Journal of Theoretical and Applied Information Technology

www.jatit.org

FUZZY LOGIC BASED LIGHT LOAD EFFICIENCY IMPROVEMENT OF MATRIX CONVERTER BASED WIND GENERATION SYSTEM

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ABSTRACT

The paper describes a variable speed wind generation system where fuzzy logic principles are used for light load efficiency improvement and optimization. A squirrel cage induction generator feeds the power to an improved topology of matrix converter which pumps power to a utility grid or can supply to an autonomous system. The power factor at the interface with the grid is controlled by the matrix converter to ensure purely active power injection into the grid for optimal utilization of the installed wind turbine capacity. Furthermore, the reactive power requirements of the induction generator are satisfied by the matrix converter to avoid self-excitation capacitors. The generation system has fuzzy logic control with vector control in the inner loops. Fuzzy controller tracks the angular frequency with the wind velocity to extract the maximum power and programs the machine flux for light load efficiency improvement. The complete control system has been developed, analyzed, and validated by simulation study. Performances have then been evaluated in detail.

Index Terms- Wind energy, squirrel cage Induction generator, matrix converter, fuzzy control, wind power generation

I. INTRODUCTION

During the last decade, due to the increased energy demand and environmental concern, wind farms (WFs) have penetrated to the field of power generation worldwide. Wind power is integrated into electricity grids and accounts for a noticeable share of the total power generation. Although the history of wind power goes back more than two centuries, its potential to generate electrical power began to get attention from the beginning of this century. However, during the last three decades, wind power has been seriously considered to supplement the power generation by fossil fuel and nuclear methods. In recent years, wind power is gaining more acceptances because of environmental and safety problems of conventional power plants and advancement of wind electric generation technology. The world has enormous resources of wind power. It has been estimated that even if 10% of raw wind potential could be put to use, all the electricity needs of the world would be met [1]. Of course, the main drawback of wind power is that its availability is somewhat statistical in nature and must be supplemented by additional sources to supply the demand curve. Suitable places for big clusters of windmills installations are uninhabited islands and offshore platforms; because they offer high, uniform wind speed and acceptable visual impact. Attractive locations for future turbines would be remote, such as offshore, where wind conditions are improved and planning restrictions are reduced.

The wind energy can be harnessed by a wind energy conversion system (WECS), composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system. Based on the types of components used, different WECS structures can be realized. However, the objective in all structures is the same, i.e., the wind energy at varying wind velocities has to be converted to electric power at the grid frequency [2]. Wind turbine configurations for extracting energy from the wind are categorized based on horizontal or vertical axis, number of blades and power rating. Modern wind turbines are of horizontal-axis type, normally have three blades, and their output power can be as high as 2MW per machine [3].

It has been shown that, for grid connected wind turbine systems; the efficiency of variable-speed systems is higher than that of constant-speed systems as total energy captured is larger. Therefore, despite the extra cost of power electronics and control, the life-cycle cost is lower. Many different configurations of variable-speed wind turbines have been introduced in the literature [4], [5], [6]. The Authors of [4] introduces a high- performance configuration, commonly known as Scherbius drive, composed of a doubly-fed induction generator (DFIG) and a PWM AC/DC/AC converter connected between the stator and rotor terminals to implement variable speed operation. Another configuration for variable-speed wind turbines has been introduced by Zhang, Watthanasarn, and Shepherd [5], where system is composed of a DFIG with a matrix converter connected between the stator control winding and the main stator terminals. Variable speed is implemented through control of the matrix converter. But these configurations suffer from the disadvantages of having a wound rotor and a brush-slip ring arrangement, and high cost of the doubly fed induction generator.

There have been active studies regarding the topologies of variable-speed turbines including those using cage induction[7]
and slow rotating, direct-drive machines [8]. Such topologies usually require 100% rated, four-quadrant power-electronic converters. As the converter cost decreases, such topologies will no doubt become increasingly more popular. So, recently, the use of squirrel-cage induction generator (SCIG) for grid-connection of WECS has been well established, due to its simplicity, robustness, small size per generated kilowatt, and low cost in comparison with other types of electric machines [9], [10], [11]. However, the major drawbacks of the IGs are reactive power consumption and poor voltage regulation under varying speed, but the development of static power converters has facilitated the control of the output voltage of IG [12]–[16].

The most common configuration of power converters for WECS based on variable-speed wind turbine and SCIG is that composed of two back-to-back voltage source converters with a large capacitor on the dc-link but it suffers from the demerit of bulky capacitor and having relatively reduced lifetime [10].

The major problems in above mentioned traditional power conversion schemes are the poor line power factor and harmonic distortion in line and machine currents. The IEEE Standard 519 [17] severely restricts line harmonic injection. Therefore, to satisfy the stringent harmonic standard and poor power factor problem, active type VAR and harmonic compensators can be installed at additional cost. Again, the conventional control principles used in these systems make the response sluggish and give nonoptimum performance. Very recently, a matrix converter based WECS has been proposed to overcome some of the above problems.

Matrix Converter (MC) provides direct AC-AC conversion and is considered an emerging alternative to the conventional two-stage AC-DC-AC converter topology [18],[19] as it provides a large number of control levers that allows for independent control on the output voltage magnitude, frequency and phase angle, as well as the input power factor. When compared with the AC-DC-AC converter system, the bold feature of MC is elimination of the DC-link reactive elements, e.g., bulky capacitors and/or inductors. A four-output leg improved MC topology with advantages over the conventional nine-bidirectional-switch topology has been developed in which voltage gain is improved, control is simplified, free from commutation problems, and forth leg creates a three-phase plus neutral utility power supply which provides the facility for unbalanced and single-phase loads.

This paper, a complete simulation study to validate the theoretical concepts, describes a variable speed wind turbine system with a squirrel cage induction generator and a four-output leg commutation free matrix converter where fuzzy logic control has been used extensively light load efficiency improvement. All the control algorithms have been validated by simulation study and system performance has been evaluated in detail.

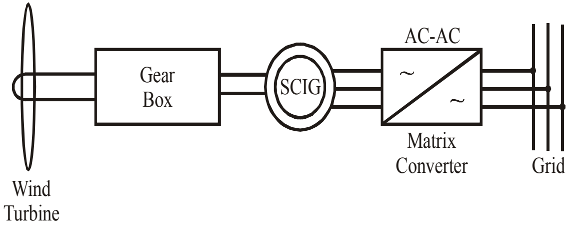


Fig. 1. Schematic diagram of proposed wind energy conversion scheme

THE PROPOSED WIND GENERATION SYSTEM DESCRIPTION

Fig. 1 shows a block diagram of the proposed system where four-output leg improved topology of matrix converter is used for interfacing WECS with the grid and fuzzy logic control has been used for performance enhancement and efficiency optimization. As the entire power generated by the wind turbine is transferred through the matrix converter, this work targets low-to-medium-power wind turbines. For medium-to-high-power wind turbines, doubly-fed induction generator with a pilot converter connected to the auxiliary winding will be more appropriate. The wind turbine is followed by a gear box which steps up the shaft speed. Note that working at a low shaft speed translates into a low induction generator terminal frequency which can result in core saturation unless a low terminal voltage is imposed. At low terminal voltages, the operating current will be high, making the scheme impractical. The matrix converter interfaces the SCIG with the grid and implements shaft speed control to achieve maximum power point tracking at varying wind velocities. It also performs power factor control at the grid interface and satisfies the Var demand at the induction generator terminals. The proposed scheme allows for connecting individual wind turbines to the grid. It also permits paralleling the outputs of several wind turbine generation units at the grid interface. The power handling capability of the system can be enhanced by adopting a multi-converter approach. In the following sub-sections, different elements of the system will be described.

A. *Wind Turbine Characteristics*

Both horizontal and vertical axis wind turbines are used in wind generation systems. The vertical Darrieus (egg beater) type has the advantages of being located on the ground and accepting wind from any direction without any special yaw mechanism. It is, therefore, preferred for high power output. The disadvantages are that the turbine is not self-starting and there is a large pulsating torque which depends on wind velocity, turbine speed, and other factors related to the design of the turbine. The aerodynamic torque(T_m) and mechanical power (P_0) generated by a wind turbine is given by Equation (1)-(2) [20].

$$T_m = C_p(\lambda)\ .\left[0.5\ \frac{\rho\pi R_\omega^3}{\eta\, gear}\right].\ V_w^2 \qquad (1)$$

$$P_0 = \frac{1}{2}\rho C_p A_r V_w^3 \qquad (2)$$

where P_0 is the power in W, *p* the air density in g/m^3, C_p a dimensionless factor called power coefficient, A_r the turbine rotor area in m^2 (A_r = □R_r^2, where R_r is the rotor blade radius), η $_{gear}$ is and V_w the wind speed in m/s. The power coefficient is related to the tip speed ratio □ and rotor blade pitch angle □ according to Equation (3) [20].

$$C_p(\lambda,\theta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2\right)e^{-18.4/\lambda_i} \qquad (3)$$

where

$$\lambda_i = \frac{1}{\dfrac{1}{\lambda - 0.02\theta} - \dfrac{0.003}{\theta^3 + 1}} \qquad (4)$$

and

$$\lambda = \frac{\omega_r R_r}{V_w} \qquad (5)$$

In (5), □$_r$ is the angular speed of the turbine shaft. The theoretical limit for C_p is 0.59 according to Betz's Law [21], but its practical range of variation is 0.2-0.4. In this paper, the rotor pitch angle is assumed to be fixed. Fig. 2 shows a typical C_p versus □ curve. As Equations (1)-(5) suggest, the aerodynamic torque($T_m = Kw_r^2$) and the mechanical power ($P_0 = Kw_r^3$) generated by the wind turbine at a given wind velocity is a function of the shaft speed.

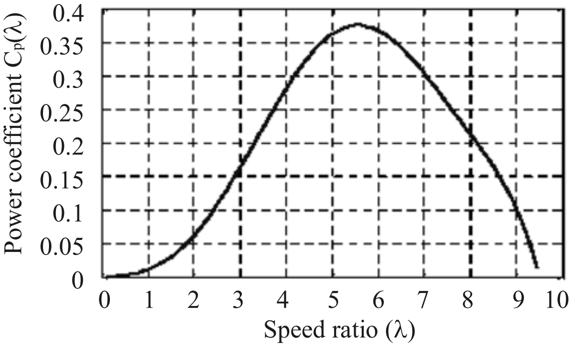


Fig. 2. Polynomial function curve fitting of turbine power coefficient (Cp)

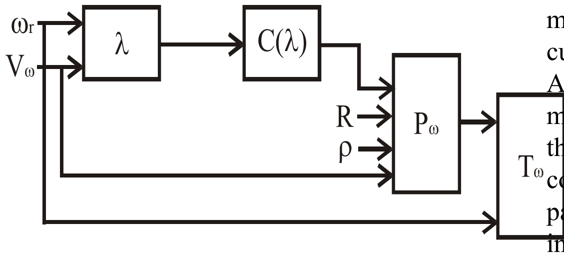


Fig. 3. Block diagram of the wind turbine model ω_r: shaft speed, V_ω: wind velocity, R: radius of the shaft, ρ: Air Density.

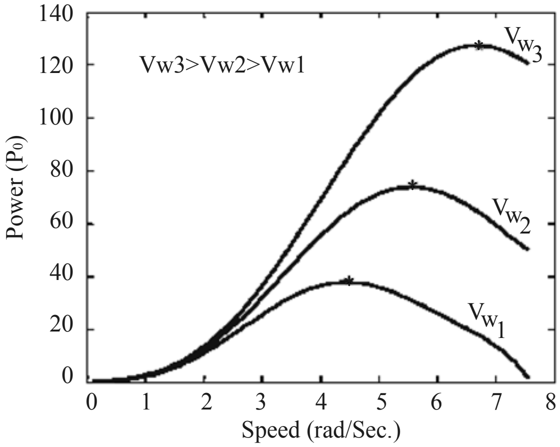


Fig. 4. Typical P_0 versus ω_r curves for different wind velocities (* = PMax).

This means that, at reduced speed light load steady state conditions, generator efficiency can be improved by programming the flux [22] and [23], which will be discussed later.

In this paper, a wind turbine model has been created in MATLAB simulation package based on the equations (1)-(5). The block diagram of the model is shown in Fig. 3 and a typical P versus ω_r curve produced by the model is shown in Fig. 4. As seen from Fig. 4, at any given wind velocity, maximum power can be captured from the wind if the shaft speed is adjusted at the value corresponding to the peak power. The idea in this paper is to change the angular frequency of the induction generator through matrix converter PWM control to track the shaft speed corresponding to the maximum turbine power at all times.

B. Improved Matrix Converter Topology

Matrix Converter represents a new generation of AC-AC converters with a compact design due to the lack of large energy storage elements. By properly operating the switches in the matrix converter, one can achieve control on the output voltage magnitude, frequency and phase angle, as well as control on the input displacement angle.

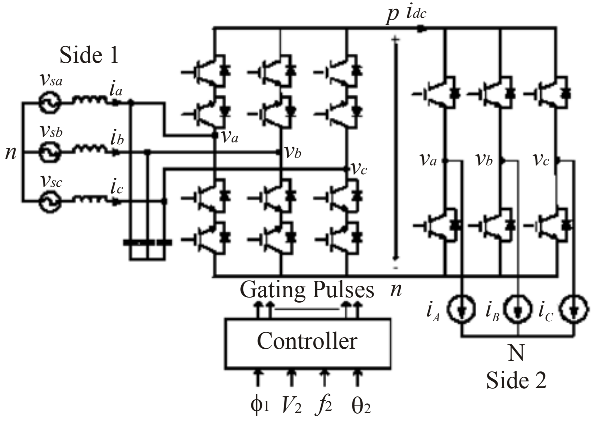


Fig. 5. Schematic diagram of the improved matrix converter topology

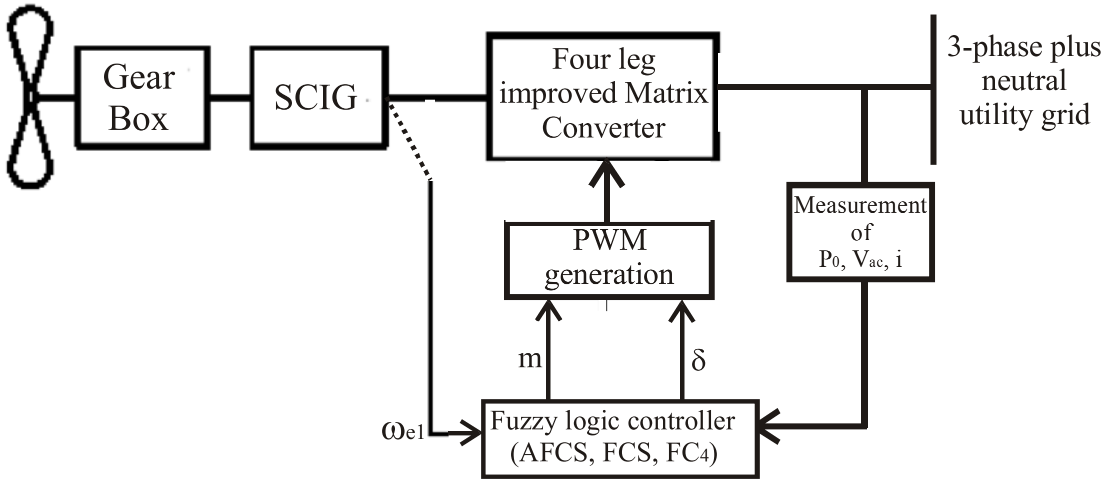


Fig. 6. Fuzzy logic based control block diagram of a wind generation system.

Matrix converter is a bi-directional power flow device with the capability of producing high quality input and output waveforms. A serious drawback attributed to the conventional matrix converter topology is the commutation problems associated with the operation of the four-quadrant switches. Safe operation of the switches requires complicated switching strategies impairing the elegance of the topology. Fig. 5 shows the schematic diagram of the improved matrix converter topology developed by Wei and Lipo [24]. A four-output leg improved matrix converter and variable-speed SCIG are integrated to create a three-phase plus neutral utility power supply. The matrix converter is designed to meet tight harmonic and the forth leg provides the facility to supply unbalanced and single-phase loads.

The improved four-leg matrix converter is based on the concept of "fictitious dc link" used in controlling the conventional matrix converter. However, there is no energy storage element between the line-side and load-side converters. The improved matrix converter topology has the following advantages with respect to the conventional matrix converter topology:

- The commutation problems associated with the switches have been solved.
- All the switches at the line-side turn on and turn off at zero current.
- As four-output leg matrix-converter topology is used so the forth leg provides the facility to supply unbalanced and single-phase loads.
- Line side power factor is unity with no harmonic current injection (satisfies IEEE 519).
- Machine current is sinusoidal—no harmonic copper loss.
- Continuous power generation from zero to highest turbine speed is possible.
- Power can flow in either direction permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine.
- Extremely fast transient response is possible.
- Multiple generators or multiple systems can be operated in parallel.

Considering all the above advantages, and with the present trend of decreasing converter and control cost, this type of conversion system has the potential to be universally accepted in the future. As shown in Fig.5, matrix converter offers four control levers that can be used to control the input displacement angle and output voltage magnitude, frequency and phase angle.

C. *Control System*

It appears that fuzzy logic based intelligent control is most appropriate for performance improvement of wind generation systems. Fig.6 shows the control block diagram of the system that uses the power circuit of Fig.1. This type of control, approaching the human reasoning that makes use of the tolerance, uncertainty, imprecision, and fuzziness in the decision- making process, manages to offer a very satisfactory performance, without the need of a detailed mathematical model of the system, just by incorporating the experts' knowledge into fuzzy rules. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations). The main drawback of an FL-based control system is that the tuning of its membership functions (MFs) needs too much "trial and error." In order to reduce the time-consuming process of the MFs tuning or to ameliorate the performance when it does not satisfy the specification, we can apply an online-tuned adaptive fuzzy control system (AFCS). AFCSs can adapt to their environment and acquire new knowledge by themselves through learning. A possible arrangement of such a system is the implementation of a fuzzy controller (FC) to adjust the parameters of another FC. This adjustment is accomplished online. The main FCs MFs are tuned online through the supervisor-FC, which follows the reasoning of an expert which would manually tune the MFs. This type of control offers, except for the automatic MFs adjustment, an adapting tuning of the MFs, according to the behavior of the system. The system can be satisfactorily controlled for start-up and regenerative braking shutdown modes besides the usual generating mode of operation. AFCs are thus very suitable for the control of systems which are strongly fluctuating, such as wind turbine generation system.

III. CONTROL SYSTEM DESCRIPTION

The system has following fuzzy logic controllers.

A. *Angular Frequency Regulator (AFCS)*

In order to achieve maximum wind power absorption according to the wind speed, matrix converter regulates the angular frequency. This is managed through an AFCS (Fig.6). This system [25] consists of FC$_1$, which is the main controller of the AFCS, FC$_3$, whose main role is to fine-tune FC$_1$ and FC$_2$, which dynamically detects online the angular frequency that corresponds to the maximum aerodynamic efficiency of the wind turbine for a specific wind speed $\square_{ref}$ (Fig.7).

The meaning of the symbols shown at Fig.7 is the following:

P_0	output real power;
$\square_{e1}$	angular frequency at the terminal of generator;
$\square_{ref}$	angular frequency for maximum aerodynamic efficiency;
δ	phase angle of PWM firing pulse generation,
$\Delta\delta$	phase shift of the phase angle δ (positive for increment of δ and negative for decrement of δ);
RF	regulating factor of FC$_1$ MFs;
ΔRF	step change of RF;
σ	variance of $\square_{e1}$;
$\left\|\overline{\omega_{e1}-\omega_{ref}}\right\|$	absolute mean deviation of w_{e1} from $\square_{ref}$.

The frequency at the point, $\square_{e1}$ is compared to $\square_{ref}$, and the error is passed through FC$_1$, which produces a signal $\Delta\delta$ (Fig.7). By accumulating the successive values of $\Delta\delta$, the value of δ comes up, according to (6)

$$\delta^{new} = \delta^{old} + \Delta\delta \qquad (6)$$

where δ^{new} is the new value of the phase angle δ and δ^{old} is the previous value of the phase angle δ. As was previously mentioned, $\square_{ref}$ is the angular frequency, when the wind turbine operates at the maximum aerodynamic efficiency for a specific wind speed. The value of $\square_{ref}$ is dynamically approached in real time from FC$_2$ (Fig.7), using a maximum power point tracking (MPPT) technique. This is achieved by changing the reference value of the frequency by $\Delta\square_{ref}$ and monitoring the corresponding change of the output power, P_0. With an incrementation (or decrementation) of reference frequency, the corresponding incrementation (or decrementation) of output power P_0 is estimated. If ΔP_0 is positive with last positive $\Delta\square_{ref}$, in per-unit value by $L\Delta\square_{ref}$, the search is continued in the same direction.

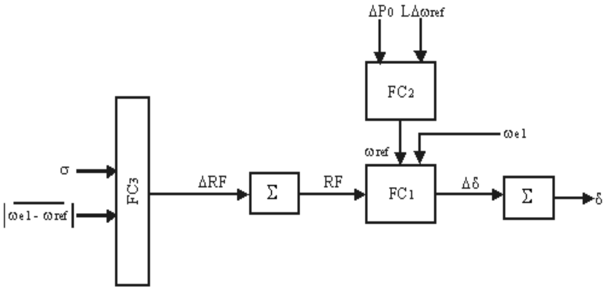


Fig. 7. Angular frequency regulator control system AFCS

If,o n the other hand, $+\Delta\square_{ref}$ causes $-\Delta P_0$, the direction of search is reversed. The variables ΔP_0, $\Delta\square_{ref}$ and $L\Delta\square_{ref}$ are described by membership functions and rule table. In the implementation of fuzzy control, the input variables are fuzzified, the valid control rules are evaluated and combined, and finally the output is defuzzified to convert to the crispy value. The wind vortex and torque ripple can lead the search to be trapped in a minimum which is not global, so the output Δ□$_r$ is added to some amount of *L*Δ□$_{ref}$ in order to give some momentum to continue the search and to avoid such local minima. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm is universal to any system. The advantages of fuzzy control are obvious. It provides adaptive step size in the search that leads to fast convergence, and the controller can accept inaccurate and noisy signals. The AFCS operation does not need any wind velocity information, and its real time based search is insensitive to system parameter variation.

The structure of the FCs is described in detail in the following paragraphs.

1) Structure of FC$_1$*:* FC$_1$ is the main FC of the angular frequency regulator control system. Its inputs are the deviation of w_{e1} from its reference □$_{e1}$ – □$_{ref}$ and its derivative. Its output is the phase shift of δ¸ Δδ.

The initial MFs for the input are □$_{e1}$ – □$_{ref}$ shown in Fig.8. The term initial is used because these MFs are tuned online by FC$_3$. These MFs are the initial MFs before their tuning. Of course, the general form of the final MFs will remain the same. As shown in Fig.8, five fuzzy subsets are needed for the input □$_{e1}$ – □$_{ref:}$ negative big (NB), negative small (NS), (OK), positive small (PS), and positive big (PB).

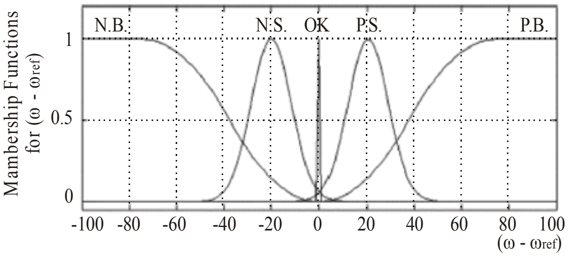


Fig. 8. Membership functions for the fuzzy set □ – □$_{ref}$

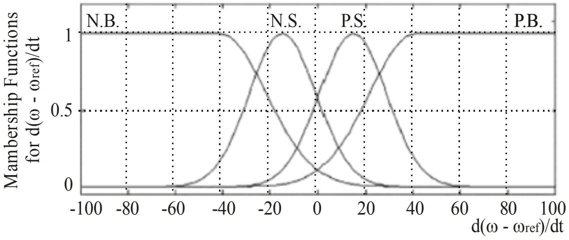


Fig. 9. Membership functions for the fuzzy set derivative of □ – □$_{ref}$

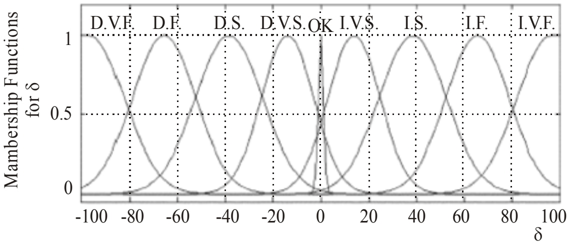


Fig. 10. Membership functions for the fuzzy set phase angle δ

TABLE I
FUZZY RULES FOR FC$_1$

□ – □$_{ref}$ \ d(□ – □$_{ref}$)/dt	PB	NB	PS	NS
PB	IVF	IVF	IVF	IVF
PS	IF	OK	IS	OK
OK	IVS	DVS	OK	OK
NB	DVF	DVF	DVF	DVF
NS	OK	DF	OK	DS

TABLE II
FUZZY RULES FOR FC$_2$

$\left\|w_{e1}-w_{ref}\right\| \setminus \sigma$	S	M	B
S	OK	NS	NB
M	PS	PM	PM
B	PB	PB	PB

TABLE III
FUZZY RULES FOR FC$_2$

ΔP \ LΔ□$_{ref}$	P	ZE	N
PVB	PVB	PVB	NVB
PB	PB	PVB	NB
PM	PM	PB	NM
PS	PS	PM	NS
ZE	ZE	ZE	ZE
NS	NS	NM	PS
NM	NM	NBV	PM
NB	NB	NVB	PB
NVB	NVB	NVB	PVB

For the derivative of the □$_{e1}$ – □$_{ref,}$ the fuzzy sets needed are NB, NS, PS, and PB, and they are shown in Fig.9.

The fuzzy sets required for the phase angle Δδ are decrease very fast (DVF), decrease fast (DF), decrease slowly (DS), decrease very slowly (DVS), OK, increase very slowly (IVS), increase slowly (IS), increase fast (IF), and increase very fast (IVF), and they are shown in Fig.10.The corresponding outputs are selected as given in Table I.

2) Structure of FC_3*:* The role of FC_3 is to fine-tune on line the MFs of FC_1. The online tuning of the MFs is a good way to deal with the continuing variation of the system parameters. Obviously, there is no combination of parameters that ensures optimum performance under any operating conditions. Through FC_3, it is possible to online tune FC_1 MFs in order to optimize its parameters under any circumstances. In fact, FC_3 acts similar to an experienced control system designer, who continuously monitors the system and modulates the MFs in order to make the system more or less "strict" according to the circumstances.

The inputs of FC_3 are the following:

- the absolute mean deviation of w_{e1} from its reference $\left|\omega_{e1} - \omega_{ref}\right|$;
- the variance of w_{e1} , σ , and the output of this controller is the signal ΔRF (Fig.7).By accumulating the successive values of ΔRF, according to (7), the regulating factor RF is produced, which will optimize FC_1MFs. The variance of $□_{e1,}$ σ, and the output of this controller are:

$$RF^{new} = RF^{old} + \Delta RF \qquad (7)$$

Specifically, RF increases or decreases the range of the MFs, which correspond to the output δ in order to render FC_1 "stricter" or "looser." For example, in case of a large variation of the wind velocity, the system must become "stricter." To achieve this, the range of δ increased, producing bigger variations of δ. The priority of this controller is to regulate the FC_1 MFs in order to drive $□_{e1}$ as close to its reference as possible. When this goal is achieved, FC_1 can be further fine tuned in order to minimize the width of fluctuations of $□_{e1}$ near its reference.

Gaussian MFs are used for both inputs and outputs. Three fuzzy subsets are needed for each input: big (B), medium (M) and small (S). The fuzzy sets required for are PB, positive medium (PM), PS, (OK), NS, and NB. The fuzzy control rules are shown in Table II.

3) Structure of FC_2*:* The role of FC_2 is to compute the angular frequency reference value online $□_{ref}$, used by FC_1.

The inputs of this controller are the following:

- the last change of $□_{ref,}$ $L\Delta□_{ref}$;
- the corresponding change of real power ΔP_0 ; and its output is the current change of $\Delta□_{ref}$ Gaussian MFs are used for both inputs and outputs.

The fuzzy sets used by inputs and outputs are the following:

PVB	positive very big;
PB	positive big;
PM	positive medium;
PS	positive small;
P	positive;
ZE	zero;
NVB	negative very big;
NB	negative big;
NM	negative medium;
NS	negative small;
N	negative.

The fuzzy control rules used by $FC_2$are shown in Table III

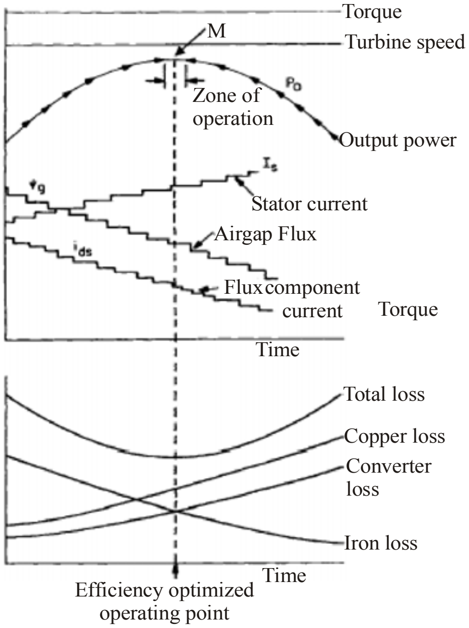


Fig. 11. Search method of efficiency optimization control of machine by flux
Programming

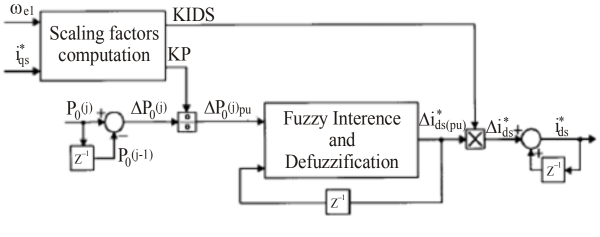


Fig. 12. Block diagram of fuzzy control FLC_4

B. Generator Flux Programming Control (FC_4*)*

Since most of the time the generator is running at light load, the machine rotor flux i_{ds} can be reduced from the rated value to reduce the core loss and thereby increase the machine-converter system efficiency [22], [23]. The principle of online search based flux-programming control by fuzzy controller FC_4 is explained in Fig.11. At a certain wind velocity V_w and at the corresponding optimum speed $\square_{ref}$ established by FC$_2$ (which operates at rated flux ΨR_{rated}), the rotor flux ΨR is reduced by decreasing the magnetizing current i_{ds}. This causes increasing torque current i_{qs} by the speed loop for the same developed torque. As the flux is decreased, the machine iron loss decreases with the attendant increase of copper loss. However, the total system (converters and machine) loss decreases, resulting in an increase of total generated power P_0. The search is continued until the system settles down at the maximum power point M, as indicated in Fig.11. Any attempt to search beyond point M will force the controller to return to the maximum power point. The principle of fuzzy controller FC$_4$ is somewhat similar to that of FC$_2$ and is explained in Fig.12. The system output power P_0 is sampled and compared with the previous value to determine the increment ΔP_0. In addition, the last excitation current decrement ($L\Delta i_{ds}$) is reviewed. On these bases, the decrement step of i_{ds} is generated from fuzzy rules through fuzzy inference and defuzzification, as indicated. It is necessary to process the inputs of FC$_4$ in per-unit values. Therefore, the adjustable gains KP and KIDS convert the actual variable to variables with the following expressions

$$\mathrm{KP} = aw_r + b \tag{5}$$

$$\mathrm{KIDS} = c_1 w_r - c_2\, i_{qs} + c_3 \tag{6}$$

Where a, b, c_1, c_2 and c_3 are derived from simulation studies.

The current i_{qs} is proportional to the generator torque, and $\Delta\square_{ref}$ is zero because the fuzzy controller FC$_4$ is exercised only at steady-state conditions. The FC$_4$ controller operation starts when FC$_2$ has completed its search at the rated flux condition. If wind velocity changes during or at the end of FC$_4$, its operation is abandoned, the rated flux is established, and AFCS control is activated.

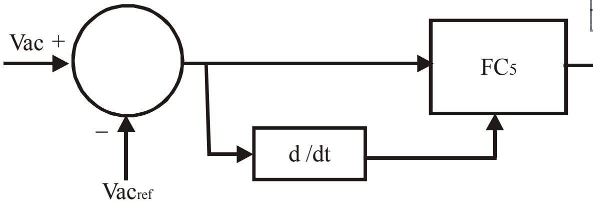


Fig. 13. AC voltage regulator (FCS)

C. *AC Voltage Regulator*

The ac voltage regulator for matrix converter compares the amplitude of the ac voltage generated by the MC to the amplitude of a reference voltage and apply the error into an FC$_5$ (Fig. 13). The output of the regulator is the modulation index "m" of the sinusoidal PWM reference signal and, consequently, the modulation signal of the magnitude of the ac voltage generated by the MC. The structure of the FC$_5$ is similar to that of FC$_1$.

IV. SIMULATION RESULTS AND DISCUSSSION

Simulations were performed in MATLAB/SIMULINK. Through C++ programming, the design of AFCs was accomplished, converting the simple fuzzy controllers of the fuzzy logic toolbox into AFCs, which can be self-tuned online. The objective of simulation is to illustrate interacting phenomena which have not been understood before and verify the control strategy [Fig. 6] proposed in this study.

The system is simulated with a wind velocity which fluctuates with a mean value near 10m/s and at 25 s, following an almost step change, rises to a mean value near 12.5m/s (Fig. 14). No local load is connected. The generator speed and air-gap torque both increase [Fig. 15(a)].

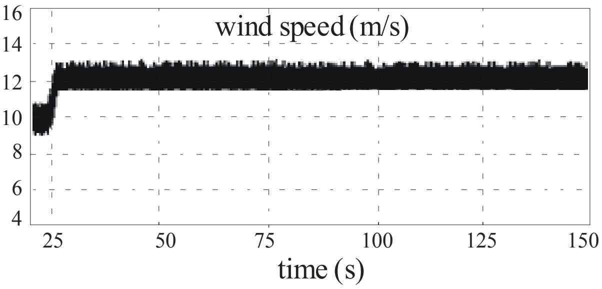
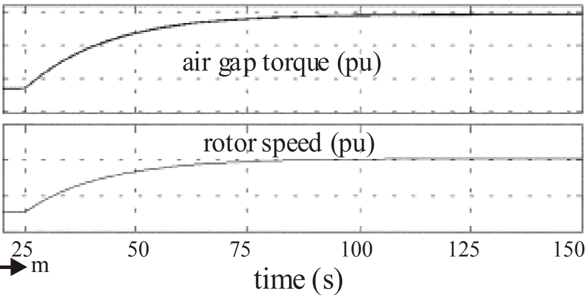
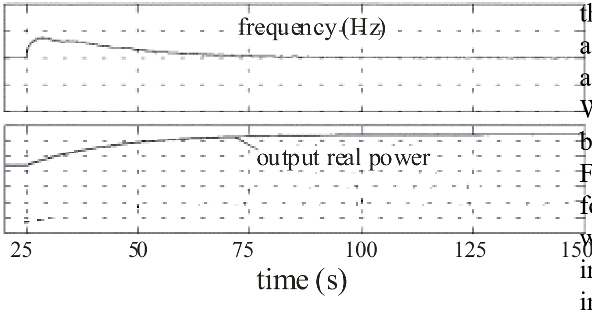


Fig. 14. Wind velocity



(a)



(b)

Fig. 15. Response of WECS with the Grid—wind speed change.

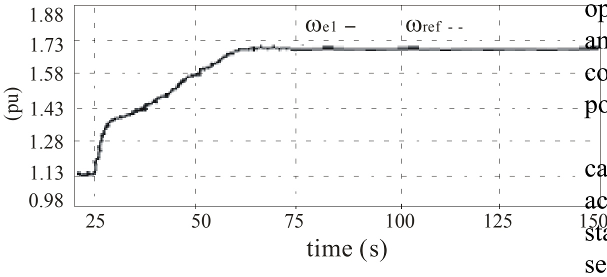


Fig. 16. Electrical frequency and its reference.

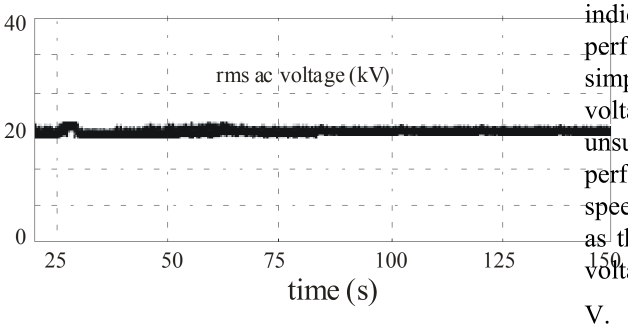


Fig. 17. RMS ac voltage at the grid.

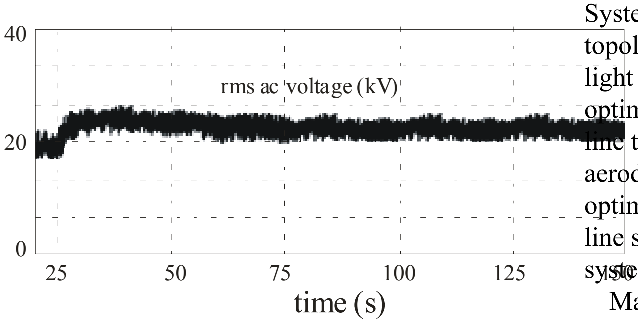


Fig. 18. RMS ac voltage at the grid when the controllers are simple FCs

The output real power from the generator increases as the changes of system frequency is largely constrained [Fig. 15(b)]. The constant local frequency and voltage are predominantly due to the control effect of fuzzy logic controller, which adjusts the firing delay angle at the rectifier end according to the change of system frequency. While the increase of output real power is caused by the increase of wind speed.

Figure 15 and 16 show the response of the system for the above-mentioned disturbance. When the wind velocity increases, output power starts to increase and then control system gives an order to increase $\square_{ref}$ (Fig.16). We can observe that $\square_{e1}$ is continuously attached to $\square_{ref}$. $\square_{ref}$ keeps increasing, trying to reach its optimal value for the specific wind velocity. During the disturbance, $\square_{e1}$ stays close to $\square_{ref}$ and increases until it reaches its optimal value. When this happens, output power and $\square_{e1}$ reach a new steady state, which corresponds to the maximum absorption of real power from the wind turbines.

Fig. 17 shows the rms ac voltage at the grid. We can observe that the ac voltage stays between the acceptable limits, even during the disturbances. It starts deviating from its reference for a few seconds after the wind speed changes, but the control system quickly detects this deviation and drives the voltage to its initial level. In order to indicate the amelioration of the system performance when AFCs are used instead of simple unsupervised FCs, fig. 18 shows the ac voltage at the grid bus when the controllers are unsupervised FCs. The FCs offer satisfactory performance in steady-state, but when the wind speed changes suddenly, they cannot react as fast as they should, resulting in a big deviation of the voltage from its reference.

V. CONCLUSION

In the paper, a new wind turbine generation System based on an improved matrix converter topology with fuzzy control system is studied for light load efficiency improvement and optimization. Fuzzy logic controllers searches on-line the optimum angular frequency so that aerodynamic efficiency of the wind turbine is optimum, & programs the machine flux by an on-line search so as to optimize the machine-converter system efficiency.

Matrix converter along with FCs controls the terminal voltage and frequency of the induction generator in such a way that the wind turbine is operating at its maximum power point for all wind velocities and offer the possibility to achieve, apart from an optimum integration of the WECS to the grid, maximum wind power acquisition, driving the wind turbines to the maximum aerodynamic efficiency. The matrix converter also implements unity power factor at the interface with the grid for optimal utilization of the installed wind turbine power and satisfies the reactive power demand of the induction generator to avoid self-excitation capacitors. The system was analyzed and designed, and performances were studied extensively by simulation to validate the theoretical concepts.

REFERENCES

[1] "Time for action: Wind energy in Europe," *European Wind Energy Asso.*, Rome, Italy, Oct. 1991.

[2] L.L. Freries, Wind Energy Conversion Systems, Prentice Hall, 1990.

[3] S. Heier, Grid Integration of Wind Energy Conversion Systems, New York: Wiley, 1998.

[4] R.Pena, J.C.Clare, and G.M.Asher, " A doubly fed induction generator using back-to- back PWM converters supplying an isolated load from a variable speed wind turbine" IEE Proc., Electric Power Applications, Volume: 143 , Issue: 5 , Sept. 1996 pp.:380 – 387.

[5] L Zhang, C Watthanasarn, and W. Shepherd, "Application of a matrix converter for the power control of a variable-speed wind-turbine driving a doubly-fed induction generator" IECON 97,Vol.2, pp.906 – 911, Nov. 1997.

[6] *R. Spee, S. Bhowmik, J.H.R. Enslin,* "Adaptive control strategies for variable-speed doubly-fed wind power generation systems ", IEE Industry Applications Society Annual Meeting, Vol.1, Oct. 1994 pp. 545 - 552

[7] W. Lu and B. T. Ooi, "Optimal acquisition and aggregation of offshore wind power by multiterminal voltage-source HVDC," *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 201–206, Jan. 2003.

[8] E. Spooner, P. Gordon, J. R. Bumby, and C. D. French, "Lightweight ironless-stator PM generators for direct drive wind turbines," Proc. *Inst.Elect. Eng., Electr. Power Appl.*, vol. 152, no. 1, pp. 17–26, 2005

[9] E. Suarez and G. Bortolotto, "Voltage-frequency control of a self-excited induction generator," *IEEE Trans. Energy Convers.*, vol. 14, no. 3, pp. 394–401, Sep. 1999.

[10] R. Teodorescu, and F. Blaabjerg, "Flexible Control of Small Wind Turbines With Grid Failure Detection Operating in Stand-Alone and Grid- Connected Mode",IEEE Trans. On Power Electronics, Vol. 19, NO. 5, SEP. 2004, pp 1323, 1332.

[11] W. Lu and B. T. Ooi, "Multiterminal LVDC system for optimal acquisition of power in wind-farm using induction generators", IEEE Tran. On Power Electronics Vol. 17, NO. 4, JULY 2002, pp. 558-563.

[12] O. Ojo and I. Davidson, "PWM-VSI inverter assisted stand-alone dual stator winding induction generator," in *Conf. Rec. IEEE-IAS Annu. Meeting*, Oct. 1999, pp. 1573–1580.

[13] D. Seyoum, F. Rahman, and C. Grantham, "Terminal voltage control of a wind turbine driven isolated induction generator using stator orientated field control," in *Proc. IEEE APEC*, Miami Beach, FL, 2003, vol. 2, pp. 846–852.

[14] M. Naidu and J. Walters, "A 4-kW 42-V induction-machine-based automotive power generation system with a diode bridge rectifier and a PWM inverter," *IEEE Trans. Ind. Appl.*, vol. 39, no. 5, pp. 1287–1293, Sep./Oct. 2003.

[15] R. Leidhold, G. Garcia, and M. I. Valla, "Induction generator controller based on the instantaneous reactive power theory," *IEEE Trans. Energy Convers.*, vol. 17, no. 3, pp. 368–373, Sep. 2002.

[16] T. Ahmed, K. Nishida, and M. Nakaoka, "A novel induction generator system for small-scale AC and DC power applications," in *Proc. IEEEPESC*, Jun. 12–16, 2005, vol. 1, pp. 250–256.

[17] "IEEE recommended practices and requirements for harmonic control in electric power systems," *Project IEEE- 519*, Oct. 1991.

[18] M. Venturini and A. Alesina, "The generalized transformer: A new bidirectional sinusoidal waveform frequency converter with continuously adjustable input power factor " in *Proc. IEEE PESC'80*, 1980, pp. 242– 252.

[19] P. W. Wheeler, *IEEE*, J. Rodríguez, J. Clare,L. Empringham, and A. Weinstein, " Matrix Converters: A Technology Review " , IEEE Trans. On Industrial elctronicas, Vol. 49, NO. 2, APRIL 2002,pp 276-289.

[20] J. G. Slootweg, S. W. H. de Haan, H. Polinder, and W. L. Kling, "General Model for Representing Variable SpeedWind Turbines in Power System Dynamics Simulations", IEEE Trans. On Power Systems, Vol. 18, NO. 1, FEB.2003, pp. 144-151.

[21] L.S.T. Ackermann, "Wind Energy Technology and current status. A Review", Renewable and Sustainable Energy Review, 4:315-375, 2000.

[22] G. C. D. Sousa, B. K. Bose, and J. G. Cleland, "Fuzzy logic based on-line efficiency optimization control of an indirect vector controlled induction motor drive," in *Proc. IEEE-IECON Conf.*, Maui, HI, pp. 1168–1174, Nov. 1993.

[23] G. C. D. Sousa and B. K. Bose, "A fuzzy set theory based control of a phase controlled converter dc machine drive," in *IEEE-IAS Annu. Meeting Conf. Rec.*, Dearborn, MI, Oct. 1991, pp. 854–861

[24] L. Wei, T.A. Lipo, " A Novel Matrix Converter Topology with simple Commutation".

[25] Vinod Kumar and R.R. Joshi, "Investigating AC/DC Interactions in Advanced Converter Based WECS Connected to a Weak AC Grid," Proceedings *of International Conference on Recent Advancements and Applications of Computer in Electrical Engineering (RACE)*, Govt. Engineering College, Bikaner (India), March 24-25, 2007, pp. 626-632.