Fuzzy Controlled SEPIC Based Micro Wind Energy Conversion System with Reduced Ripple and Improved Dynamic Response

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Abstract:

Wind Energy Conversion System (WECS) which includes the Permanent Magnet Synchronous Generator (PMSG), the Single-Ended Primary-Inductor Converter (SEPIC) and the load is modeled, simulated and implemented. SEPIC is proposed to control the output voltage of WECS. A composite filter is proposed at the output of the SEPIC to minimize the ripple in the output voltage .The proposed wind energy conversion system, subjected to the variations in the wind can supply power to the connected loads. The main purpose is to generate 230-V/50-Hz supply to domestic appliances through a single-phase inverter. In this paper, the comparison of various controllers like Proportional Integral Derivative (PID) and Fuzzy Logic controller (FLC) for the control of SEPIC based micro wind energy conversion system is presented. The SEPIC is preferred to other converters for the wind energy conversion system as it provides low input current ripple compared with other converter. The voltage ripple in the proposed system is minimized using a composite filter. The Total Harmonic Distortion (THD) of SEPIC based WECS with linear and non-linear loads are analyzed. Fuzzy Logic control is proposed for the micro-wind energy conversion system, since it improves the damping characteristics of the wind energy system over a wide range of operating points. The simulation results and the experimental results are presented in this paper.

***Keywords**: PID, Micro Wind Energy Conversion System, Fuzzy Logic Controller, PMSG, Total Harmonic Distortion.*

1. Introduction:

Renewable energy inducements, research and development have made wind power generation technically effective and economically attractive. In reducing the dependence of electric power generation on fossil fuel, wind energy proffers a substantial share to renewable power generation. This energy conversion system includes a conventional rectifier-inverter system along with a transformer to supply power to domestic loads. A matrix converter can be used as one of the conventional rectifier–inverter combination (AC–DC–AC) as it features no energy storage components. It has both the bidirectional power flow capability and controllable input power factor. The bidirectional power flow capability increases the complexity of the control in the matrix converter, also increasing the switching components [1]-[3]. Owing to this fact, a conventional rectifier-inverter combination (AC-DC-AC) is commonly employed along with a Boost converter. It has higher efficiency than the Buck-Boost converter. But, it is mostly applicable for cases where the battery is used. This also increases the cost [4]-[10]. These drawbacks can be overcome by a Cuk converter. This converter generates high output and input current ripples [11]. The SEPIC provides low input current ripple, which is the major advantage when compared with other converters. But, a bulk inductor should be used to minimize the current ripple. Input current ripple becomes one of important requirements due to the wide use of low voltage sources. It is because large ripple current may truncate the epochs of the input sources [12]–[16]. The SEPIC provides better reduction of ripples than other converter. Moreover, the size and cost of the components used in the SEPIC is comparatively less than other converters.

In order to minimize the output voltage ripple of the converter, filters such as LC, π, T and composite filters can be used. A better reduction in output ripple and noise can be achieves using the π and T filters. However, the T filter is more sensitive to the parasitic shunt capacitors and it must be fine-tuned to account for the PCB layout parasitic [17]. Hence a composite filter is used in this paper.

With variations in the wind speed, a controlled output has to be obtained using a closed loop system, which generally includes a PI or a PID controller. The steady state error can be reduced using PI controller, which is an active control scheme. Then again the ripple content is high [18]-[21]. In order to reduce the ripple, current control scheme is used. The bandwidth of current control is higher than the bandwidth of the DC link voltage regulator. It takes a time to settle besides the cost being higher [22]. To overcome this, a two loop digital control strategy is proposed. The response time is moderate [23]. In order to improve the response time and also to reduce the voltage ripple at the output, larger output capacitance with low Equivalent Series Resistance (ESR) is used [24]. To achieve the smoothness of the converter firing angle sliding mode controller is used. But the reliability of the system is reduced [25]. In order to increase the system reliability, a Fuzzy Logic Controller is used over a conventional PI Controller, to improve the damping characteristics of the wind energy system over a wide range of operating points[26]. The PID and fuzzy controllers for various DC-DC converters have been dealt with in [27]-[29]. According to the authors' knowledge, the literature does not cite works that compare these controllers with reference to Micro Wind Energy Conversion System (μWECS). Hence in this paper, the authors have chosen to present a comparitive study of PID and Fuzzy Logic Controller for the SEPIC based wind energy conversion system along with the linear and non-linear loads.

This paper is organized as follows: Section 2 presents the proposed system. Section 3 describes the modeling of SEPIC. Section 4 illustrates the System description. Section 5 presents the Simulation Results .The Comparison of the Controllers is discussed in Section 6 while Section 7 is devoted to a discussion of the Experimental Results. The conclusion and the Scope for Future Work are presented in Section 8.

2. Proposed System:

The block diagram of the proposed system is shown in Fig 1. It consists of the Wind Turbine, Rectifier, SEPIC along with a Controller, Inverter, Transformer, and Load. A Permanent Magnet Synchronous Generator delivers the ACinput voltage to the three-phase rectifier which converts 24V-AC to 24V-DC. A boosted DC Voltage of 48V-DC is obtained using a SEPIC. The output voltage ripple is minimized using a composite filter.This DC voltage isconverted into AC voltage of frequency 50Hz using an inverter circuit. A transformer steps up the 48V-AC to230V-AC which is eventually applied to the load. During wind speed variations, the output voltage of the SEPIC is controlled by tuning the PID / Fuzzy Logic controller.

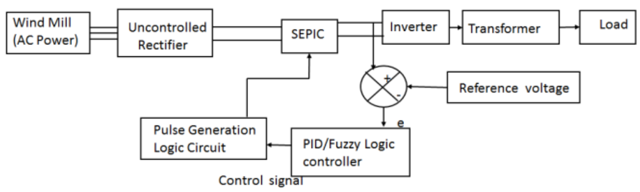


Fig 1.Block Diagram of Micro-Wind Energy Conversion System

3. Modeling of SEPIC:

SEPIC is a type of DC-DC converter which allows the voltage at its output to be greater than or less than or equal to that of its input. It is similar to buck-boost converter except for the output polarity of this converter is positive with respect to its common terminal. The input current ripple is comparatively less than the ripple in the other converters, thus reducing the stress on the source [12]. A DC voltage with reduced ripple content at the output is obtained by adding a composite filter [17]. Fig 2 shows the circuit of SEPIC with composite filter.

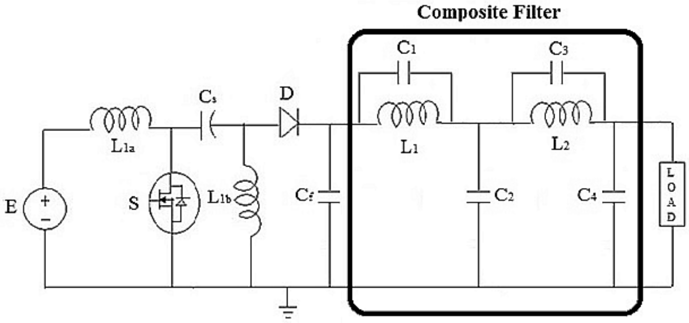


Fig 2. SEPIC with composite filter

The model of the converter is represented by the equations (1) – (4).

$$L_{1a}\frac{di_1}{dt} = -(1-h)(V_1+V_2)+E \qquad (1)$$

$$C_s\frac{dV_1}{dt} = (1-h)i_1 - hi_2 \qquad (2)$$

$$L_{1b}\frac{di_2}{dt} = hV_1 - (1-h)V_2 \qquad (3)$$

$$C_f\frac{dV_2}{dt} = (1-h)(i_1+i_2) \qquad (4)$$

Where,

V_1 - Voltage across the capacitor C_s (V)

i_1 - Current through the inductor L_{1a} (A)

V_2 - Voltage across the capacitor C_f and the load Resistor (V)

i_2 - Current through the inductor L_{1b} (A)

h - Control Input function of the switch position taking values {0, 1}

The matrix of state co-ordinate transformation is given in equation (5).

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} = \begin{pmatrix} \frac{1}{E}\sqrt{\frac{L_{1a}}{C_s}} & 0 & 0 & 0 \\ 0 & \frac{1}{E} & 0 & 0 \\ 0 & 0 & \frac{1}{E}\sqrt{\frac{L_{1a}}{C_s}} & 0 \\ 0 & 0 & 0 & \frac{1}{E} \end{pmatrix} \begin{pmatrix} i_1 \\ V_1 \\ i_2 \\ V_2 \end{pmatrix} \quad (5)$$

The time scaling factor of the SEPIC is given by,

$$\tau = \frac{t}{\sqrt{L_{1a} C_s}} \quad (6)$$

t - Switching time

τ - Time scaling factor

The state-space model of the SEPIC is provided by the following equations (7), (8), (9), and (10).

$$\dot{x_1} = -(1-h)(x_2 + x_4) + 1 \quad (7)$$

$$\dot{x_2} = (1-h)x_1 - hx_3 \quad (8)$$

$$a_1 \dot{x_1} = h(x_2) - (1-U)x_4 \quad (9)$$

$$a_2 \dot{x_4} = (1-U)(x_1 + x_3) - \frac{x_4}{Q} \quad (10)$$

$$Q = R\sqrt{\frac{C_s}{L_{1a}}}$$

$$a_1 = \sqrt{\frac{L_{1b}}{C_s}}$$

$$a_2 = \sqrt{\frac{C_f}{C_s}}$$

4. System Description:

The simulation of the SEPIC based WECS provides better results than other DC-DC converters. Table 1 provides the comparison of the input and output parameters for various converters based WECS.

Table 1. Comparison of input and output parameters for various converter based WECS

Converters	Input current ripple (A)	Output current ripple (A)
Boost Converter	1.3	2.1
Cuk Converter	0.9	3.1
Zeta Converter	1.2	1.6
SEPIC	0.8	1.7

4.1 PID Controller:

The SEPIC based WECS with variation in wind speed can be controlled using PI controller. However, the peak overshoot of the system using this PI controller is higher than that of the PID controller [27].The SEPIC based WECS with PID controller is shown in Fig.3. A DC voltage of 48V is obtained at the output of the SEPIC and is compared with a reference voltage to produce the error signal.It is then given to the PID controller and the pulse width modulated signals are produced.These pulses are applied to the switch of the SEPIC.

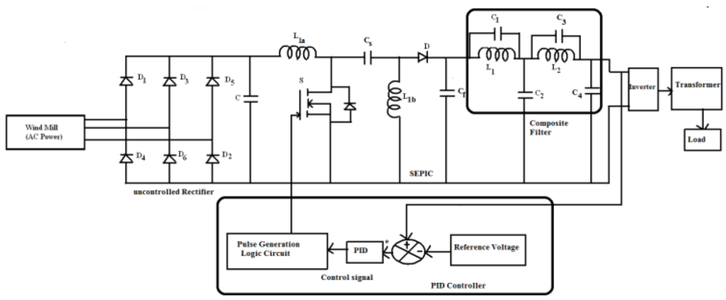


Fig 3. SEPIC based WECS with PID Controller

The output current ripple of the system is reduced by choosing a capacitance of 100µF.The composite filter further minimizes the output voltage ripple.The specifications of the SEPIC are provided in Table 2. From Table 3, it is observed that the inclusion of the composite Filter has minimized the output voltage rippple to 0.2V. Variation of wind speed occurs at time t = 0.5s. The output voltage across the load is controlled using the PID Controller. The output of the PID Controller is compared with a repeating sequence of 20 kHz to provide gate pulses to the switch in the SEPIC. An output voltage of 48V DC and an output current of 0.48A DC at the SEPIC with PID Controller for the variable speed wind energy conversion system are obtained.

Table 2. Specifications of SEPIC

Parameter	Symbol	Designed Value	Simulated Value
Duty Cycle	δ	0.67	0.67
Inductor Values	L_{1a} , L_{1b}	1.34 mH	1.34 mH
Output Capacitor	C_{out}	80.5 µF	100 µF

Table 3. Summary of Voltage Ripple in SEPIC with and without Filter

Parameter	Existing System (without filter)	Proposed system (with Composite Filter)
Output Voltage Ripple	0.8 V	0.2 V

The output voltage of the SEPIC is applied as the input voltage to the inverter. An output voltage of 48V-AC/50-Hz is provided as input to the transformer. The transformer steps up the voltage from 48V-AC/50-Hz to 230V-AC/50-Hz.

The PID controller is tuned at a frequency of 20kHz for a specific linearized model. Hence, it does not provide sufficient damping of oscillations for different operating points caused by disturbances and uncertainities of wind parameters. This may lead to undesirable and sustained oscillations in power. Furthermore, large wind deviations may even lead to an unstable system. Hence, a Fuzzy Logic Controller is used to improve the damping characteristics of the wind energy system over a wide range of operating points.

4.2 Fuzzy Logic Controller:

The control variables act as the input to the fuzzy logic controller. They are intially fuzzified by means of appropriate fuzzy membership functions and the control strategy is defined by some heuristic IF-THEN rules. The output control signal is then defuzzified and the correction is used finally to generate the gate pulses required for the switch. The available heuristic expert knowledge about the system operation is used in the FLC fuzzification, rule base, and defuzzification stages. The fuzzy method used here is Mamdani, where the maximum of minimum composition technique is used for the inference. The block diagram of the FLC is shown in Fig. 4.

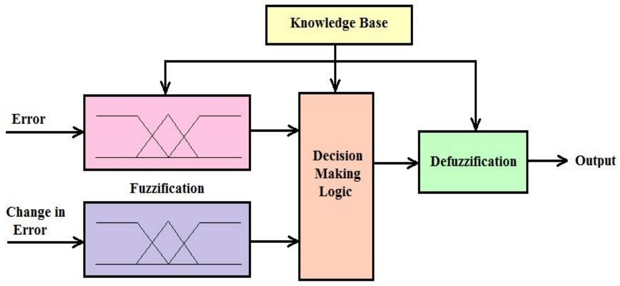


Fig 4. Block Diagram of Fuzzy Logic Controller

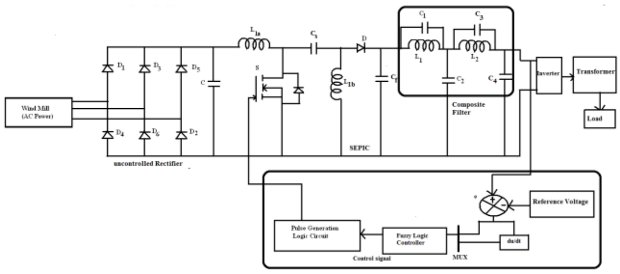
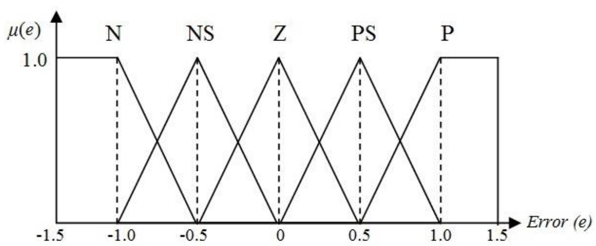


Fig 5. SEPIC Based WECS with Fuzzy Logic Controller for Variable Speed Condition

From Fig 5, the input control variables to the Fuzzy Logic Controller (FLC) are the error in voltage and its derivative. The membership functions like the voltage error, its time derivative (dE/dt), and the correction are shown in Fig.6.The trapezoidal and the triangular membership functions are suggested based on expert knowledge.



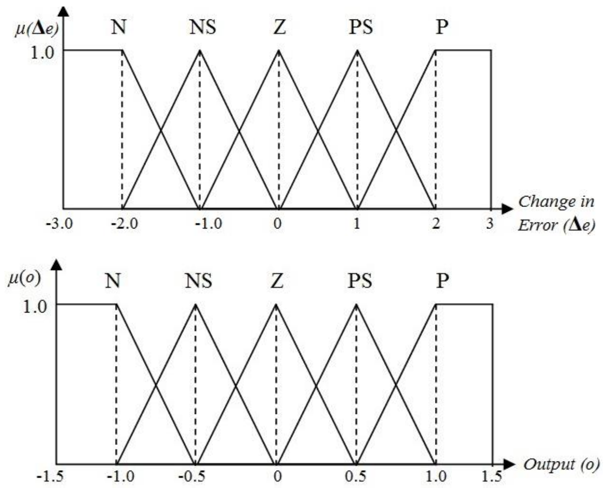


Fig 6. Membership Functions of Fuzzy Logic Controller

After defining the fuzzy sets, a control strategy is defined by a set of IF-THEN rules. These rules can be formulated as shown in Table 4. For example, if the error is negative and dE/dt is negative, then the output is low. These heuristic rules are based on expert control knowledge of the system operation. It is also important to highlight the freedom in choosing more precise and adequate rules; however, such a task would require considerable expertise with very little reward in the performance of FLC [26]. The Rule Viewer of the Fuzzy Logic Controller is as shown in Fig.7.

Table 4. Rule Base for Fuzzy Logic Controller

Error / dE/dt	N	Z	P
N	L	L	M
Z	L	M	H
P	M	H	H

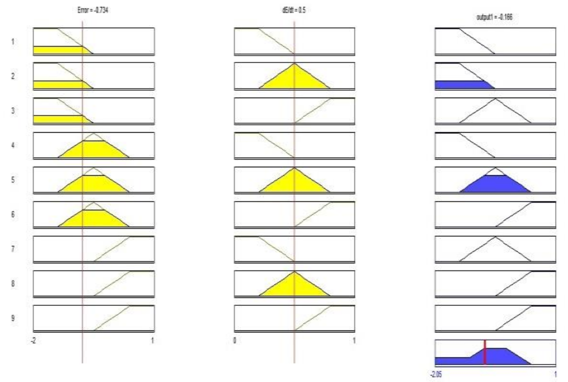


Fig 7. Rule Viewer of Fuzzy Logic Controller

The output linguistic variables are transformed to crisp values to control the width of the gate pulses of the switch. The Surface Viewer of the Fuzzy Logic controller is as shown in Fig. 8.The output obtained with the Fuzzy Logic controller is compared with the repeating sequence voltage of 20kHz frequency. The gate pulses obtained are applied to the switch of the SEPIC.

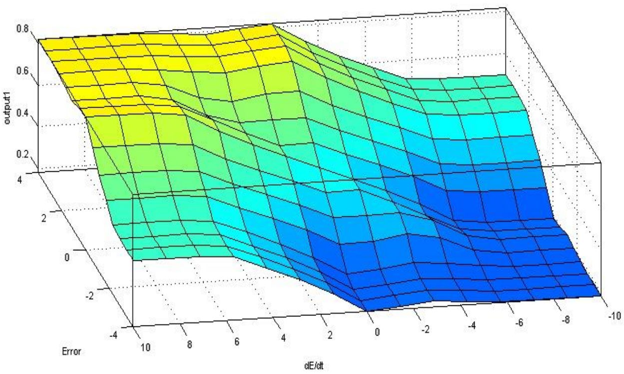


Fig 8. Surface Viewer of Fuzzy Logic Controller

The defuzzification method used in this work is the centroid method.The wind speed variation takes place at 0.5s. The output voltage across the load is controlled using the Fuzzy Logic Controller.The gate pulse of the SEPIC is generated by comparing the output of the Fuzzy Logic Controller with the triangular function.The algorithm used for pulse generation is as follows:

Algorithm

Step 1: Obtain control signals by taking the error of the voltage and its derivative.

Step 2: Fuzzify control inputs in the fuzzification interface using Mamdani Method, where the maximum of minimum composition technique is used for the inference.

Step 3: Make decision using the knowledge base wherein the membership functions and the rules set with heuristic IF-THEN rules are provided.

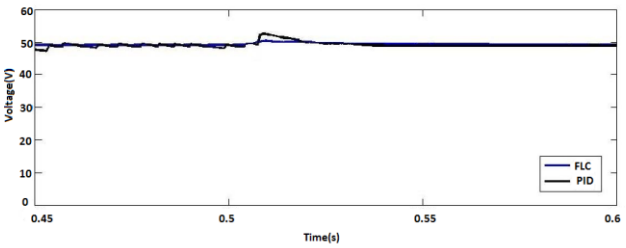
Step 4: Defuzzify the results using the centroid method.

Step 5: Compare the output with the repeating sequence to generate the pulses for the switch.

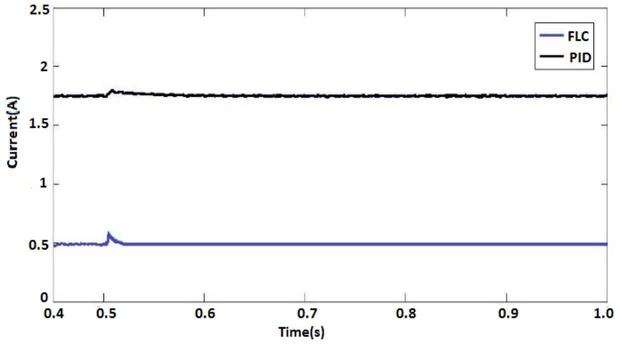
5. Simulation Results:

The circuits are modeled and simulated using the blocks of Simulink and the results with PID and Fuzzy controllers are presented here.

An output voltage of 48V DC at the SEPIC with PID Controller and FLC for the variable speed wind turbine of wind energy conversion system are obtained and they are shown in Fig.9(a).The SEPIC based WECS with PID controller and FLC system produces output current as shown in Fig.9(b).It is inferred that the voltage and the current waveforms of the system with the Fuzzy Logic Controller are smoother with low over-shoot than those of the system with the PID Controller. However, the current through the load of the PID Controlled WECS is higher than the case of the Fuzzy Logic controlled WECS.



9(a)

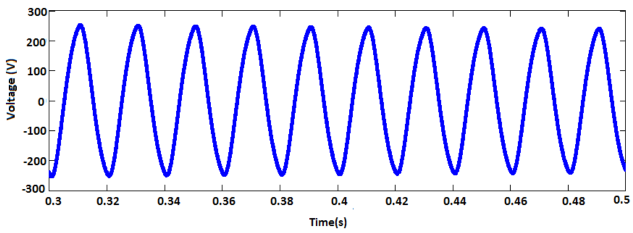


9(b)

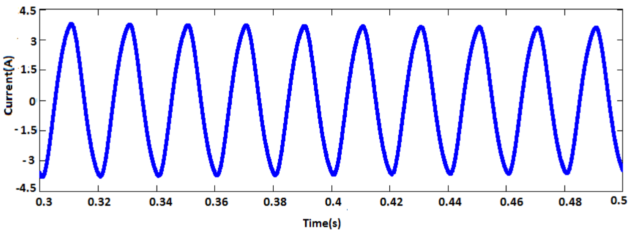
Fig 9. Simulation Results (a) Output Voltage of SEPIC with PID and Fuzzy Logic Controllers (b) Output Current of SEPIC with PID and Fuzzy Logic Controllers

The AC output voltage and current of the SEPIC based Wind Energy Conversion System with Fuzzy Logic Controller are shown in Figs.10 and 11 respectively. The DC output of the SEPIC is provided as the input to the inverter. An output voltage of 48V-AC / 50-Hz is applied as input to the transformer and the output is stepped up to 230V-AC / 50-Hz.

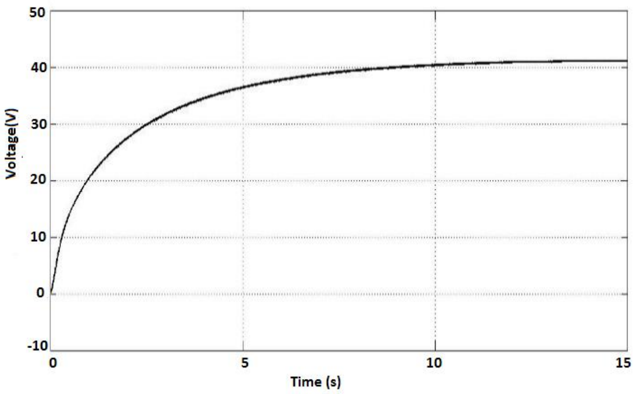
The output voltage and current of the SEPIC based WECS for linear load are shown in Figs.10(a) and 10(b) respectively. From Figs.10(a) and 10(b), it is inferred that the output voltage and the current obtained for linear load are 220 V and 3.9A.



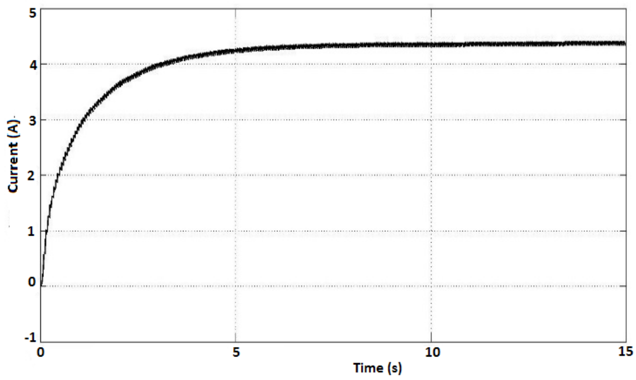
10 (a)



10(b)



10 (c)



10 (d)

Fig 10. Simulation Results for WECS (a) Output Voltage with linear load (b) Output Current with linear load (c) Output Voltage with Non-Linear load (d) Output Current with Non-Linear load

The output voltage and current of the SEPIC based WECS for non-linear load are illustrated in Figs.10(c) and 10(d) respectively. From Figs.10(c) and 10(d), it is observed that the output voltage and the current obtained for Non-linear load are 217 V and 4.4A.

The Total Harmonic Distortion of the SEPIC based WECS with the Linear and Non-linear loads are shown in the Fig.11. The THD obtained for Linear load is 1.34% and almost constant, whereas for a Capacitive load, it tends to be decreasing and for Inductive load, it is increasing for increase in the values of C/L.

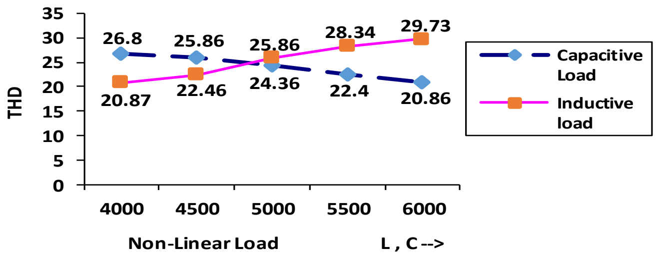


Fig 11. Total Harmonic Distortion of the SEPIC based WECS with Non-linear loads

6. Comparison:

The output voltages obtained from the simulation of the SEPIC based wind energy conversion system with the PID and the Fuzzy Logic Controllers are compared. Wind speed varies at t=0.5s for SEPIC based WECS with the PID and with the Fuzzy Logic Controllers. The comparison of the performance using the PID and Fuzzy Logic Controllers is summarized in Table 5. From Table 5, it is inferred that the FLC system produces smoother output with reduced rise time, settling time, and peak over-shoot.

Table 5. Comparision of the SEPIC based WECS with PID and Fuzzy Logic Controllers

Parameters	Rise Time (s)	Settling Time (s)	Peak Overshoot (V)
PID	0.005	0.025	2.7
FLC	0.001	0.005	1.52

7. Experimental Results:

The complete hardware set-up and the corresponding circuit diagram of SEPIC based WECS are illustrated in Figs. 12 and 13 respectively.

The hardware set-up comprises of power circuit, controller circuit, and a driver circuit. MOSFET (IRF840) switches are used in the converter and the inverter power circuits. The SEPIC requires one MOSFET and the single phase inverter requires four MOSFETs. The supply to this circuit is obtained from a transformer of 230/24V,using regulator ICs of 5V and 12V rating. The gate pulses generated by the micro-controller are driven through the driver circuit in order to increase the amplitude of the voltage required for the

MOSFETs to turn on the switches. The hardware specifications for the experimental set-up are provided in Table 6. The waveforms are recorded using RIGOL DS1052E type Digital Oscilloscope and the amplitudes are measured using RISHMAX10 type Digital Multimeter.

Table 6. Hardware Specifications

PARAMETER	SPECIFICATIONS
Source voltage	1-phase 230V,50HZ
Micro wind generator (Luminous make)	1KW,50HZ
	Rs = 0.62Ω
	Wind velocity 7m/s
	Tph = 120, N = 400RPM
DC link parameter	DC link voltage 24V
	C=150µF;
	L_1,L_2=3.18mH
Interfacing transformer	1KVA,48/220V,50Hz
Load parameters	230V ,R=100Ω

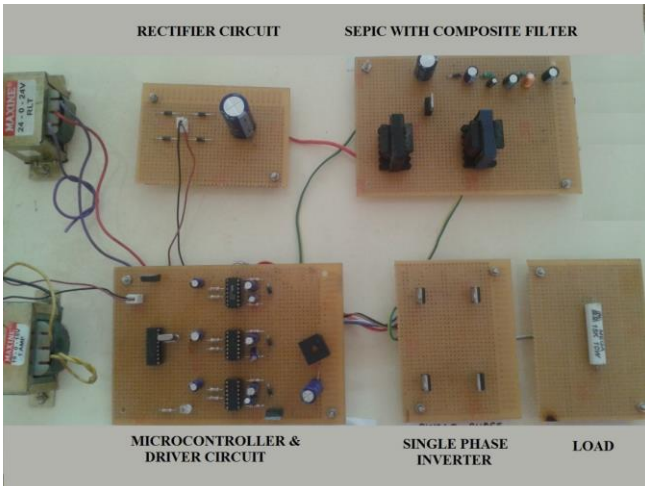


Fig 12. Hardware Set-up

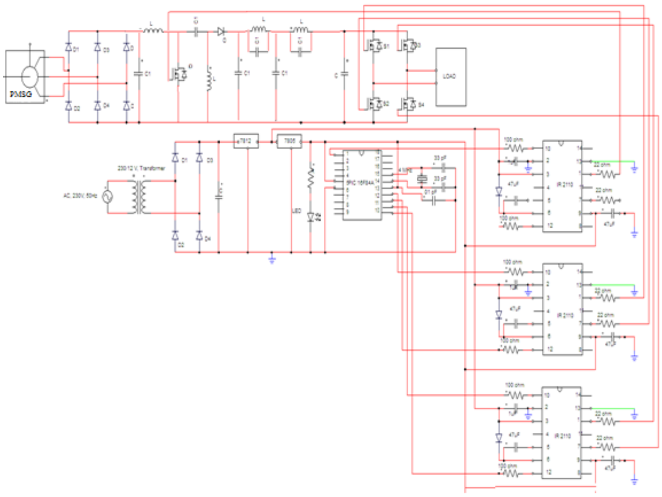
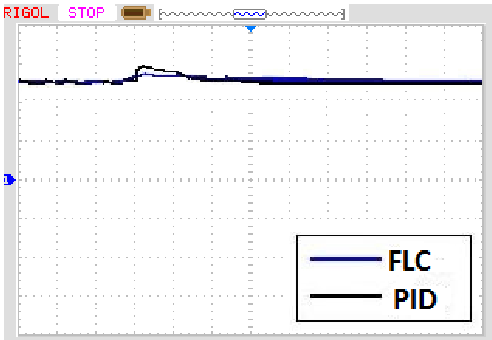
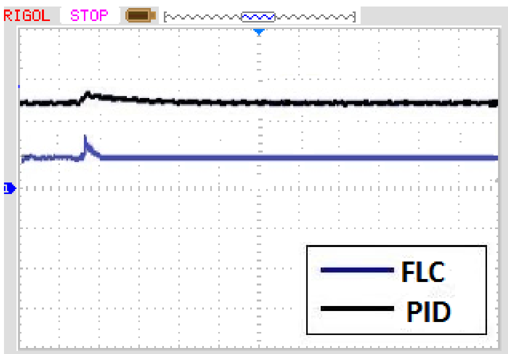


Fig.13. Hardware Circuit Diagram

The output waveforms for various components of the hardware set-up with SEPIC and single phase inverter are as follows. The output voltage waveform of the SEPIC circuit with resistive load is shown in Fig.14.The output voltage of the SEPIC is 47.6V and the output current of 0.32 A is obtained using FLC.



(a)



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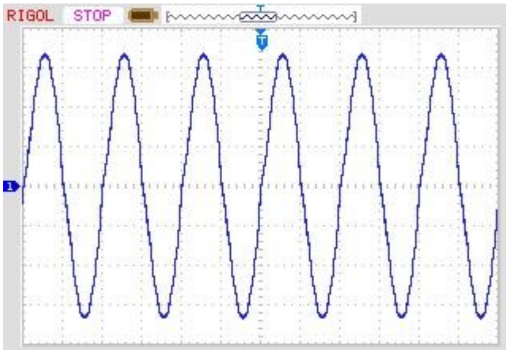

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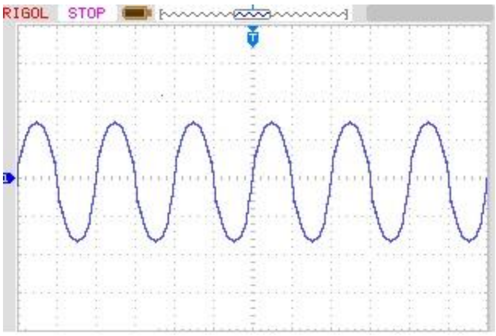

(e)

Fig. 14. Experimental Results (a) Output voltage of SEPIC with PID and FLC (X axis-20s/div; Y axis-20V/div) (b) Output Current of SEPIC with PID and FLC (X axis-20s/div; Y axis-0.2A /div) (c) Output voltage across the load (X axis-40s/division, Y axis-100V/division) (d) Output current through the load (X axis-10s/division, Y axis-2A/division).

The output voltage and current obtained are 216V and 3.1A as shown in Figs.14(c) and (d) respectively. Table 7 presents the simulation and experimental values of the system validated with a linear load. The experimental values are close to the simulation values.

Table 7. Validation of Results

Parameters	Simulated value	Experimental value
Input voltage of the converter	25	27.6V
Output voltage of the converter	48V	47.6V
Output Current of the converter	0.48A	0.32A
Output voltage across the load	220V	216V
Output current through the load	3.9A	3.1A

8. Conclusion and Scope for Future Work

The proposed Micro-Wind Energy Conversion scheme using SEPIC is analyzed and interfaced with the inverter, transformer, and the load. The simulation of the SEPIC based Micro-Wind Energy Conversion System and its closed loop control with wind speed variation was performed. Simulation with various controllers like PID and Fuzzy controller for wind speed variations was performed using MATLAB Simulator by maintaining the desired output voltage, current, and power. The fuzzy logic controlled system produced output with less overshoot. The hardware was implemented using PIC16F84A microcontroller, which generated the triggering pulses. The experimentally generated waveforms closely matched the ones obtained by simulation. The contributions of this work are development of SEPIC based FLC-WECS which can maintain constant voltage at the output with minimized ripple content and improvement of dynamic response using Fuzzy Logic Controller. The drawback of this system is that this converter can be used only at low power levels and the drop in output voltage is high with Non-Linear loads. The present work has focused on the comparison of PID and Fuzzy Logic controlled systems with Linear and Non-Linear Loads. The future direction will be a comparison of PID controlled system with neural network controlled system. The power level may be increased by using parallel cascaded converter system.

References

[1] Azad Ghaffari, Miroslav Krsti´c and Sridhar Seshagiri: *Power Optimization and Control in Wind Energy Conversion Systems Using Extremum Seeking*, IEEE Transactions on Control Systems Technology, Vol. 22, No. 5, pp. 1684 – 1695, September 2014.

[2] Zhanfeng Song, Changliang Xia: *Predictive Current Control of Three-Phase Grid-Connected Converters with Constant Switching Frequency for Wind Energy Systems*, IEEE Transactions on Industrial Electronics, Vol. 60, No. 6, pp.2451-2464, June 2013

[3] Juan Carlos Lopez, Manuel Ortega & Francisco Jurado: *New topology for DC/DC bidirectional converter for hybrid systems in renewable energy*, International Journal of Electronics, Volume 102, Issue 3, pp. 418-432, Mar 2014.

[4] G.Pandu Ranga Reddy, M.Vijaya Kumar: *Analysis of Wind Energy Conversion System Employing DFIG*

with SPWM and SVPWM Type Converters, Journal of Electrical Engineering, pp.1-12.

[5] Gnana Sheela.K, and Deepa S.N.: *A New algorithm to find number of hidden neurons in Radial Basis Function Networks for Wind Speed Prediction in Renewable Energy Systems*, Journal of Control Engineering and Applied Informatics, Vol (15), 30–37, June 2013.

[6]S. M. R. Kazmi, H. Goto, H.-J. Guo, and O. Ichinokura: *A novel algorithm for fast and efficient speed-sensor less maximum power point tracking in wind energy conversion systems*, IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 29–36, Jan. 2011.

[7] Jiawei Chen: *On Optimizing the Aerodynamic Load Acting on the Turbine Shaft of PMSG-Based Direct-Drive Wind Energy Conversion System*, IEEE Transactions on Industrial Electronics, Vol. 61, No. 8, pp. 4022-4031, August 2014.

[8] Venkata Yaramasu*: Predictive Control of a Three-Level Boost Converter and an NPC Inverter for High-Power PMSG-Based Medium Voltage Wind Energy Conversion Systems*, IEEE Transactions On Power Electronics, Vol. 29, No. 10, pp. 5308 -5322, October 2014.

[9]Jiawei Chen, Jie Chen: *On Optimizing the Transient Load of Variable-Speed Wind Energy Conversion System during the MPP Tracking Process*, IEEE Transactions on Industrial Electronics, Vol. 61, No. 9, pp. 4698 – 4706, September 2014.

[10] O. Trescases, A. Prodic, and N. Wai Tung: *Digitally controlled current mode DC-DC converter IC*, IEEE Trans. Circuits Syst., vol. 58, no. 1, pp. 219–231, Jan. 2011.

[11] A. J. Sabzali, E. H. Ismail, M. A. Al-Saffar, and A. A. Fardoun: *New bridgeless DCM SEPIC and cuk PFC rectifiers with low conduction and switching losses*, IEEE Trans. Ind. Appl., vol. 47, no. 2, pp. 873–881,Apr. 2011.

[12] Hyun-Lark Do: *Soft-Switching SEPIC Converter with Ripple-Free Input Current*, IEEE Transactions on Power Electronics, vol. 27, no. 6, pp. 2879-2887, June 2012.

[13] Ebrahim Babaei, and Mir Esmaeel Seyed Mahmoodieh: *Calculation of Output Voltage Ripple and Design Considerations of SEPIC Converter*, IEEE Transactions on Industrial Electronics, vol. 61, no. 3, pp.1213-1222, March 2014

[14]Xuefeng Hu and Chunying Gong: *A High Gain Input-Parallel Output-Series DC/DC Converter with Dual Coupled Inductors*, IEEE Transactions on Power Electronics, Vol. 30, No. 3, pp. 1306-1317, March 2015.

[15] S. Pradhan, S. K. Mazumder, J. Hartvigsen, and M. Hollist: *Effects of electrical feedbacks on planar solid-oxide fuel cell*, ASME J. Fuel Cell Sci. Technol., vol. 4, No. 2, pp. 154–166, May 2007.

[16]W. Choi, P. N. Enjeti, and J. W. Howze: *Development of an equivalent circuit model of a fuel cell to evaluate the effects of inverter ripple current*, IEEE Appl. Power Electron. Conf. (APEC), vol. 1, pp. 355–361, 2004.

[17]K. H. Torvmark: *LC filter with improved high-frequency attenuation*, Application Note AN028, Chip con Products from Texas Instruments, www.Texas instruments.org, 12.8.2014.

[18]Jae-Won Yang and Hyun-Lark Do: *Bridgeless SEPIC Converter with a Ripple-Free Input Current*, IEEE Transactions on Power Electronics, Vol. 28, No. 7, pp.3388-3394, July 2013.

[19]A. Mesemanolis, C. Mademlis, and I. Kioskeridis: *High-efficiency control for a wind energy conversion system with induction generator*, IEEE Trans. Energy Convers., vol. 27, no. 4, pp. 958–967, Dec. 2012.

[20] Giampaolo Buticchi, Emilio Lorenzani: *Active Rectifier with Integrated System Control for Micro wind Power Systems*, IEEE Transactions on Sustainable Energy, Vol. 6, No. 1, pp. 60 -69, January 2015.

[21] J. Espí and J. Castelló: *Wind turbine generation system with optimized dc-link design and control*, IEEE Trans. Ind. Electron., vol. 60, no. 3, pp. 919–929, Mar. 2013.

[22] Maren Kuschke and Kai Strunz: *Energy-Efficient Dynamic Drive Control for Wind Power Conversion with PMSG: Modeling and Application of Transfer Function Analysis*, IEEE Journal of Emerging and Selected Topics In Power Electronics, Vol. 2, No. 1, pp.35-46,March 2014.

[23] Mummadi Veerachary: *Two-Loop Controlled Buck–*

SEPIC Converter for Input Source Power Management, IEEE Transactions on Industrial Electronics, vol. 59, no. 11, pp. 4075-4087, November 2012.

[24] Mustafa A. Al-Saffar: *An Improved Topology of SEPIC Converter with Reduced Output Voltage Ripple*, IEEE Transactions on Power Electronics, Vol. 23, No. 5, pp. 2377-2386, September 2008.

[25] C. Evangelista, P. Puleston: *Lyapunov-Designed Super-Twisting Sliding Mode Control for Wind Energy Conversion Optimization*, IEEE Transactions on Industrial Electronics, vol. 60, no. 2,pp. 538-545, February 2013.

[26] H. K. Lam and F. H. F. Leung: *Fuzzy controller with stability and performance rules for nonlinear systems*, Fuzzy Sets Syst., vol.158, no. 2, pp. 147–163, Jan. 2007.

[27] L. Guo: *Evaluation of DSP-based PID and Fuzzy controllers for DC–DC converters*, IEEE Trans. Ind. Electron., vol. 56, no. 6, pp. 2237–2248, Jun. 2009.

[28]Elkhatib Kamal, Mohamad Oueidat: *Robust Scheduler Fuzzy Controller of DFIG Wind Energy Systems*, IEEE Transactions on Sustainable Energy, Vol.4, No.3, pp.706-715, July2013.

[29] Elkhatib Kamal, Abdel Aitouche: *Fuzzy Scheduler Fault-Tolerant Control for Wind Energy Conversion Systems*, IEEE Transactions on control systems Technology, vol. 22, no. 1, pp.119-131,January 2014.