MPPT Control of DFIG Wind Turbine System based on the Characteristic Power Curve

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Abstract— Most of the electricity in India comes from fossil-fuels like coal, oil and natural gas. Today the demand of Electricity in India is increasing and is already more than the production of Electricity whereas the reserves of fossil-fuel are depleting every day. There is strong need to shift for other sources and the best option is renewable energy sources. The aim of this project is to design a maximum power point tracking for wind turbine. The maximum power point tracking (MPPT) for wind energy conversation system is used for large and small scale wind turbine systems. The diversity of MPPT methods are developed, these methods vary in implementation, cost, complexity, convergence speed and faster tracking speed. This paper proposes the power characteristics curve of MPPT method in wind power systems. Proposed MPPT is implemented by applying the small-signal analysis on a nonlinear turbine-rotor mechanical system. To verify the performance of the wind turbine system, simulation system is implemented based on MPPT power control. By the variation of wind speed, the behavior of the generator speed presents good consistency among the proposed theory.

Key words: Gust Speed, MPPT, Doubly Fed Induction Generator (DFIG), Converters, Wind Turbine

I. INTRODUCTION

Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines. Human efforts to harness wind for energy date back to the ancient times. Later, wind energy conversion systems have been attracting wide attention as it served the mankind energizing his grain grinding mills and water pumps .Wind energy, even though abundant, varies continually as wind speed changes through the day. It is gaining momentum in this field of clean energy and the energy recourses are becoming very popular in the world where demands for more power and sustainable development are increasing dramatically. While large wind turbines remain the dominant force in wind power, wider adoption may lie with small scale turbines fit for urban and low wind conditions.

To achieve high efficiency in a wind power conversion system, the maximum power point tracking (MPPT) in variable speed operation systems, like doubly fed induction generator (DFIG) and permanent magnet synchronous generator systems, attracts a lot of attention [1]–[3]. The studied MPPT methods in the history include three strategies, namely: 1) methods relying on wind speed;2) methods relying on output power measurement and calculation; and 3) methods relying on characteristic power curve.

In most of wind-energy generation systems, anemometers are used to measure the wind speed for the maximum-power-point-tracking (MPPT) control. The anemometer installed on the top of nacelle may be a source of inaccurate measurement of the wind speed. In wind farms, several anemometers are often placed at some locations to measure the average wind speed. The use of anemometers raises a problem of calibration and measurement accuracy, as well as increasing the initial cost of the wind generation systems. For these reasons, it is desirable to replace the mechanical anemometers by the digital wind-speed estimator based on the turbine characteristics.

This paper studies the performance of wind turbine under reference power curve MPPT power control. In particular, it presents a small-signal analysis on generator speed dynamics induced by variable wind speed. Also, an experimental setup to emulate the wind turbine operation in torque control mode is presented. Both steady-state and dynamic responses are implemented to verify the proposed analysis and conclusions.

II. POWER VERSUS ROTOR SPEED CHARACTERISTIC CURVE

The first important issue in characteristic power curve MPPT is how to obtain the reference power curve. The second issue is whether the generator speed and output power will converge to the points along this reference power curve regardless of the wind variations, i.e., “whether this method is stable with respect to the varying wind speed.” Section II-A will first capture the optimal reference operation points from the experimental tests when power variation rate is zero through varying the generator speed and the measurements of power and then a reference power curve $P_e(w_m)$ for the fitting curve of connection of all the optimal operation points is constructed. This section is followed by Section II-B, where a simple mechanical model is utilized to do small-signal analysis and a transfer function is proposed based on the optimal reference power curve P_e (ω_m). The transfer function reveals the relationship between the variation of wind speed and that of generator speed and helps in predicting the stability and dynamic responses.

A. Optimal Reference Power Curve Pe (ω_m)

The fitting curve is then used as reference power curve Pe (ω_m). The procedure for preparing the Pe(ω_m) curve is summarized in Fig.1 .The optimal reference power curve Pe(ω_m) is obtained by finding the optimal power (P_{opt}) and optimal generator speed (ω_{mopt}) for any given wind speed (V_w). For a given Vw, the generator speed ω_m is swept, and the output power P is observed. The ω_m and P that would give the dP/dωm = 0 are selected as ωopt and P_{opt} for the specific Vw. By

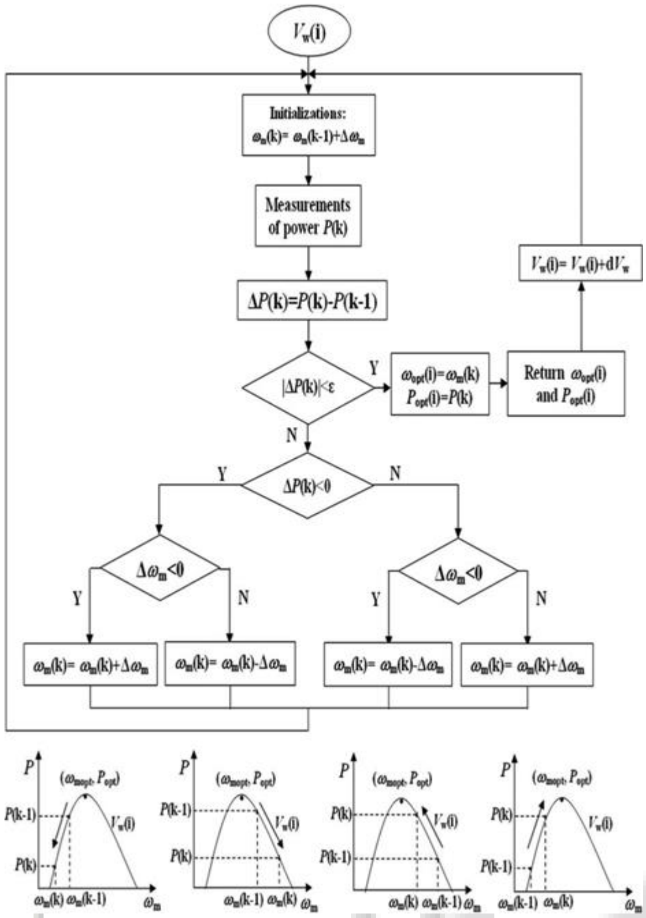

Fig. 1: Procedure for preparing $P(W_m)$

Repeating the same procedure for different Vw, a fitting curve can be obtained by connecting all optimal operating points (ω_{mopt}, P_{opt}).

B. *Small Signal Model of Wind Turbine System*

Once the reference power curve $Pe(\omega m)$ is obtained, the stability of reference operating points (ωmopt, Popt) is investigated. Whether the system (generator speed and output power) would converge to the $Pe(\omega m)$ or not is a dynamic stability issue, as shown in Fig. 2.

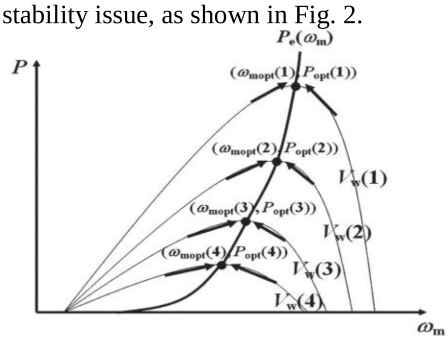

Fig. 2: Convergence of system operation to the reference power curve.

In the MPPT method discussed in this paper, the reference electrical power Pe is dependent on ωm according to the polynomial

$$P_{e=b_1 w_m^3} + b_1 w_m^2 + b_1 w_m + b_4 \quad (1)$$

Where the coefficients b_1 to b_4 are determined by the fitting curve of optimal operation point connection. The mechanical model that connects the wind turbine shaft and generator rotor can be written as

$$J\frac{dw_m}{dt} = T_m - T_e - Bw_m \quad (2)$$

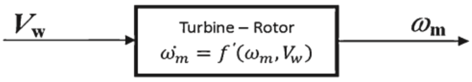

Fig. 3: SISO model of wind mechanical system.

Where J denotes the inertia of the combined system, B is the damping coefficient, w_m is the generator rotor speed, and T_m and T_e represent the turbine and generator torques, respectively. Combining the relationship between torque and power, (2) can be rewritten in terms of power as

$$J\frac{dw_m}{dt} = \frac{P_w}{w_m} - \frac{P_e}{w_m} - Bw_m \quad (3)$$

Where P_w and P_e are the turbine and generator powers, respectively. P_w is determined by wind speed V_w, generator speed ω_m, air density ρ, and blade swept area $A = \pi R^2$ as

$$P_w = 0.5\rho A V_w^3 C_p(\omega_m, V_w) \quad (4)$$

Where $C_p(\omega_m, V_w)$ is the turbine performance coefficient and is expressed as follows equation:

$$C_P(w_{m,}V_m) = c_1\left(\frac{c_2}{\lambda_p} - c_3\beta - c_{4)}\right) e^{\frac{-c_5}{\lambda_1}} + c_6 \quad (5)$$

Where $1/\lambda_p = (1/(\lambda + 0.08\beta)) - (0.035/(\beta^2 + 1))$, $\lambda = (\omega_m R/V_w)$, β is the pitch angle, and $c_1 \sim c_6$ are the coefficients determined by individual turbine characteristics. Combining (1)–(5), we can write

$$\dot{\omega}_m = f(\omega_m, V_w). \quad (6)$$

Therefore, the mechanical system can be modeled as a nonlinear single-input single-output (SISO) system as shown in Fig. 3. Linearizing at optimal operating points leads to

$$\Delta\dot{\omega}_m = a_1\Delta\omega_m + a_2\Delta V_w \quad (7)$$

where, for given wind speed index i,

$$a_1(i) = \frac{\partial f}{\partial w_m} \,|\, _{w_m = w_{mopt}}(i), V_w = V_w(i) \quad (8)$$

$$a_2(i) = \frac{\partial f}{\partial V_M} \,|\, _{w_m = w_{wopt}}(i), V_w = V_W(i) \quad (9)$$

In other words, $\Delta\dot{\omega}_m$ explores the stability of system transitioning from one optimal point to another, due to the variation in V_w. Applying the Laplace transform on $\Delta\dot{\omega}_m$ yields

$$s\Delta\omega_m(s) = a_1\Delta\omega_m(s) + a_2\Delta V_w(s). \quad (10)$$

The transfer function between $\Delta\omega_m(s)$ and $\Delta V_w(s)$ is derived as

$$\frac{\Delta w_m(s)}{\Delta V_w(s)} = \frac{a_2(i)}{s - a_1(i)}. \quad (11)$$

From (11), it is clear that the transition from optimal point to another stable as long as $a_1(i) < 0$

III. SIMULATION RESULTS

To verify the stability analysis, the characteristic power curve MPPT method is employed on a simulation of a 1.5-MW DFIG wind power system. The system parameters are listed in Table I. The control schemes are shown in Fig. 4, where $h(\Psi_s, P_{ref}, \omega_m)$ is the relationship between stator flux and rotor d-axis current and is discussed in detail in . By applying the stator voltage field orientation, the rotor- and stator-side converters are controlled to regulate the output active and reactive powers and the dc bus voltage, respectively, where P_{loss} and Ψ_s are the power loss and stator flux while the subscripts d, q, r, s, rc, and sc represent the d-axis, q-axis, rotor, stator, rotor-side converter, and stator-side converter quantities.

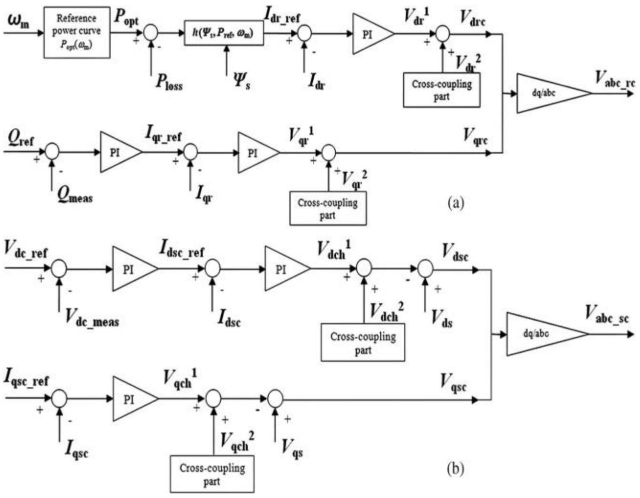

Fig. 4: Control schemes of DFIG system converters. (a) Rotor-side converter. (b) Stator-side converter.

Parameter	Value
Performance Coefficients $c_1 \sim c_6$	0.5, 116, 0.4, 5, 21, 0
Nominal Active Power P_{nom}	1.5 MW
Grid Frequency f	60 Hz
DC-link Voltage V_{dc}	1200 V
Blade Radius R	40 m
Air Density ρ	1.225 Kg/m^3
System Inertia Coefficient J	84.4 Kg.m^2
Generator Friction Damping B	0.1
Pitch Angle β	0 deg

Table 1: Simulation System Parameters

To conduct the MPPT, the optimal operating power curve $P_e(\omega_m)$ must be determined by finding the optimal operating points ($\omega_{mopt,Popt}$). The method of determining the ω_{mopt} and P_{opt} for the wind speed of 9 m/s is executed first through simulations. A continuous step in the generator speed command is applied with fixed step magnitude $|\Delta\omega_m|$ = 0.005 rad/s and period T_s_var= 2 s. The power and generator speed data are obtained from DFIG system simulations and are shown in Fig. 5. Although the oscillations appear at each moment when the generator speed varies, the dc-link voltage V_{dc} and reactive power Q are kept at the same values while the output power P varies according to the variation of ω_m. Through the sampling of the measured data, the power variation rate is easily calculated and compared. The generator speed and output power are first measured with a 0.001-s sampling rate and then are chosen discretely with a 2-s sampling rate to calculate the power variation rate. It is worth noting that the generator speed varying period T_s_var must be long enough to ensure that both ω_m and P reach their steady states. Moreover, the calculation sampling points of $\omega_m(k)$ and P(k) should be chosen at steady state value range. Based on the power variation tolerance ($\varepsilon \approx 10^{-3}$), the optimal power and generator speed are returned when

$$|\Delta p(k)| = \left|\frac{p(k)-p(k-1)}{p(k)}\right| \le \varepsilon \qquad (12)$$

Applying the above procedure to all the wind speed V_w cases, the optimal operation points are obtained and listed in Table II. Since the rough relationship between reference power and generator speed is a third-order polynomial [16], [17], a third order fitting curve given in (13) is built by connecting points in Table II as a reference power curve $P_e(\omega_m)$.

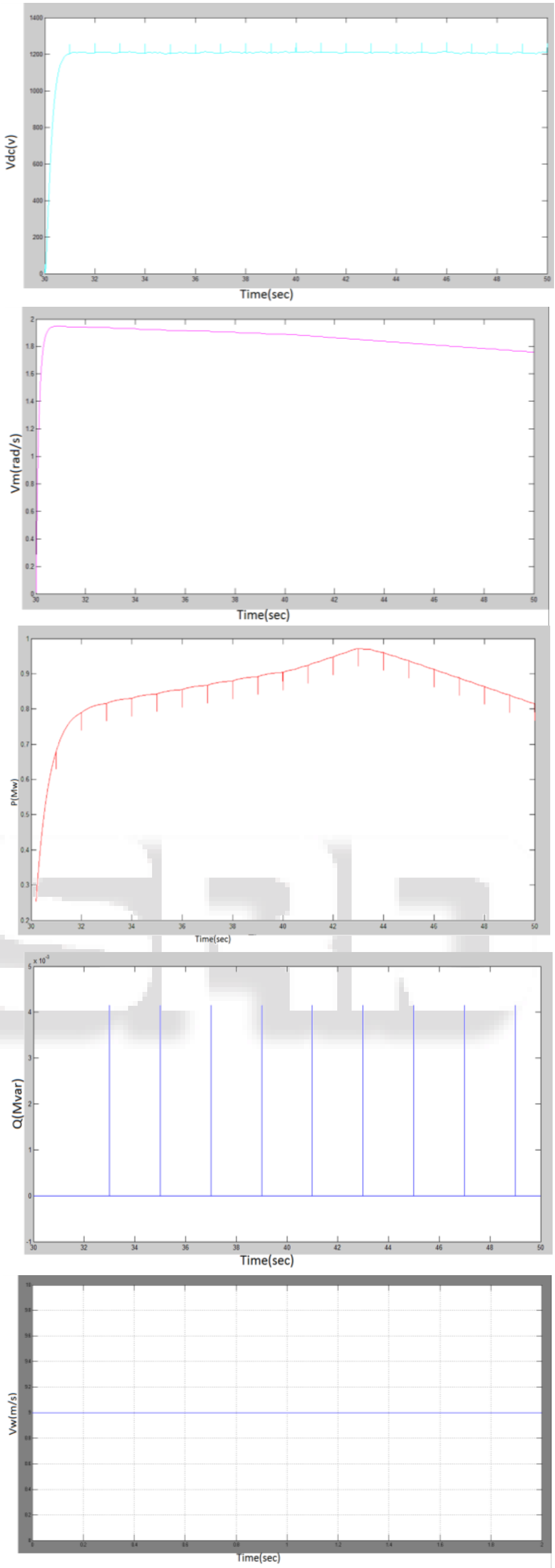

Fig. 5: System simulation results of varying generator speed operation under constant wind speed.

$P_e = 10^5(1.871\omega_m^3 - 0.513\omega_m^2 - 0.02\omega_m + 0.007.$

Fig. 6 presents a simulation of the DFIG-based wind turbine system under characteristic curve MPPT control. The results imply a stable wind power system. With the random variation in wind speed, the generator speed and the power output follow up to vary accordingly and thus match the conclusion drawn in the stability analysis.

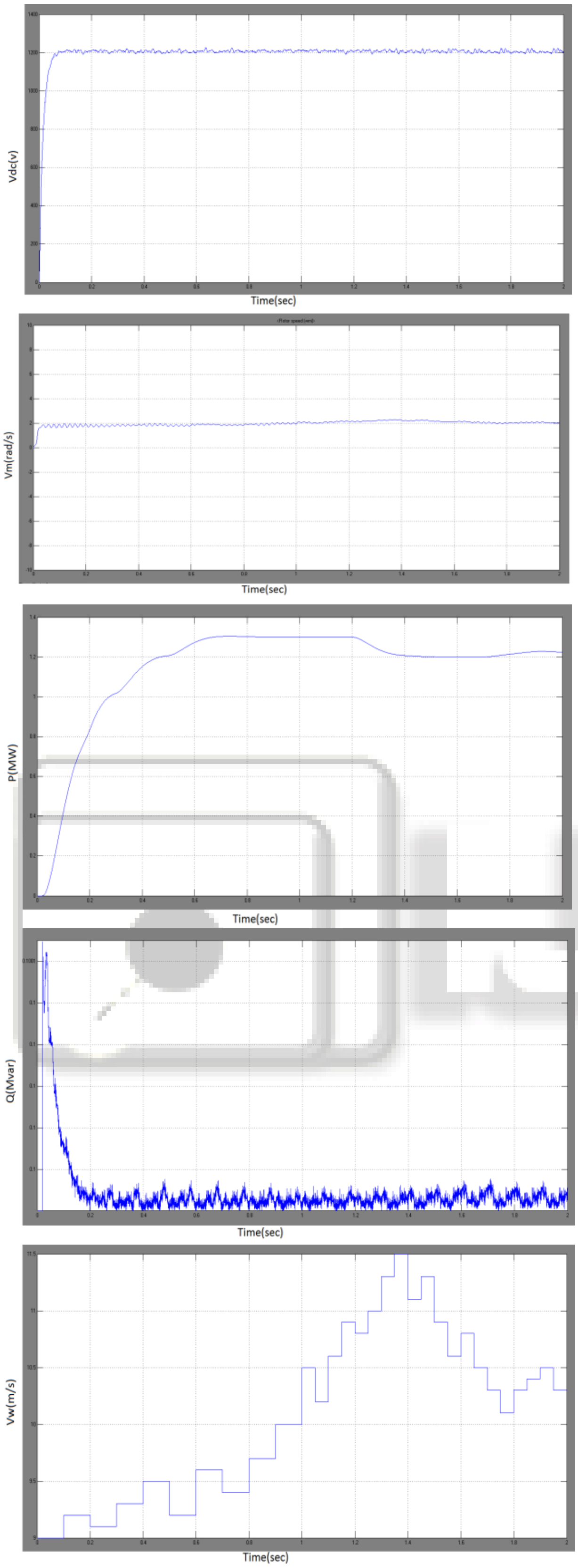

Fig. 6: Random wind speed response of simulation system.

IV. Conclusion

The power curve-based MPPT algorithm would provide robust and cost effective control method for wind turbine systems. In this paper, the small-signal model of the power curve-based MPPT algorithm is developed. The conditions for stable MPPT operation have been determined based on the small-signal model. The transfer function for the variation of wind speed to the generator speed is determined to be of the first order. The simulation result confirms the validity of the proposed transfer function that the dynamic behavior of the generator speed is independent of instantaneous.

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