Maximum power point tracking techniques for wind energy systems using three levels boost converter

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Abstract. This paper presents modeling and simulation of three level Boost DC-DC converter in Wind Energy Conversion System (WECS). Three-level Boost converter has significant advantage compared to conventional Boost. A maximum power point tracking (MPPT) method for a variable speed wind turbine using permanent magnet synchronous generator (PMSG) is also presented. Simulation of three-level Boost converter topology with Perturb and Observe algorithm and Fuzzy Logic Control is implemented in MATLAB/SIMULINK. Results of this simulation show that the system with MPPT using fuzzy logic controller has better performance to the Perturb and Observe algorithm: fast response under changing conditions and small oscillation.

1. Introduction
Nowadays, among the all renewable energy sources, wind energy is one of the fastest expanding. It is a common source which not only for electrical power generation but also in rural sites using around the world. Small wind power systems are appropriate for remote areas.

The variable speed wind turbine technology using permanent synchronous generator (PMSG) is rapidly growing due to higher efficiency, lower mechanical stress and reduction in installation and maintenance costs [1]. Many power converter topologies are being developed for PMSG in wind energy conversion systems (WECS) to reduce cost, increase reliability and improve wind energy conversion efficiency [2].

In order to extract the maximum energy from the WECS, the generator rotational speed must be controlled by the MPPT algorithm; therefore, the MPPT is one of the factor importance in WECS. The goal of MPPT is to maximize the wind power capture at different wind speeds by adjusting the turbine speed. There are many different techniques for maximum power point tracking in the literature last decades [4-][6], but two groups are most common. The first group requires prior knowledge of turbine parameters to calculate the operating point and the second group is based on iterative research.

The three level Boost converter (TLBC) have the advantages of the low stress, the low inductor current ripple and the low stitching loss as compared to conventional Boost converter [3]. Therefore, the TLBC are widely used in the modern power electronics applications, such as ac/dc PFC application [11], [12], dc/dc PV applications [3], the fuel-cell applications [13], [14] and the wind energy application [15].

2. Wind Turbine Systems
There are many possible configurations of power electronic converters and electrical generators for variable speed wind turbine systems. The figure 1 below shows the diagram of our wind energy conversion system.
• The wind turbine is directly coupled to the PMSG. Compared to other generators, the PMSG has advantage that it could couple directly to a wind turbine with no need for a gear box. WECS with PMSG can avoid the problem of wear and tear of gear, it can help wind turbine operate more reliable and reduce maintenance [7].
• The generated AC Voltage from PMSG cannot directly supply DC link so there are an uncontrolled rectifier and three level converter Boost DC-DC between the generator and DC bus.
• DC Resistive load

![Figure 1. Configurations of Wind Power system](image)

2.1. Model of wind turbine
Wind turbine is applied to convert the wind energy to mechanical torque. The conversion from wind speed to mechanical power ($P_m$) can be described in steady state by [8], [9]:

$$ P_m = \frac{1}{2} C_p \rho \pi R_{blade}^2 v_{wind}^3 $$

(1)

In wind power equation (1), $\rho$ is air density (1.225 kg/m$^3$), $R_{turbine}$ is the turbine radius in meters, $v_{wind}$ is the wind speed in m/s, and $C_p$ is the turbine performance coefficient.

In order to maximize the output power of a wind turbine, we have to optimize the value of $C_p$. The coefficient of performance is a strong and nonlinear function of the “Tip Speed Ratio”. It depends on such factors as the number of blades, the pitch and shape of the blades. The maximum value $C_p$ can attain around 59% theoretically. This coefficient is also known as Betz limit. The speed ration $\lambda$ is defined:

$$ \lambda = \frac{\Omega_{turbine}}{v_{wind}} $$

(2)

Output torque of the turbine is calculated:

$$ T_m = \frac{P_m}{\Omega} = \frac{1}{2} \frac{C_p(\lambda, \beta) \rho \pi R_{blade}^2 v_{wind}^3}{\Omega} $$

(3)

If the speed ratio $\lambda$ is maintained at its optimal value $\lambda_{opt}$, the power coefficient is at its maximum value $C_{pM}=C_p(\lambda_{opt})$, the maximum power of the wind turbine will be:

$$ P_{m opt} = \frac{1}{2} C_{pM} \rho \pi R_{blade}^2 v_{wind}^3 $$

(4)

When the speed ratio assumed to be maintained at the optimum value, we obtain the optimum speed rotor:

$$ \lambda_{opt} = \frac{\Omega_{blade}}{v_{wind}} \Rightarrow \Omega_{opt} = \frac{\lambda_{opt} v_{wind}}{R_{blade}} $$

(5)

Thus, for each wind speed, there is a maximum rotor speed $\Omega_{opt}$ which made a maximum power recovered from the wind turbine as shown in the figure 2.
2.2. Rectifier

In order to supply the DC-link, the PMSG should be connected to a rectifier that converts the AC voltage into DC voltage. In the literature, there are two possible configurations:

- Generator - diode rectifier - chopper - DC link
- Generator - PWM rectifier - DC link

In this study, we work with the first configuration.

2.3. Model of three-level boost converter

In the diagram of TLBC as shown in the figure 3, the input is a DC voltage source in series with an inductor L. The resistive load is connected across the capacitors to provide output voltages $V_0$. The midpoint of the capacitors $C_1$ and $C_2$ are connected to the centre point of the switches $S_1$ and $S_2$. By cause of the input inductor L and two diodes $D_1$ and $D_2$ in the TLBC, both switches can be turning ON at the same time without the concern of the sort-circuit damage. The ideal inductor and the ideal capacitors are assumed.

2.4. Mode operation

The TLBC will be operated in four different modes according to the power switches conduction state, which can be both conducting, or both turned off, or one of them conducting and the other turned off as shown in the figure 4a, 4b, 4c, 4d.
2.5. Operation principles

The converter operated depends on the input voltage, which is lower or higher than half of the output voltage:

- **In region 1: \( V_{\text{in}} > V_{\text{out}}/2 \):** In both of mode 3 and 2, as \( V_L > 0 \), the inductor current raising polarity is positive. This occur only when duty ratio \( d_1 \) and \( d_2 \) are less than 0.5. In this region, both of two switches must not be “ON” at the same time; thus, only switching mode 2, mode 3 and mode 4 can be found.

- **In region 2: \( V_{\text{in}} < V_{\text{out}}/2 \):** In both of modes 3 and 2, as \( V_L < 0 \), the inductor current raising polarity is negative. Both of two switches must not be “OFF” at the same time; thus, only switching mode 1, mode 2 and mode 3 can be found.

In this study, we work in the symmetrical operation and continuous conduction mode by choosing \( C_1 = C_2 \) and the duty ratio \( d_1 = d_2 = d \).

Equations to calculate a TLBC:

- The voltage gain of TLBC:
  \[
  \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{1-d} \tag{6}
  \]

- Inductor current ripple:
  \[
  \Delta I_L = \begin{cases} 
  \frac{V_{\text{in}}(1-2d)d}{2Lf(1-d)} & \text{for } d < 0.5 \\
  \frac{V_{\text{in}}(2d-1)}{2fL} & \text{for } d > 0.5
  \end{cases} \tag{7}
  \]

- Output voltage ripple:
  \[
  \Delta V_{\text{out}} = \begin{cases} 
  \frac{V_{\text{in}}(1-2d)}{RCf(1-d)} & \text{for } d < 0.5 \\
  \frac{V_{\text{in}}(2d-1)}{RCf(1-d)} & \text{for } d > 0.5
  \end{cases} \tag{8}
  \]

3. Proposed MPPT methods

3.1. Perturbation and observation control

Perturbation and Observation (P&O) is the simplest MPPT algorithm that does not require any prior knowledge of the system, the turbine’s characteristic curve or any additional sensor except the measurement of the power which is subjected to maximization. The principle of P&O algorithm is kept perturbing the control variable in the same direction until the power is decreased. The flowchart and principle of P&O method are shown in the figure 5 and 6 respectively.
In P&O method, choosing an appropriate step size is very important task. A larger step size leads to a faster response but more oscillations around the MPPT point. In reversed, a smaller step-size improves efficiency but reduces the convergence speed which can be incapable of tracking MPP under rapidly varying wind conditions.

3.2. Fuzzy control logic
The advantages of fuzzy logic controller (FLC) over the conventional methods are: (a) it does not need an accurate mathematical model; (b) it can work with imprecise inputs; (c) it can handle nonlinearity; and (d) it is more robust than conventional nonlinear controllers [16].

Our fuzzy logic controller is designed to vary the duty cycle of the converter to track the optimum rotor speed, thus maximizing the power recovered by the turbine. Our method based also on principle:

- On the MPP, we have \( \frac{dP_{WT}}{dV_{WT}} = 0 \).
- If we are in the region \( \frac{dP_{WT}}{dV_{WT}} > 0 \), we should increase the voltage or decrease the duty cycle to reach the MPP.
- If we are in the region \( \frac{dP_{WT}}{dV_{WT}} < 0 \), we should decrease the voltage or increase the duty cycle to reach the MPP.

Fuzzy logic controller (FLC) MPPT method consists of four major elements: fuzzification, rules, interference engine and defuzzification [10].

Input and Output Variables: To implement the FLC for MPPT algorithm, the input and output variables of the FLC have to be determined. In this paper, we need two inputs: change in wind turbine power \( dP/dV \) and its derivative, output is duty cycle \( D \) of the three level Boost converter. The output of the FLC is the DC/DC converter duty cycle given as:

\[
D(n) = D(n-1) + \Delta D(n)
\]

Membership Functions: In the FLC, the input and output variables are expressed by linguistic variables. The linguistic terms used here are:

- \( dP/dV \) [VeryNegative, Negative, Zero, Positive, VeryPositive]
- \( (dP/dV)' \) [Negative, Zero, Positive]

The five various terms of \( (dp/dV) \) and three terms of its derivative \( (dP/dV)' \) are shown in the figure 7 and 8 respectively.

The Control Rules: The control rules are derived from the experience or knowledge on the control system. The fuzzy rules are defined as follows:

- \( R_i \); IF \( dP/dV \) is \( A_i \) and \( (dP/dV)' \) is \( B_i \), THEN \( \Delta D(k+1) \) is \( C_i \)

Where \( A_i \) and \( B_i \) is the fuzzy subset, and \( C_i \) is a fuzzy singleton.
To get the output of inference, many methods are proposed by the researchers. There are some known methods such as Mandani, Sugeno, and Larsen. This paper used the min-max inference method and Takagi-Sugeno system.

Fuzzy rules are designed to achieve zero error at the state of the MPP. The main idea of the rule is to bring operating point of MPP by increasing or decreasing the duty ratio D depending on the position of the operating point from the MPP. If the operating point is distant from the MPP, the duty ratio will increase or decrease largely. In the proposed fuzzy controller, fifteen rules are formed, and it shown in the table 1:

| dP_{WT}/dV_{WT} | (dP_{WT}/dV_{WT})' | Negative | Zero | Positive |
|-----------------|---------------------|----------|------|----------|
| NB              | 3%                  | 3%       | 3%   |
| NS              | 3%                  | 1%       | 1%   |
| ZE              | 0%                  | 0%       | 0%   |
| PS              | -1%                 | -1%      | -3%  |
| PB              | -3%                 | -3%      | -3%  |

**Defuzzification:** After the fuzzification, the defuzzification is performed which converts the fuzzied value into defuzzied value. It gives the final output value. In this paper, the center gravity defuzzification method is used.

The weighting factor is obtained by minimum operation, which is given by:

$$ w_i = \min \left\{ \mu_{dP/dV}, \mu_{(dP/dV)'} \right\} $$

(10)

The final output of the system is the weighted average of all rules output:

$$ \Delta D(k) = \frac{\sum_{i=1}^{N} \omega_i C_i}{\sum_{i=1}^{N} w_i} $$

(11)

4. Simulation and results

4.1. Simulation

The system described in the section 2 is implemented Matlab Simulink as show figure 9.
The model of wind turbine subsystem is built based on equation (1) - (4). Wind speed and load demand are varied within 80 seconds to test our controllers in various climatic and operating conditions. Figure 10 and figure 11 show our proposed fuzzy logic controller and P&O controller implemented in Simulink.

4.2. Results
In the first twenty seconds, the wind speed is 8m/s. According to the generator curve in the figure 2, we have the optimal rotor speed and the maximum power output is around 1500 rpm and 8.64 kW respectively. Our controller has chosen the good value of D in order to keep the rotor speed at around 1496 rpm, which make power attracted around 8.639 kW. From 20th seconds to 40th seconds, when wind speed change from 8 m/s to 6 m/s (for an optimal rotor speed of 1126 rpm and maximum power output of 3.64 kW), the wind turbine system moves toward to the new MPP. The generator speed changes to new optimal value as the figure 13. Our controller increases rotor speed at around 1117 rpm, which make power around 3.639 kW.

Other tests are applied when wind speed changes from 6 m/s to 9 m/s and finally 9m/s to 7 m/s all the 20 seconds. We notice well that the rotor speed change according to the wind speed variation (at the 20th second, 40th second, 60th second) in order to have the maximum power output. On the other side, the figure 12 and 13 shows that our controller also works well to track the maximum power point when load demand change (30th and 70th second). These results still have some oscillation in P&O method because of the complex and nonlinear nature of the WECS, but it does not affect the final objective of our controller. Compared with conventional MPPT method, a FLC method has not only fast response under changing climatic or operating conditions but also small oscillation at the maximum power point.
5. Conclusion
This paper presents the modeling and simulation of three-level Boost converter in Wind Energy Conversion System. Based on the simulation it can be concluded that with the both controllers can track the maximum power however the FLC has better performance to the P&O: fast response under changing conditions and small oscillation. In the future, we think about the case of failure of converter, for example an open-circuit fault. The TLBC will allow to the system go into degraded mode to provide a convenient service of nominal behavior during an open-circuit fault state by reconfiguring to the conventional DC-DC Boost converter.

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