n) \cdot \frac{V_{dc}(n) - V_{dc}(n-1)}{\text{grad}(n) - \text{grad}(n-1)} \quad (12)$$

Therefore, reference voltage is calculated through the following equality:

$$V_{dcref}(n+1) = V_{dcref}(n) + \Delta V_{dc} \quad (13)$$

Using variable steps, maximum power point tracker converges to the maximum power value more rapidly and power fluctuations will decrease around MPP. Range of ΔV_{dc} variations has been limited. ΔV_{dc} limit changes depending on generator size and system design parameters.

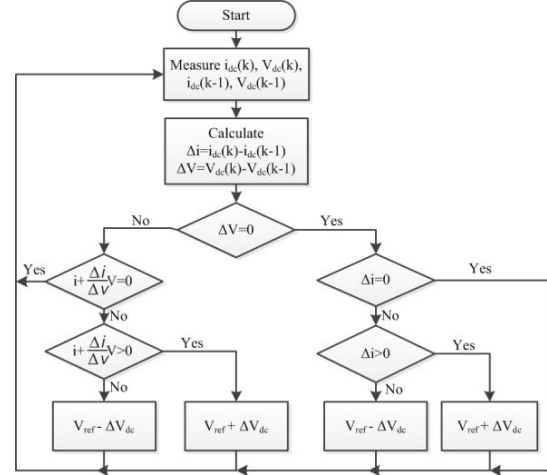


Fig. 5. Incremental conductance (INC) flowchart

3.3. Model Predictive Controller Design of Boost Converter

The model predictive controller aims to estimate the future behavior of the controlled variables so that proper control actions could be determined [9, 10]. As it is shown in Fig. 4, a DC/DC boost converter is employed to control the voltage of the capacitor C_l (V_{dc}) in order to extract the maximum power from the system. The reference value of the V_{dc} is provided by the MPPT algorithm.

For a boost converter shown in Fig. 4, there are only two switching states. The operation of the converter can be described as follows when the switch is closed.

$$\frac{di_L}{dt} = \frac{1}{L} V_{dc} \quad (14)$$

In the case of the open switch, the inductor current can be written as:

$$\frac{di_L}{dt} = \frac{1}{L} V_{dc} - \frac{1}{L} V_{C2} \quad (15)$$

Also, the voltage of the capacitor (C_l) is given as:

$$\frac{dV_{dc}}{dt} = \frac{1}{C_l} (i_{dc} - i_L) \quad (16)$$

Discrete model of the system can be rewritten using the Euler approximation as follows:

$$i_L(k+1) = \frac{T_s}{L} V_{dc}(k) + i_L(k) \quad (17)$$

$$i_L(k+1) = \frac{T_s}{L} [V_{dc}(k) - V_{C2}(k)] + i_L(k) \quad (18)$$

$$V_{dc}(k+1) = \frac{T_s}{C_l} [i_{dc}(k) - i_L(k)] + V_{dc}(k) \quad (19)$$

Where T_s is the sampling frequency. To predict the future behavior of the inductor current (i_L) and the voltage of the capacitor C_1 (V_{dc}) for both switching states at time instant $K+1$, it is required to know the V_{dc} , V_{C2} , i_{dc} and i_L at time instant K . Two-step ahead prediction can be done for the controlled variable V_{dc} .

$$V_{dc}(k+2) = \frac{T_s}{C_1} [i_{dc}(k+1) - i_L(k+1)] + V_{dc}(k+1) \quad (20)$$

Then a cost function must be minimized to determine the switching state at next time instant.

Definition of the cost function plays a major role in MPC constraining the deviations of the controlled variables from their references so the cost function is given as follows:

$$J_{S=n}^{n=0,1} = |V_{dcS=n(k+2)} - V_{dcRef}| \quad (21)$$

The cost function assures the tracking of V_{dc} from the reference voltage provided by MPPT algorithm. For each sampling sequence the cost function is evaluated twice for each switching state. Comparison of cost function for different switching states determines the control actions for the following time instant.

4. Model Predictive Control Applied to Three-Leg Inverter

Model predictive controller is also applied to the inverter. Since the switching states are limited, finite control set MPC is an efficient scheme to control the inverter. There are eight possible switching states for a two-level inverter as follows:

$$S = \left\{ \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \right\}$$

According to Fig. 6, inverter output phase voltages can be obtained as follows:

$$\begin{aligned} V_{un} &= \frac{V_c}{3} (2S_u - S_v - S_w) \\ V_{vn} &= \frac{V_c}{3} (2S_v - S_u - S_w) \\ V_{wn} &= \frac{V_c}{3} (2S_w - S_u - S_v) \end{aligned} \quad (22)$$

Where S_u , S_v and S_w are equal to 1 if the corresponding device is on, 0 if the device is off.

The dynamics of the inverter currents can be expressed as:

$$\begin{aligned} V_{un} &= (R_f + R_i) i_{ou+} (L_f + L_i) \frac{di_{ou}}{dt} \\ V_{vn} &= (R_f + R_i) i_{ov+} (L_f + L_i) \frac{di_{ov}}{dt} \\ V_{wn} &= (R_f + R_i) i_{ow+} (L_f + L_i) \frac{di_{ow}}{dt} \end{aligned} \quad (23)$$

Discrete time model of the system is also given as:

$$\begin{aligned} i_{ou}(k+1) &= \left(1 - \frac{T_s(R_f + R_i)}{L_f + L_i}\right) i_{ou}(k) + \frac{T_s}{L_f + L_i} V_{un}(k) \\ i_{ov}(k+1) &= \left(1 - \frac{T_s(R_f + R_i)}{L_f + L_i}\right) i_{ov}(k) + \frac{T_s}{L_f + L_i} V_{vn}(k) \\ i_{ow}(k+1) &= \left(1 - \frac{T_s(R_f + R_i)}{L_f + L_i}\right) i_{ow}(k) + \frac{T_s}{L_f + L_i} V_{wn}(k) \end{aligned} \quad (24)$$

To control the output current of the load, a cost function is defined as:

$$J = |i_{ou}(k+1) - i_{ouref}(k+1)| + |i_{ov}(k+1) - i_{ovref}(k+1)| + |i_{ow}(k+1) - i_{owref}(k+1)| \quad (25)$$

For each sampling time, the cost function will be calculated for all switching states. Then the proper control actions will be chosen for the next time instant.

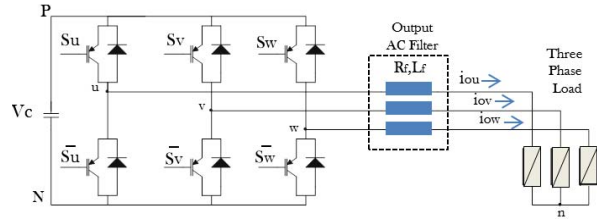


Fig. 6. Two-level three-leg inverter

4. Simulation Results

In order to analyze performance of the proposed MPPT strategy, a wind system as shown in Fig. 4 is simulated using MATLAB/SIMULINK. Table 1 includes parameters of wind turbine. Electrical system consists of: permanent magnetic synchronous machine (PMSM), rectifier, boost DC/DC converter, and voltage source inverter (VSI). Specifications of PMSM generator are shown in Table 2. Simulation results of MPPT algorithm are displayed for variable wind velocity profile.

Wind velocity at $t = 2(s)$, has a step variation from 12 m/s to 13 m/s and at $t = 3(s)$ there is a sudden variation of wind velocity from 13 m/s to 14 m/s. As shown in Fig. 7, with operation of MPPT control system in response to wind velocity variation, rotor speed of PMSM generator is changed to the updated value. As a result of increase in wind velocity and effective control of MPPT system, output power and torque of wind turbines increase as illustrated in Fig. 8, 9. Turbine output power in stable state fails to have any fluctuation around the new operating value.

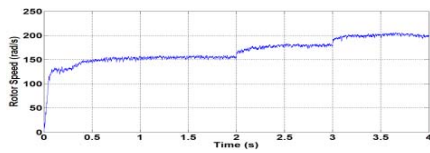
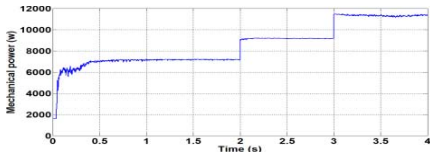
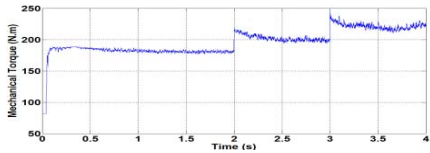
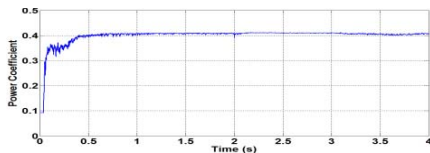
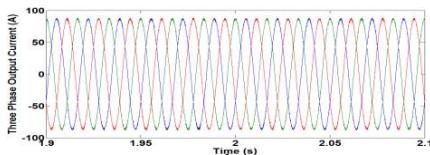
Turbine power coefficient (C_p) in different moments of system operation is the most important index for assessing performance of system. It can be observed in Fig. 10 that turbine operates with a C_p very close to the optimal value (0.41). Besides, at the moments when wind velocity changes ($t=2, 3 s$), MPPT control system maintains the power coefficient of turbine in the same optimal value as a suitable and immediate response to these variations. Fig. 11 also depicts the output load current which is stable in spite of the variations in wind velocity.

Table 1. Wind turbine parameters

Parameter	Value
Nominal Power	12.3 kw
Cut-in Wind Velocity	3 m/s
Nominal Wind Velocity	12 m/s
Rotor Diameter	4.6 m
Blade Turning Angle	0 deg
Maximum Power Coefficient	0.41

Table 2. Parameters of PMSG generator

Parameter	Value
Nominal Power	14 kw
Stator Resistance “r”	0.0485 Ω
Stator inductance “Lq, Ld”	0.395 mH
Flux Induced by Permanent Magnetism	0.1194 Wb
Equivalent Inertia (J)	0.0027 Kg.m ²
Number of poles (P)	4

**Fig. 7.** Rotor Speed (rad/s)**Fig. 8.** Mechanical power (w)**Fig. 9.** Mechanical torque (N.m)**Fig. 10.** Wind turbine power coefficient**Fig. 11.** Output load current (A)

5. Conclusions

In the current paper, a new strategy of maximum power point tracking was proposed for variable-speed PMSG wind power systems. The algorithm used modified incremental conductance (INC) method with variable steps. Variable step approach is applied using an iterative Secant root finding method (SM). Model predictive control (MPC) is employed to control the boost converter so that the maximum power would be extracted efficiently from wind turbine. To feed the load with a stable output voltage, a three-phase inverter is used which is also controlled by MPC. Simulation results indicated that MPPT strategy can automatically probe optimal operation values and yield maximum output power for fluctuations of weather conditions including wind velocity.

6. References

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