

# A Fuzzy Logic Control Approach for Doubly Fed Induction Generator Wind Turbines Based on Nonlinear Wind Speed Estimation

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## ABSTRACT

This paper presents a detailed description of the control algorithm for a wind turbine with a doubly fed induction generator (DFIG). The aerodynamic properties of the wind turbine are estimated using a nonlinear input-output mapping approach, namely a Gaussian radial basis function network. The wind speed is estimated using a nonlinear mapping, which considers the measured generator electrical output power, as well as the power losses in the wind turbine generator (WTG) and the dynamics of the WTG shaft system. The novel control methodology entails the development and comprehensive evaluation of the fuzzy logic controller. Ultimately, the method described in this study is implemented in the wind generation system. Subsequently, the estimated wind speed is employed to ascertain the most favorable command for the DFIG rotor speed, with the objective of maximizing the extraction of wind power. The speed controller of the Doubly Fed Induction Generator (DFIG) is appropriately engineered to efficiently mitigate the effects of low-frequency torsional oscillations. The WTG system achieves optimal electrical power output to the grid, exhibiting superior efficiency and dependability, all while eliminating the need for mechanical anemometers.

**Keywords:** Doubly fed induction generator, wind turbine generator, wind speed estimation.

## 1. INTRODUCTION

Permanent magnet generators (PMGs) are commonly used in small and medium-size wind turbine systems for electrical power generation [1], [2]. Compared to the wind turbines equipped with induction generators, there are several advantages of using PMGs. First, the PMGs can provide high-efficiency and high-reliability power generation, since there is no need for external excitation and no copper losses in the rotor circuit. Second, the high-power-density PMGs are small in size, which reduces the cost and weight of the wind turbine generator (WTG) system. Moreover, the wind turbine equipped with a direct-drive PMG removes the need of using a gearbox. According to the statistical data reported in [3], about 19.4% downtime of WTGs is caused by failures of gearboxes. Without gearboxes, the WTG systems need less maintenance and have a reduced downtime and a higher reliability. Control, monitoring, and protection of WTGs usually require the information of wind speed and generator rotor position/ speed, which can be measured by well-calibrated mechanical sensors, such as anemometers and rotor position sensors, respectively. However, the use of these mechanical sensors increases the cost and failure rate of WTG systems. According to [3], sensor failures contribute to more than 14% of failures in WTG systems; and more than 40% of failures are related to the failure of sensors and the consequent failures of the control or electrical systems. Repairing the failed components requires additional cost and leads to a significant loss in electrical power production. The problems incurred in using mechanical sensors can be solved through mechanical sensor less control. In [4] and [5], the wind speed was estimated based on power signal feedback, but the generator rotor position or speed was still measured for wind speed estimation and WTG control. The control systems in [6]–[8] used a hill-climb searching algorithm, which employed an incremental control action to track the maximum power point of the wind turbine. That method does not need the information of wind speed. However, it may take a long search time for that method to locate the optimal operating point. Therefore, if the wind speed changes from time to time, the

WTG may operate at nonoptimal conditions frequently. In [9], the wind speed was predicted for WTG control from an autoregressive statistical model by using historical data. Most of these works still used generator rotor position/speed measurements. In existing WTG control systems, rotor position sensors are used not only to get the shaft speed information but also to control the frequency of the power electronic converters. The previous research on rotor position sensor less control has been focused in the area of permanent magnet (PM) motor drives. For example, in [10] a sliding-mode observer was developed for rotor position sensor less control of PM synchronous motors without saliency. Reference [11] pointed out that the output voltage of the d-axis current regulator of the drive system would have the information of rotor position errors in a nonsalient PM synchronous motor. If a PI controller was employed to control the position errors to zero, the output of the PI controller would have the information of the rotor position. This paper proposes a novel mechanical sensorless control for direct-drive PMG wind turbines, where the measurements are not needed for wind speed or generator rotor position. First, a sliding-mode observer is designed to estimate the back electromotive force (EMF) of the PMG, which is then used to determine the rotor position of the PMG. Second, a model adaptive reference system (MRAS) observer is designed to estimate the rotating speed of the PMG by using the estimated back EMF from the sliding-mode observer. Third, based on the measured electrical power and estimated rotor speed of the PMG, the mechanical power of the wind turbine is estimated by taking into account the power losses of the system. Fourth, the wind speed is estimated with the information of the WTG shaft speed and mechanical power by using a back-propagation artificial neural network (BPANN). The estimated wind speed is then used to determine the optimal shaft speed reference. Based on the proposed estimation algorithms, a sensorless control is developed for PMG wind turbines to continuously generate the maximum electrical power without using any wind speed or rotor position sensors.

## 2. MODELLING OF THE WIND ENERGY CONVERSION SYSTEM

In this, various design and modelling aspects of different components of the Wind Energy Conversion System like the basic models of synchronous generator, AC-DC-AC PWM converter, wind turbine, drive train and their control system are described

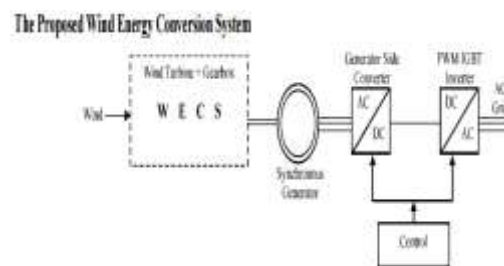


Fig 1 Proposed Wind Energy Conversion System

The proposed WECS system consists of wind turbine, two mass drive train, permanent magnet synchronous machine (PMSG) which is torque controlled and AC-DC-AC PWM converter.

### Permanent Magnet Synchronous Generator (PMSG)

The PMSG is a Synchronous Machine, where the DC excitation circuit is replaced by permanent magnets, by eliminating the brushes. PMSG has a smaller physical size, a low moment of inertia which means a higher reliability and power density per volume ratio as it has permanent magnets instead of brushes and the slip rings. Also by having permanent magnets in the rotor circuit, the electrical losses in the rotor are eliminated. The PMSG are becoming an interesting solution for wind turbine applications [1]. However, the disadvantages of the permanent magnet excitation are high costs for permanent magnet materials and a fixed excitation, which cannot be changed according to the operational point. The PMSG can be classified according to the rotor configuration: • Interior

magnet type (IPMSG) for this configuration, the magnets is buried inside the rotor. The interior magnet PMSG usually presents magnetic saliency. The d-axis inductance is smaller than the q-axis inductance ( $L_d < L_q$ ), because the effective air gap of the d-axis is bigger than the q-axis air gap. This results in a component of reluctance torque in addition to the torque produced by the magnet. Because of this, the rotor position is much easier to detect. • Surface mounted magnet type (SPMSG) The SPMSG has the magnets mounted on the surface of the rotor. As the permeability of the permanent magnets is approximately equal to 1, permanent magnets act like air in magnetic circuits. This means that the air gap is very large and constant. The d- and q-axis inductances are nearly identical and the saliency ratio ( $\xi = L_q/L_d$ ) is 1. Therefore no reluctance torque occurs. One advantage of the SPMSG is that the surface mounted magnets lead to a very simple rotor design with a low weight.

### 3. SENSORLESS MPPT CONTROLLER

This section presents a maximum power tracking approach called sensorless Power Signal Feedback (PSF) method. The method has the capability of providing a power reference for the controller corresponding to maximum power point without measuring the turbine shaft speed. The maximum power curves for power mapping are established by running several simulations or offline experiments at various wind velocities and turbine speeds. In the system under study, the generator is connected to the turbine. Based on this, the generator shaft speed and corresponding power generated are measured and the quadratic optimal power-speed-curve is drawn. Figure2 shows the complete block diagram of the proposed WECS with sensorless speed estimator MPPT controller. This method has strikingly reduced the number of controller block. This controller is a very smart sensorless scheme that simply takes into account the cyclic nature of the generated voltage whose frequency is directly proportional to the speed of the generator. Knowing the number of rotor poles and measuring the time between two rising zero crossings (one complete cycle) of the generated voltage the speed of the generator is found out. Once the time taken for one cycle of the generated voltage is found, the corresponding frequency of the generated voltage can be obtained. Hence, the speed of the generator is given by

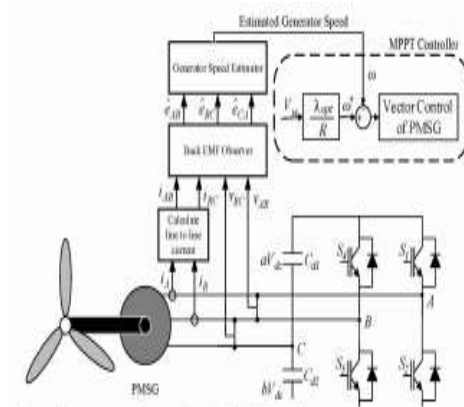


Fig. 2 Proposed Sensorless MPPT Controller

### 4. FUZZY LOGIC

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection. To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

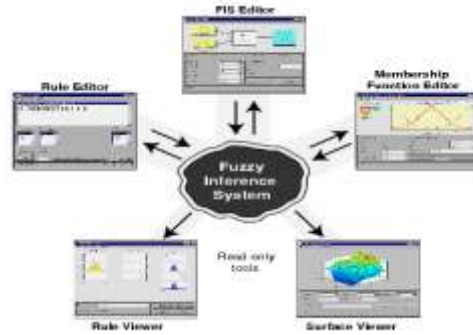


Fig.3 the Primary GUI Tools Of The Fuzzy Logic Toolbox

The FIS Editor handles the high level issues for the system How much input and output variables? What are their names? The Fuzzy Logic Toolbox doesn't limit the number of inputs. However, the number of inputs may be limited by the available memory of our machine. If the number of inputs is too large, or the number of membership functions is too big, then it may also be difficult to analyze the FIS using the other GUI tools. The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable. The Rule Editor is for editing the list of rules that defines the behavior of the system.

*The FIS Editor:*

The following discussion walks we through building a new fuzzy inference system from scratch. If we want to save time and follow along quickly, we can load the already built system by typing fuzzy tipper This will load the FIS associated with the file tipper.fis (the .fis is implied) and launch the FIS Editor. However, if we load the pre-built system, we will not be building rules and constructing membership functions.

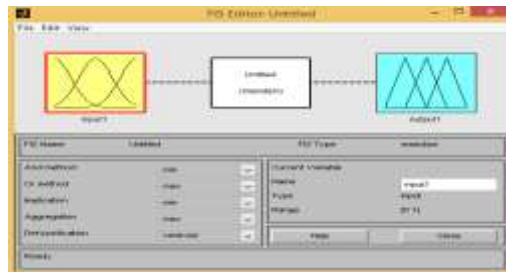


Fig.4 The FIS Editor

We will see the diagram updated to reflect the new names of the input and output variables. There is now a new variable in the workspace called tipper that contains all the information about this system. By saving to the workspace with a new name, we also rename the entire system. Our window will look like as shown in Fig.5.



Fig.5 The Updated FIS Editor

*The Membership Function Editor*



Fig.6 The Membership Function Editor

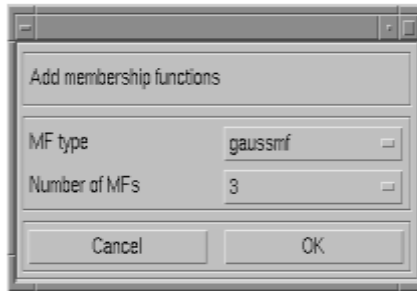


Fig.7 Add MFs... Window



Fig.8 The Updated Membership Function Editor

**5. SIMULATION RESULTS**

In this section, simulation results are presented to verify the validity of operations of the proposed system under steady- state and transient conditions. The simulated system parameters are listed in Table T. These simulations were performed using control systems mentioned in Section IV. The variable frequency mode of six switch AC/AC converter is selected since two three phase terminals of the converter work with different frequency

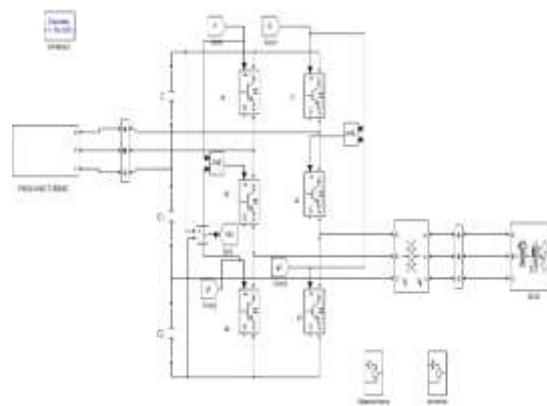


Fig 11 Simulink model of proposed system

*A. Operation of Constant Wind Speed*

In this section, the steady state operation of the proposed system is verified through simulation results. For this purpose the wind speed is considered a constant value which is equal to 13 m/s. The DC-link voltage waveform is shown in Fig 12. As it can be seen in this figure, the grid side control system in Fig. 8 works properly and the DC link voltage remains almost constant (220 0V). Another function of the grid side control system is to set the reactive power injected to the grid. In this paper the unity power operation of wind energy system is desirable and Fig. 13 shows that the control system has successfully fulfilled this criterion and the grid voltage and the input current are 180 degrees out of phase.

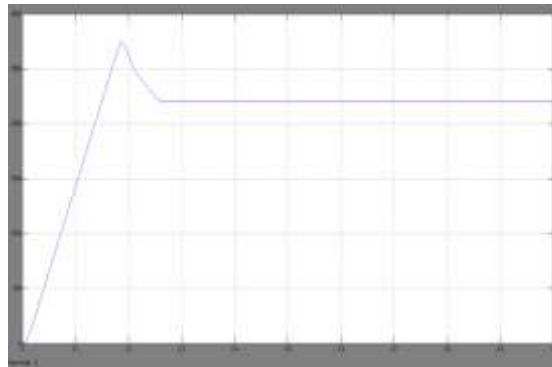


Fig 12 Dc link voltage

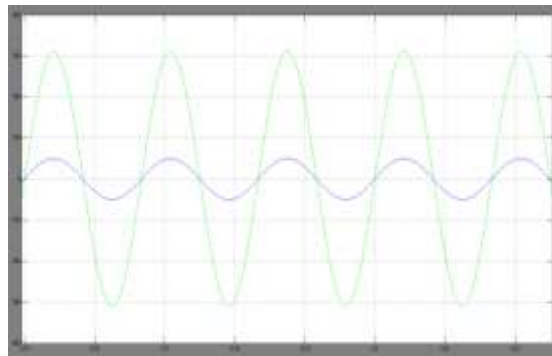


Fig 13 the grid voltage and the input current

Fig. 14 shows the extracted mechanical power from the wind and the electrical power delivered to the grid. As it is obvious in the figure, these two values are different from each other. It is because that a small portion of the mechanical power extracted from wind is dissipated in electrical and mechanical parts of WECS. In order to always track MPP, the reference value of PMSG rotor speed is set using TSR method and compared with the estimated rotor speed. The real and estimated rotor speeds as well as the obtained rotor speed from MPPT are illustrated in Fig. 15. This figure clearly shows the ability of proposed sensorless system to accurately estimate the rotor speed. It is also apparent in Fig. 4.6 that PMSG rotor speed nearly equals with the rotor speed obtained from MPPT extracted mechanical power is tracking the maximum mechanical power after a short time.

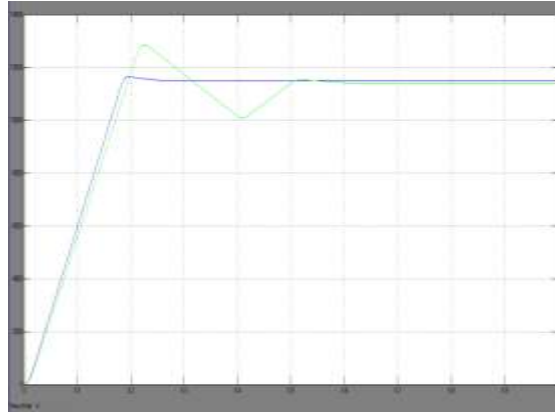


Fig 14 power delivered to the grid and extracted mechanical power

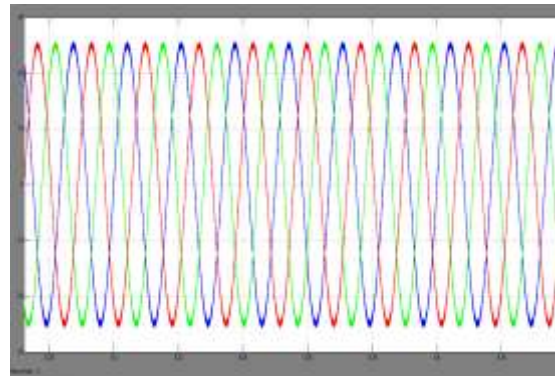


Fig. 15 Injected three phase currents to the Grid.

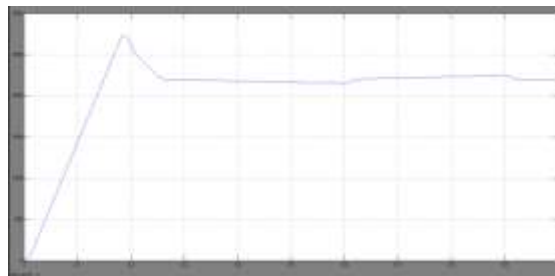


Fig 16 Dc link voltage

*B. Operation of Variable Wind Speed*

In order to examine the proposed system performance under the transient condition, wind speed has been varied from 13 m/s to 9 m/s in  $t=0.6$  sec and then from 9 m/s to 11 m/s in  $t=0.9$  sec. The previous simulation is rerun in this transient condition and the simulation results are shown in Fig. 16 to Fig. 18 . DC-link voltage is displayed in Fig. 16 which is almost constant although the wind speed undergoes two transient changes.

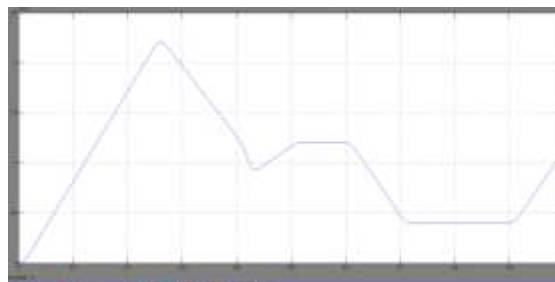


Fig 17 power delivered to the grid

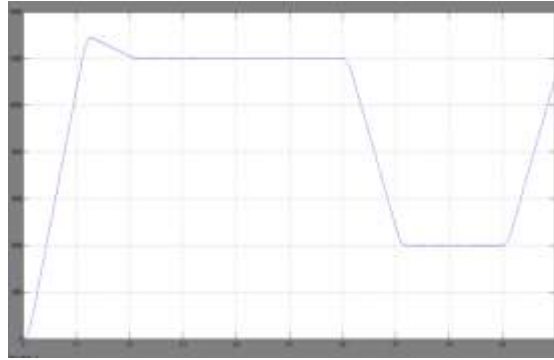


Fig 18 mechanical power

## 6. CONCLUSION

In this paper the fuzzy control of wind energy conversion system in order to get constant output power is obtained and verified through the simulation. The main goal of implementing fuzzy controller is to continuously adapt the constant power of the generator and the wind speed in a way that the turbine operates at its optimum. The advantages of using fuzzy controller are verified by its simulation results, fast response, and parameter insensitivity. Implemented system has satisfactory, dynamic and static performance.

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