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Research Article

Power Character Improvement Using Nonlinear Inductance in SWPGS with AMPTC

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Abstract

This paper describes about improvement the power character using nonlinear inductance in SWPGS with AMPTC. Wind power generation system is a one that converts the kinetic energy of the wind into electrical energy. In particular, it is very important to increase the operation efficiency because small wind power systems can be used as an efficient independent power source in areas with large power demand and no other energy sources. The SWPGS with AMPTC consists of a wind turbine, a PM generator, two rectifiers, a battery and a load. The wind turbine is a horizontal axis with three blades and the PM generator has a structure with the reactance bridges and two Y-connected winding sets. This system can automatically track the maximum power from the wind by changing the nonlinear inductance without the need for converters and control circuits. At this time, the variation of the nonlinear inductance follows the saturation characteristic of the reactance bridges in the internal magnetic circuit of the generator. In this paper, using this principle, the problem of fully approaching the maximum power curve of a wind turbine with the power characteristics of a wind power system following the rotational speed change is mathematically modeled. In other words, the output characteristics of SWPGS with AMPTC were close to the concave characteristics as well as the maximum output characteristics of wind turbines. Finally, without control circuit, the load power characteristic curve was allowed to operate at the maximum power point of the wind turbine. We also verified the accuracy of the theory by changing the nonlinear inductance in a stand-alone small-scale wind power system through simulation analysis using MATLAB.

Keywords

Double Winding, MPPT, Off-Grid, PM Synchronous Generator, Wind Power, Real Power Character, Nonlinear Inductance, Three-Phase Electrical Equivalent Circuit Model

1. Introduction

The wind turbine can achieve maximum working efficiency only by implementing the maximum power point tracking (MPPT) control in range from the cut-in speed to the rated-speed. Then the wind turbine is always operated on the maximum power curve. Many literatures have been worked on the maximum power operation of wind power generation systems. The basic method is to the output power characteristic curve of the generator system approach the maximum output power curve of the wind turbine [1-3]. For this, in the power signal feedback method [4] and the pertur-

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bation and observation method [5-7] discussed for maximum power point tracking (MPPT) in generation system with control. In addition, a winding switching strategy is proposed to design the generator to produce maximum power in static state so that the power characteristics of the wind power system can be approximated to the maximum power curve of the wind turbine [8]. In order to reduce cost, reduce losses and increase reliability in small wind power systems, a control-circuit-less wind power generation system technique has been proposed. This technique is a one to track the maximum power point so that the output characteristics of the generator automatically approximate the output characteristics of the wind turbine, according to the reactance of the winding connected to the rectifier by manufacturing a generator with several output windings of different turns. For this, the saturation characteristics of the internal inductance in the generator are used, which is a nonlinear characteristic. However, in literature [9, 10] this characteristic is assumed constant and is considered the operating principle.

In this paper, the inductance of the generator is considered to have nonlinear characteristics with respect to current variation, and the current and power characteristics with respect to rotational speed are modeled mathematically. Finally, a new power variation characteristic of SWPGS with AMPTC that completely approaches the maximum power curve of wind turbine is proposed.

2. Materials and Methods

To improve output power character at low rotational speed range using nonlinear inductance, the SWPGS with AMPTC studies theoretically. Generally, small wind power system is off-grid one. Wind turbine connects directly to generator axis without a gearbox. Figure 1 shows common scheme of conventional wind power generator system. If wind power system is without the need for converters and control circuits, the scheme can be shown as

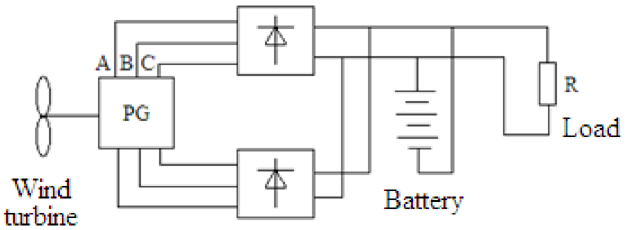

Figure 1. Block diagram of conventional double winding wind system without the need for converters and control circuits.

It is difficult problem that is completely union between the maximum power curve of the wind turbine and load power curve (wind turbine output or generator input side effective power). Because wind turbine power curve has concave character and load one has convex. In this part study about concave characteristic principle, for this make of the electric circuit to nonlinearity.

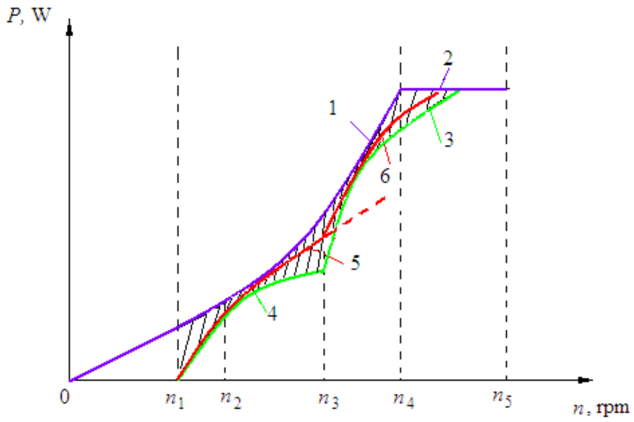

Figure 2. Character of the off-grid wind power generator system with double winding.

Figure 2 shows a simple principle for union between the maximum power curve of the wind turbine and load power curve. In Figure 2, rotational speed range $0 \le n \le n_1$ is no-load working and $n_1 \le n \le n_4$ is maximum output power characteristic range of the wind turbine, $n_4 \le n \le n_5$ range has power constant working character.

In Figure 2, curve 1 shown the maximum output power character of the wind turbine. Curve 2 is output power constant character. Curve 3 means when inductance is constant, generator input character at high rotational speed range (when both winding 1 and winding 2 outputs power) of wind turbine generator system with double winding. Curve 4 shown when inductance is constant, generator input characteristic curve at low rotational speed range (when only winding 1 outputs power) of wind turbine generator system with double winding. Curve 5 shown output power character at low rotational speed range (when only winding 1 outputs power) of wind turbine generator system using nonlinear inductance. Curve 6 is output power character at high rotational speed range (working case both windings 1 and 2) of wind turbine generator system using nonlinear inductance. As shown in Figure 2, old output power characteristic curves (load) 3 and 4 is convex, but output power characteristic curves of wind turbine is concave. Therefore is difficult that is unit output power characteristic curves of wind turbine and loads. i.e.

$$P_{W,\max}(n) \to \frac{d^2 P_{W,\max}}{dn^2} > 0, \quad \frac{d^2 P_{in}}{dn^2} < 0 \qquad (1)$$

In Figure 2, the part enclosed the area with oblique lines cannot has output power. To capture maximum output power at low rotational speed, we consider self-inductance of PMG into nonlinear. In this range, works winding 1 (a, b, c) and gets nonlinear inductance using saturation character of electric circuit.

Figure 3 shows the equivalent electric circuit.

For simplicity, core loss of generator internal effective resistance is ignored and copper loss is assumed to be only. And hysteresis loss of generator iron core is simply initial magnetization curve. The relationship between each phase is assumed to be less the magnetic connect. The loss of internal voltage drop in diode rectifiers is ignored for the sake of simplicity.

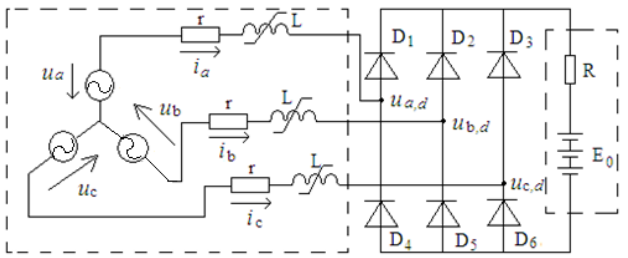

Figure 3. When only winding 1 (a, b, c) output power, equivalent electric circuit at low rotational speed range.

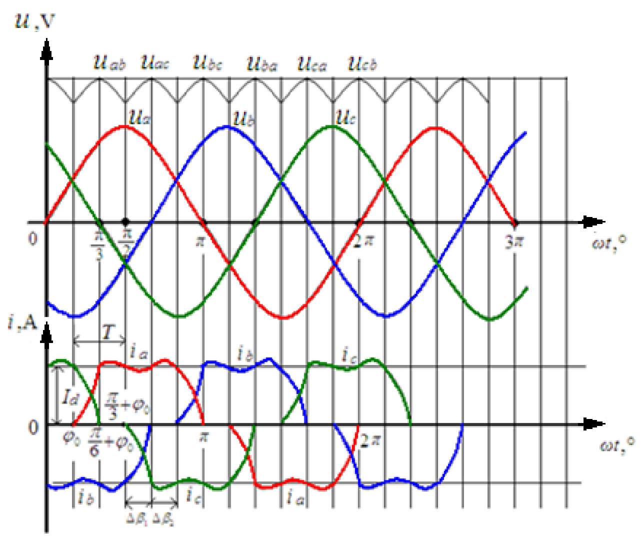

Figure 4. When only winding 1 (a, b, c) outputs power, current wave and per voltage, line voltage.

Where r is per phase resistance of a conventional generator and L is inductance of per phase of a conventional generator. R is internal effective resistance of the battery.

E_0 is ideal voltage of the battery. $u_{a,d}$, $u_{b,d}$, $u_{c,d}$ is per phase voltage of diode rectifier's input at a, b, c phase of winding 1.

Commonly, when inductance is be at diode rectifier's input, the current is assumed to be pass into per phase.

The larger inductance is, the more current continually pass. i.e approach sine wave as Figure 4.

The line voltage at diode rectifier's input-side express into $u_{ab,d}$, $u_{ac,d}$, $u_{bc,d}$, $u_{ba,d}$, $u_{ca,d}$, $u_{cb,d}$ and it can begin to charging when is large than battery voltage E_0. Its process generally has the six states.

Current wave passing into two winding of generator is distortion contained much harmonic. For simplicity, current wave approach to trapezoidal form.

Hence, in an off-grid wind power generator system that consists of a PM generator, two rectifiers, a battery and loads, equivalent electric circuit is shown in Figure 5 and Figure 6.

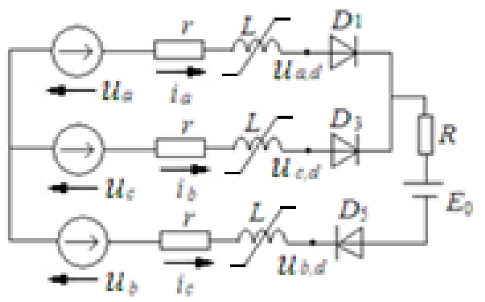

Figure 5. Equivalent electric circuit corresponding to mode of D_1, D_3, D_5.

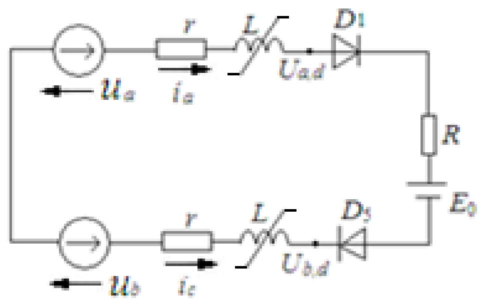

Figure 6. Equivalent electric circuit corresponding to mode of D_1, D_5.

2.1. DC Voltage Analysis of Rectifier-Side

As mentioned above, the process calculating momentary effective power is very complex. Approximately, average value of output power voltage can be calculated as

$$i_a+i_b+i_c=0 \tag{2}$$

$$\begin{cases} u_{ab,d} = u_{ab} - ri_a + ri_b - \dfrac{d\psi_a}{dt} + \dfrac{d\psi_b}{dt} \\ u_{cb,d} = u_{cb} - ri_c + ri_b - \dfrac{d\psi_c}{dt} + \dfrac{d\psi_b}{dt} \end{cases} \quad \phi_0 < \omega t \le \frac{\pi}{6} + \phi_0 \tag{3}$$

$$\begin{gathered} u_{ab,d} = u_{ab} - ri_a + ri_b - \frac{d\psi_a}{dt} + \frac{d\psi_b}{dt} \\ \frac{\pi}{6} + \phi_0 < \omega t \le \frac{\pi}{3} + \phi_0 \end{gathered} \tag{4}$$

DC-side average voltage can be expressed as

$$U_d = \frac{1}{T}\int_{\phi_0}^{T+\phi_0} U_{ab,d}\, d(\omega t) = \frac{1}{T}\left[\int_{\phi_0}^{\frac{T}{2}+\phi_0} u_{ab,d}\, d(\omega t) + \int_{\phi_0}^{T+\phi_0} u_{ab,d}\, d(\omega t)\right] \tag{5}$$

In Equation (5), from current curve DC-side average voltag e can be expressed as (when only winding 1 outputs power at low rotational speed range, output dc average voltage of diode rectifier is obtained as)

$$U_d = \sqrt{3}\frac{np}{10}W\Phi_m k_w - \frac{np}{10}L_{(I_d)}I_d - \frac{7}{4}rI_d$$

$$n_1 \le n \le n_3 \tag{6}$$

If internal effective resistance is considered, can be expressed as voltage of battery set

$$U_d = E_0 + I_d R \tag{7}$$

2.2. Current and Output Power Determination at DC-Side

Figure 7 shows desaturation section and inductance character according to current from saturation character to completed saturation. Generally, self-inductance character of winding 1 (a, b, c) by the reactance bridges is desaturate to current $I_{d,A}$. Then decrease from $I_{d,A}$ to $I_{d,B}$.

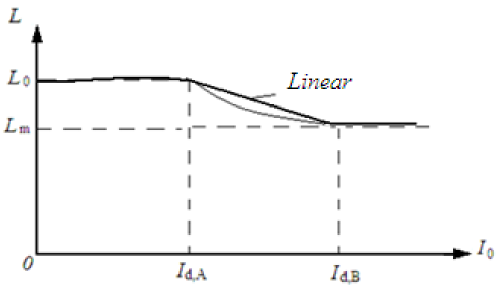

Figure 7. *Self-inductance characteristic curve by current of winding 1.*

If current is more than $I_{d,B}$, then inductance don't change. Interpretation consider more concretely. an approximate equation of inductance is expressed as

$$L = \begin{cases} L_0 & 0 \le I_d \le I_{d,A} \\ kI_d + L_B, & I_{d,A} \le I_d \le I_{d,B} \\ L_m & I_{d,B} \le I_d \end{cases} \tag{8}$$

$$k = \frac{L_0 - L_m}{I_{d,B} - I_{d,A}}, \quad L_B = \frac{L_0 I_{d,B} - L_m I_{d,A}}{I_{d,B} - I_{d,A}}$$

2.2.1. Determination of the Current and Output Power at Rotational Speed $n_1 \le n \le n_2$ Range

This range passing from the current $I_d = 0$ to $I_d = I_{d,A}$ has desaturation. So, in this case self-induction is equal as $L=L_0$. From (6) and (7), the current and output power of the circuit can be expressed as follows:

$$I_d = \frac{\sqrt{3}\frac{np}{10}W\Phi_m k_w - E_0}{\frac{np}{10}L_0 + \left(\frac{7}{4}r + R\right)} \tag{9}$$

Thus, input power of battery set can be expressed as follows:

$$P = I_d E_0 = \frac{\sqrt{3}\frac{p}{10}W\Phi_m k_w n - E_0}{\frac{p}{10}L_0 n + \left(\frac{7}{4}r + R\right)} \cdot E_0 \tag{10}$$

2.2.2. Determination of the Current and Output Power at Rotational Speed $n_2 \le n \le n_3$ Range

If the current I_d is passing through the range $I_{d,A} \sim I_{d,B}$, then self-inductance is expressed as

$$L_{(I_d)} = kI_d + L_B$$

As calculated (10), substituting (6) and (7) can express as

$$I_d = \frac{1}{2}\left\{\left[\left(\frac{L_B}{k_1} + \frac{35r}{2npk_1} + \frac{10R}{npk_1}\right)^2 - 4\left(\frac{\sqrt{3}W\Phi_m k_w}{k_1} - \frac{10E_0}{npk_1}\right)\right]^{\frac{1}{2}} + \left(\frac{L_B}{k_1} + \frac{35r}{2npk_1} + \frac{10R}{npk_1}\right)\right\} \quad P = I_d \cdot E_0 \tag{11}$$

2.2.3. Determination of the Current and Output Power at Rotational Speed $n_3 \le n \le n_4$ Range

If the current $I_d > I_{d,B}$, then magnetic circuit by the reactance bridge is in the perfect saturation mode. In this case, inductance L is equal to L_m. So, the current passing through the battery set and total input parameters are obtained as

$$\begin{cases} I_d = \dfrac{\sqrt{3}\dfrac{np}{10}W\Phi_m k_w - E_0}{\dfrac{np}{10}L_m + \dfrac{7}{4}r + R} \\ P = I_d \cdot E_0 = \dfrac{\left(\sqrt{3}\dfrac{np}{10}W\Phi_m k_w - E_0\right)\cdot E_0}{\dfrac{np}{10}L_m + \dfrac{7}{4}r + R} \end{cases} \tag{12}$$

Thus, in paper presented mathematic modeling on current and output power character of SWPGS with AMPTC at low rotational speed range.

3. Results

For output power character analysis, MATLAB/Simulink is made simulation circuit diagram and it had been analysis. Simulation circuit diagram is given as Figure 8.

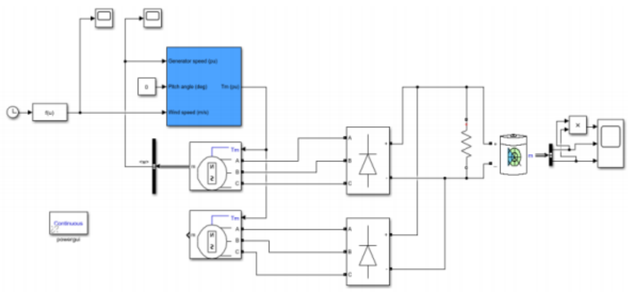

Figure 8. Simulation circuit diagram of SWPGS with AMPTC.

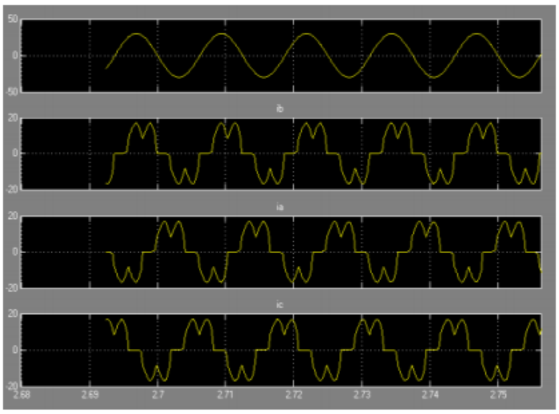

Figure 9. Phase voltage and phase current wave of windings 1.

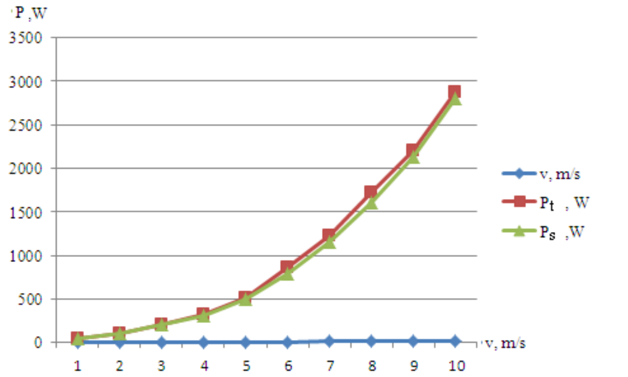

Figure 10. Output characteristic curve' comparison using Simulink.

The phase voltage and phase current wave of first windings obtained from simulation circuit diagram is shown as Figure 9.

In 3kW SWGS, the comparison between theoretical value and simulation voltage from simulink result is shown as Figure 10.

In the case using nonlinear inductance in SWPGS with AMPTC, the error between theoretical and Simulink characteristic curve shown as Figure 10 is 4 percent. So we can know that proposed mathematical modeling comparatively coincide.

4. Discussion

This paper presents the improvement of the power character using nonlinear inductance in SWPGS with AMPTC. This method is suitable for power character improvement of SWPGS without the need for control circuits.

The proposed method is based on saturation character for internal magnetic circuit of generator. This has been validated through output characteristic curve comparison using MATLAB/Simulink. In the future we will study hard the current control method to achieve maximum power operation at high speed rotation range.

5. Conclusions

This paper proposed mathematical modeling on the power character of SWGS with AMPTC approach the maximum output power curve of the wind turbine; current determination method flowing internal magnetic circuit of generator using nonlinear inductance.

Finally, the efficiency of previous wind generation system is low because inductance change is constant. But the efficiency of proposed system is high because the current flowing into circuit at low speed rotational range can control automatically. If this method use widely in SWGS then can improvement the efficiency of system.

Abbreviations

SWPGS	Small Wind Power Generator System
AMPTC	Automatic Maximum Power Tracking Capability
PM	Permanent Magnet
MPPT	Maximum Power Point Tracking

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Author Contributions

Mun Hui Kim: Conceptualization, Resources, Funding acquisition, Project administration, Writing – review & editing

Yong San Kim: Data curation, Methodology, Supervision, Validation

Hyon Guk U: Formal Analysis, Investigation, Software, Writing – original draft

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Mun Hui Kim is a professer at Kim Chaek University of Technology, Faculty of Electrical Engineering. She completed her PhD in Electrical Engineering from Kim Chaek University of Technology in 2021. Recognized for her exceptional contributions, Dr. Mun Hui has been recognized as a Professional. She use her best endeavors to participate in multiple international research collaboration projects in recent years. She currently serves on the Editorial Boards of numerous publications and has been invited as a Technical Committee Member at Kim Chaek University of Technology, Faculty of Electrical Engineering.

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Research Field

Mun Hui Kim: Double winding, MPPT, Off-grid, Electric energy generation, Wind power

Yong San Kim: Continuous conduction mode, Harmonics, Diode bridge rectifier, Discontinuous conduction mode, PM synchronous generator

Hyon Guk U: Steady-state analysis, AMPTC, SWPGS, Electrical Machines, Electric energy generation