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Experimental investigations on grid integrated wind energy storage system using neuro fuzzy controller

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ABSTRACT

This paper presents harnessing of maximum wind energy from natural resource whenever it's available. The power electronic converters role is important In between sources and load. The load may be linear and non-linear in nature, so converters performance decides the efficiency of the system. Proper controller can switch the converter in the desired time and improve the system performance and stability. Many controllers are suggests to control the converter to get better performance in at output side. The proposed system also has boost converter, bidirectional DC-DC converter and inverter for grid and wind energy integration. The boost inverter/buck rectifier in this system is controlled by ANFIS controller is for better output, boost and bidirectional DC-DC converters are controlled by PID controller in closed loop. Overall operations are based on modes main controller speedgoat, which is control the system operation in different modes. Any variation happening in the input, storage and load parameters speedgoat changing the mode and operate the system is in effective way. Based on the system conditions speedgoat generates control signal for the control breakers, these control breakers changing modes of operation. ANFIS, PID and speedgoat are the three controllers combined together which harness maximum wind energy and this system is applicable for both linear and non-linear loads in domestic applications.

1. INTRODUCTION

Modern controllers are very helpful for energy conversion system, now days most of the energy storage systems are fully depends on intelligent controllers such as digital logic and fuzzy logic [1-2].

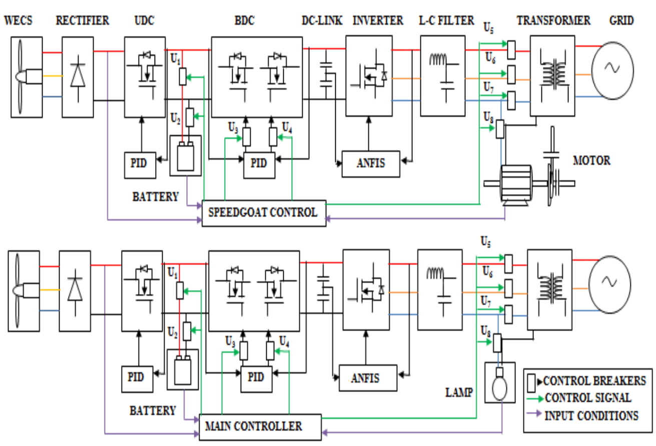


Figure 1. Wind energy conversion system with linear and non-linear load block diagram

This fuzzy logic behavior is good for tremendous intelligent control technique when compare to digital logic. The fuzzy logic consist of fuzzy controller and fuzzy sliding mode controller, these controller are robust [3-5]. Even though these are in robust, it has some drawbacks related to control parameter selection constraints and complex theory. So, this controller performance is not efficient and effective in the inverter topology [6-8]. These drawbacks are overcome by an Adaptive Neuro-Fuzzy Inference System (ANFIS), it has advantages of fuzzy logic and neural networks which are fulfill the alteration rule based demand and it can determine the inference logic rules. ANFIS can control the grid tied bidirectional converter in three modes such as grid tied boost inverter mode, grid tied buck rectifier mode and stand-alone mode in an effective way [9].

In conventional energy storage systems the converters like uncontrolled AC-DC rectifier, PID controlled boost converter, PID controlled bidirectional DC-DC converters are also using for power conversion stages with grid tied inverter [10-12]. These converters are connected between Wind Energy Conversion System (WECS), Energy Storage Device (ESD) and load/grid for effective wind energy harnessing; the converters in all the stages are controlled by separate controllers [13]. But converters in these systems are operating in closed loop but the overall system is operated by open loop configuration. There are some serious dis-advantages related to this open loop configuration such as non-reliable, inefficient operation and less utilization of natural energy [14-15]. To overcome these draw back the system should be operate in closed loop from some parameter considerations. This proposed system considers the parameters such as wind speed (v), state of charge (%) and load position (ON/OFF). Based on these parameters the speedgoat generates control signal and given to control breakers which operates the system in different modes for an effective operation with linear and non-linear load is as shown in figure 1.

2. FIVE MODES OF OPERATION

2.1 Primary source storage mode

Primary source of the system is wind energy. Based on the first two parameters consideration the wind speed (v) should be more than 5 m/s and battery charging level has to be less than 20%. Then the third parameter load position may be ON/OFF. The primary source is directly supply to only battery for the purpose of charging. In this mode load is said to be ON condition, it gets supply from secondary source otherwise the grid is isolated from the system. Figure 2 represents primary source storage mode.

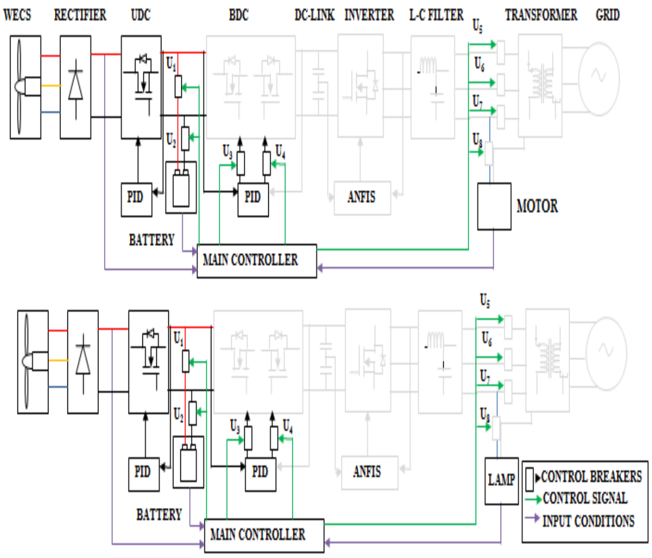


Figure 2. Primary source storage mode

2.2 Primary source storage-output mode

In the second mode of operation primary source wind energy is given to output load/grid and battery for charging. Under the parameters consideration the wind speed (v) should be more than 5 m/s and battery charging level has to be in between (40-80) %. Then the third parameter load position may be ON/OFF. The primary source is supply to both battery for the purpose of charging and output. In this mode load is said to be ON condition, it gets supply from primary source otherwise the generating power is export to grid. (Fig 3)

2.3 Primary source output mode

Third mode (fig 4) of operation is primary source output mode. In this mode primary source wind energy is directly given to output load/grid. The parameters such as wind speed (v) should be more than 5 m/s and battery charging level has to be reaching above 90 %. Then the third parameter load position may be ON/OFF. The primary source is supply to only output. In this mode load is said to be ON condition, it gets supply from primary source otherwise the generating power is directly export to grid. If the load is in ON condition, the system acts like stand-alone otherwise operates in in grid connected inverter mode.

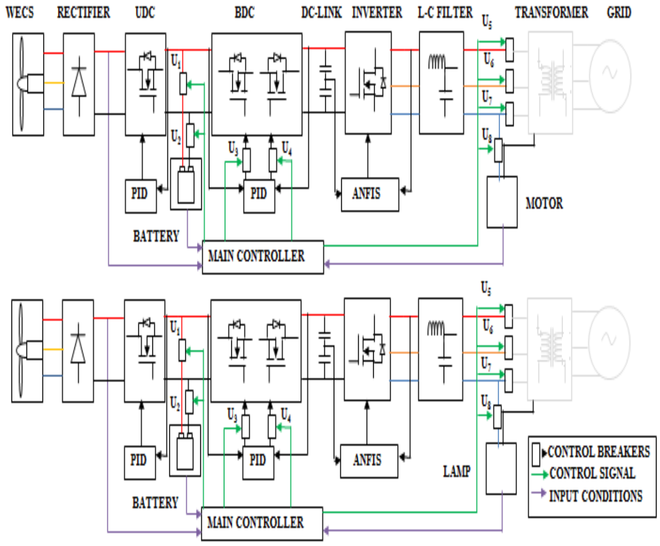


Figure 3. Primary source wind storage-output mode

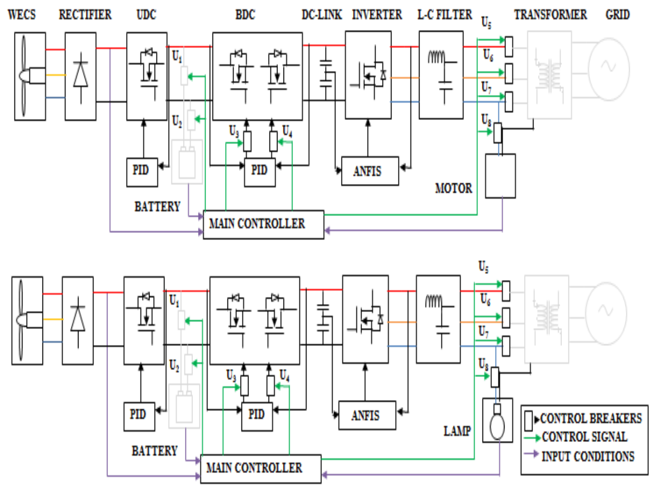


Figure 4. Primary source output mode

2.4 Battery power output mode

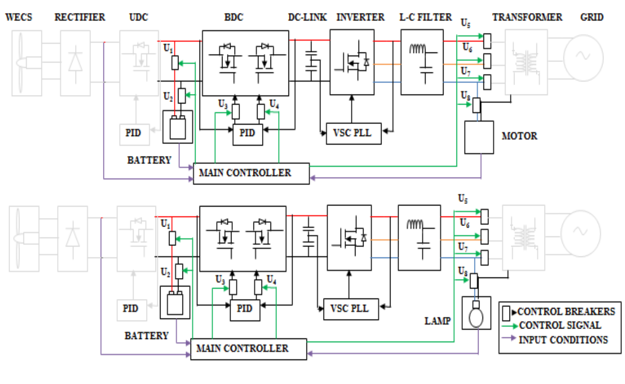


Figure 5. Battery power output mode

Back-up source of the system is battery power. In this mode primary source wind energy is less than 5 m/s. Due to low wind speed, the power is not sufficient for output and battery charging level is already in above 90 %. Then the third parameter load position should be in ON position. The primary source is not available so battery supplies the power to load. In this mode load is said to be ON condition, it gets supply from back-up source otherwise the total system is in OFF until the wind speed reach above 5 m/s. If the load is in ON condition, the system acts like stand-alone system. (fig 5).

2.5 Grid power storage-load mode

In the fifth mode of operation secondary source grid power is given to output load and battery for charging. The condition for this mode is wind speed (v) should be less than 5 m/s and battery charging level is less than 20 %. Then the third parameter load position may be either ON/OFF. The primary source is supply to both battery for the purpose of charging and load. In this mode load is said to be ON condition, it gets supply from secondary source otherwise only charging the battery from grid. This mode will continue until the wind speed reaches the level of 5 m/s. (fig 6).

All the five modes of operations are clearly explained in the Table 1. By the modes conditions the converters like UDC, BDC and inverter are controlled by main controller in different modes. The load and UDC has two positions ON-1 and OFF-0. BDC also two positions 1-boost and 2-buck. The inverter has four modes namely 0-OFF, 1-standalone, 3-grid-inverter and 4-grid-rectifier.

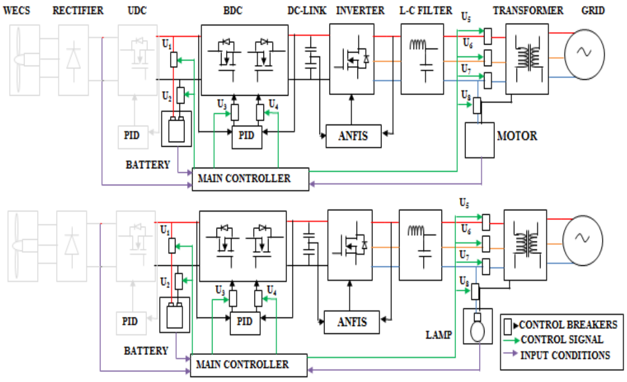


Figure 6. Grid power storage-load mode

Table 1. Modes of operation

Mode	Modes condition			Control	UDC	BDC	Inverter mode
	Load	Battery(%)	Wind speed m/s				
1	1	<40	>=5	1,2,5 & 11	1	0	0
	0	<40	>=5	1,2 & 5	1	0	0
2	1	>=40	>=5	1,2,5, 6 & 10	1	1	1
	0	>=40	>=5	1,2,5,6 & 7, 8, 9	1	1	2
3	1	>=40 &<80	>=5	5,6 & 10	1	1	1
	0	>=40 &<80	>=5	5,6,7,8 & 9	1	1	2
4	1	>=40	<5	3,4,6 & 10	0	1	1
5	1	<40	<5	3,4,6,7,8,9,& 11	0	2	3
	0	<80	<5	3,4,6,7,8 & 9	0	2	3

3. ANALYSIS OF WIND ENERGY SYSTEM

Each stage of conversion is analysed and composed by mathematical equations. Every stages of conversion consist of converters and controllers in closed loop and overall system is controlled by separate main controller called speedgoat.

3.1 Wind energy conversion

The design of wind turbine is taken from [1], horizontal axis wind turbine has to analyse from equations 1, 2 and 3. Wind passes through in area area (A) and wind speed (v) of a particular velocity. The power of wind is expressed in equation 1.

$$p = 0.5 * \rho * A * v^3 \quad (1)$$

Mechanical power is expressed in the following eqn 2.

$$p_T = 0.5 * \rho * A * (v_1 + v_2) * (v_1^{\,2} + v_2^{\,2}) \quad (2)$$

The rotor coefficient is expressed by the following eqn. 3

$$C_p = \frac{P_T}{P} = 0.5 * (1 - \frac{v_2^{\,2}}{v_1^{\,2}}) * (1 - \frac{v_2}{v_1}) \quad (3)$$

3.2 PMSG

Mathematical modeling of Permanent Magnet Synchronous

Generator (PMSG) can be written in the following equations 4 and 5.

$$\frac{di_d}{dt} = \frac{R_a}{L_d} i_d = \frac{L_q}{L_d} p\omega i_q + \frac{1}{L_d} u_d \quad (4)$$

$$\frac{di_d}{dt} = \frac{R_a}{L_q} i_q = \frac{L_d}{L_q} p\omega i_d + \frac{1}{L_d} p\omega\phi_m + \frac{1}{L_q} u_q \quad (5)$$

The EMF equation of PMSG is written in equation 6.

$$E_{ph} = 4.44 f\phi T_{ph} K_w \quad (6)$$

3.3 Rectifier unit

The three phase AC power from permanent magnet synchronous generator is supply to 3 phase bridge rectifier for AC-DC conversion.

The phase voltage amplitude V_m and output average voltage V_o is expressed by the equations 7 & 8.

$$V_m = V_{rms}\sqrt{2} \tag{7}$$

$$V_r = \frac{3\sqrt{2}}{\Pi} Vm \tag{8}$$

3.4 Uni-directional converter (UDC)

The output of unidirectional boost converter can be analysed in the input voltage and duty cycle. All stages of boost mode are controlled by adjusting the duty cycle automatically with closed loop controller. The output voltage and duty cycle is expressed by the equations 9 and 10.

$$V_b = \frac{V_r}{(1-D)} \tag{9}$$

$$\frac{T_{on}}{T_{on}+T_{off}} = \frac{T_{on}}{T_s} = D \tag{10}$$

3.5 Bidirectional converter (BDC)

The primary switch Q1 is ON position during boost mode it is expressed in equation 11

$$\left.\begin{aligned}\dot{X} &= A_1 X + B_1 V_S \\ V_{batt} &= C_1^T X\end{aligned}\right\rangle \tag{11}$$

where, **x** = state variable vector, I_L is inductor current and V_c is capacitor voltage. It consists of inductor and capacitor to represents current and voltage .It can be re-written in equation 12.

$$\left.\begin{aligned}\begin{bmatrix}\frac{di_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix} &= \begin{bmatrix}-\frac{r_c+r_L}{L} & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix} \times \begin{bmatrix}i_L\\ v_c\end{bmatrix} + \begin{bmatrix}\frac{1}{2LN}\\ 0\end{bmatrix} v_s \\ V_{batt} &= [r_c \quad 1] \times \begin{bmatrix}i_L\\ v_c\end{bmatrix}\end{aligned}\right\rangle \tag{12}$$

The state vector X dot is expressed in state variables such as A_2 and B_2. The time interval of the primary switches is ON are expressed in the equation 13.

$$\left.\begin{aligned}\dot{X} &= A_2 X + B_2 V_S \\ V_{batt} &= C_2^T X\end{aligned}\right\rangle \tag{13}$$

which are re-written in the equation 14.

$$\begin{bmatrix}\frac{di_L}{dt}\\ \frac{dv_c}{dt}\end{bmatrix} = \begin{bmatrix}-\frac{r_c+r_L}{L} & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix} \times \begin{bmatrix}i_L\\ v_c\end{bmatrix} + \begin{bmatrix}0\\ 0\end{bmatrix} v_s \tag{14}$$

The small signal analysis of AC perturbation in a DC operating point, the circuit variables is added to the ac perturbations is expressed in equation 15.

$$d_{ss} = D_{ss} + \hat{d}_{ss} \quad x = X + \hat{x} \quad v_s = V_s + \hat{v}_s \tag{15}$$

AC small signal is denoted by cap symbol. The perturbation approximation is small so negligible. Steady state value is expressed in equation 16.

$$\frac{\hat{d}_{ss}}{D_{ss}} << 1 \quad \frac{\hat{x}}{X} << 1 \quad \frac{\hat{v}_s}{V_s} << 1 \tag{16}$$

It provides the final linearized ac small signal model.

$$\dot{\hat{x}} = A\hat{x} + B\hat{V}_s + [(A_1 - A_2)X + (B_1 - B_2)V_s]\hat{d}_{ss} \tag{17}$$

The transfer function of boost converter in the boost mode operation is expressed in s-domain. Thus the s-domain form of boost converter is expressed in an equation 18.

The current-programmed state equation (19) is minimized to a function of X(s) &$V_{control}$(s). It allows x(s) to an expression as in $V_{control}$(s) in a matrix multiplication,

$$\begin{bmatrix}s\hat{i}_L(s)\\ s\hat{v}_c(s)\end{bmatrix} = \begin{bmatrix}-\frac{r_c+r_L}{L} & -\frac{1}{L}\\ \frac{1}{C} & -\frac{1}{RC}\end{bmatrix} \times \begin{bmatrix}\hat{i}_L(s)\\ \hat{v}_c(s)\end{bmatrix} + \begin{bmatrix}\frac{1}{2LN}\\ 0\end{bmatrix}\hat{v}_s(s) + \begin{bmatrix}\frac{V_s}{2LN}\\ 0\end{bmatrix}\hat{d}_{ss}(s) \tag{18}$$

$$\hat{X}(s) = [sI - A^1]^{-1} C^1 \hat{V}_{control}(s) \tag{19}$$

where, I = identity matrix. The small-signal expression for output voltage is given by

$$\hat{v}_{batt}(s) = C\,\hat{x}(s) \tag{20}$$

$$\frac{\hat{v}_{batt}(s)}{\hat{v}_{control}(s)} = G_{vf}\frac{1+\frac{s}{\omega_s}}{1+\frac{s}{\omega_L/C_1}+\frac{s^2}{\omega_L\omega_c/C_1}} \tag{21}$$

$$\frac{\hat{v}_{batt}(s)}{\hat{v}_s(s)} = A_{gvf}\frac{1+\frac{s}{\omega_s}}{1+\frac{s}{\omega_L/C_1}+\frac{s^2}{\omega_L\omega_c/C_1}} \tag{22}$$

where, the corner frequencies are identical to those in the control-to-output transfer function.

3.6 ANFIS

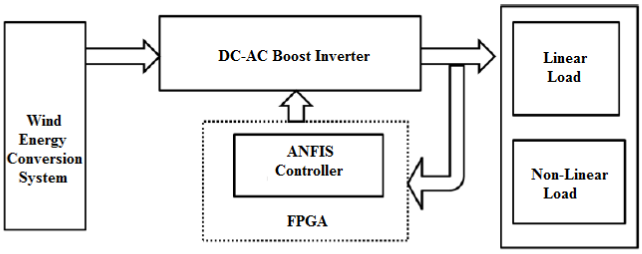
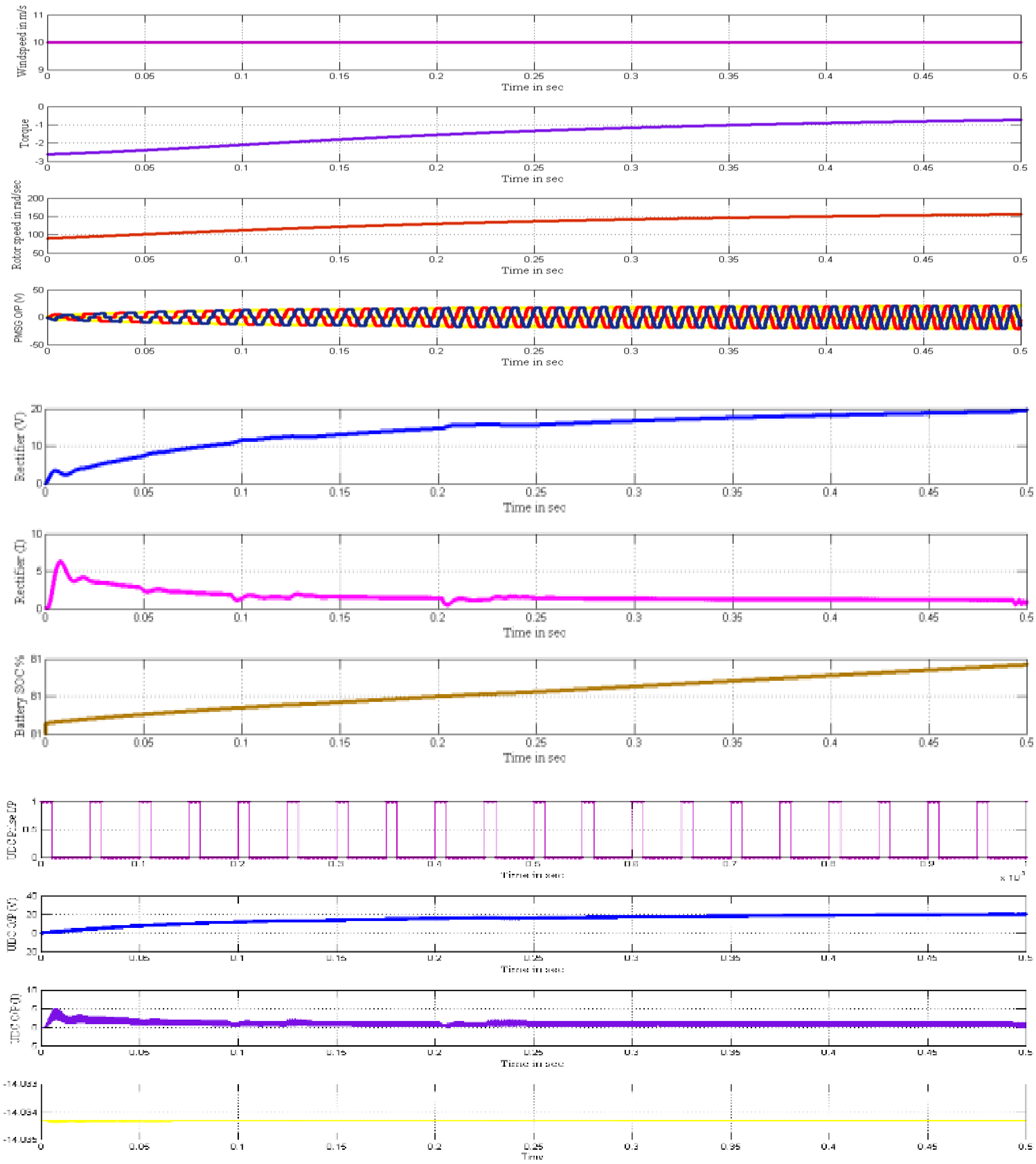


Figure 7. ANFIS Interface

ANFIS controller is connected to boost inverter is as shown in figure 7. This Set up operation is bidirectional and operates in three modes such as grid-inverter ANFIS control mode, grid- uncontrolled rectifier mode and stand alone ANFIS control mode. During first and third mode the inverter acts like a boost converter and during second mode it acts like buck rectifier.

4. SIMULATION AND RESULTS

Output waveforms of the entire mode are as shown in the figure 8. During the load is in ON (manual) position the control breakers (U_1&U_2), U_5&U_6 are turn ON by speed goat and wind power is supply to charging the battery and supply to load or else load is in OFF (manual) the control breakers (U_7 U_8 U_9) turn ON and supply the wind power to grid and remaining control breakers remain in OFF condition. The other two conditions are wind speed (v) is >= 5m/s and state of charge is in between (40-80) %.



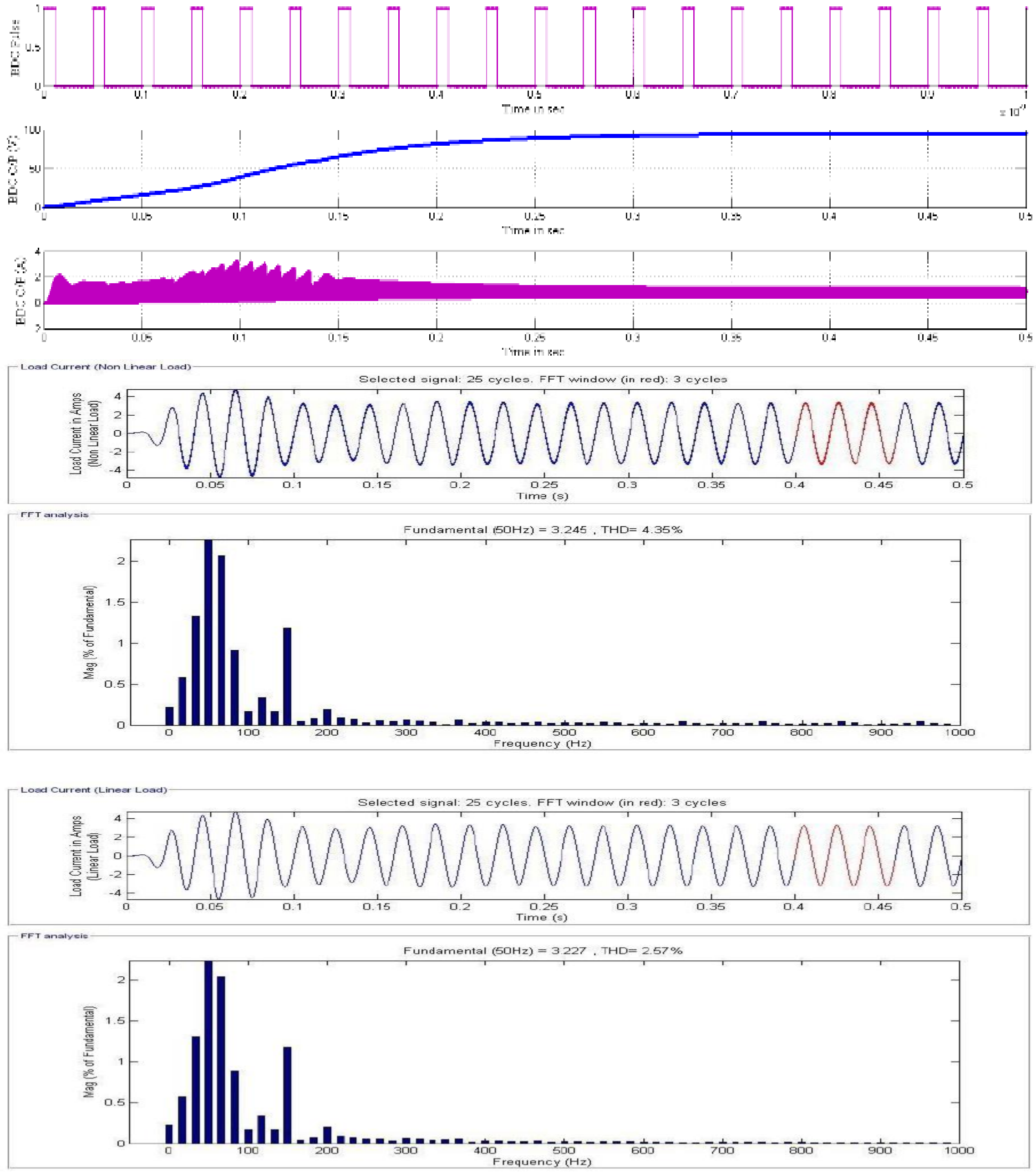


Figure 8. Simulation output

In this mode the battery is charging and also used to load, then this mode is called wind sourced battery-load mode. The carrier and reference signal is compared and the output signal of PWM controlled by the converter switches. The carrier and reference signal are compared, and PWM signal is generated given to the converter switches. The unidirectional converter output value is now obtained as 24 V, and the bidirectional converter operates in boost mode and the getting input voltage from UDC is step-up to 48 V, and the current value is 1A. Then the filtered pure DC is given to the inverter then the inverter converts DC-AC and also step-up to 98V. Finally, the electrical AC output is applied to two types of loads. ANFIS controller is used to control the inverter switching and finally LC filter is used to filter the output signal Final inverter output is given to both linear and non-linear loads. The Total Harmonics Distortions (THD) of linear load is 2.57% and THD value of non-linear load is 4.35%.

The input of the wind energy conversion system is 8 m/s. with this wind speed the output of wind profiles values of rotor torque is -0.5 N-m and rotor speed is 160 rad/sec. The output of PMSG is 24V. This 24V AC supply is provided to converters circuit, and the final 24V DC supply is given to charge the battery and also load. The input is getting from PMSG the variable 24V AC supply is initially converted to DC by three phase uncontrolled bridge rectifier.

The output of bridge rectifier is 20V DC because the rectifier efficiency is only 81.2%. The variable 20V DC voltage is converted into fixed 24V DC by using unidirectional boost converter, and the converter current is almost 2A. This 24V constant DC is supplied to the battery for charging and also supply to BDC. The bi-directional converter operates in boost mode, and the input voltage of BDC 24V is step-up to 48V. Then the filtered pure DC is given to the inverter. Finally, the electrical AC output is applied to Load. In the other side battery also charging from UDC constant output 24V DC.

5. HARDWARE AND RESULTS

Hardware implementation is shown in the figure 9. The output waveform of modes wind sourced battery-load mode is as shown in figure 10 the output is taken when the wind speed is at 5.5m/s. During the load is in ON (manual) position the control breakers (U_1&U_2), U_5&U_6 are turn ON by speed goat and wind power is supply to charging the battery and supply to load or else load is in OFF (manual) the control breakers (U_7 U_8 U_9) turn ON and supply the wind power to grid and remaining control breakers remain in OFF condition. The other two conditions are wind speed (v) is >= 5m/s and state of charge is in between (40-80) %.

Figure 9. Hardware Implementation

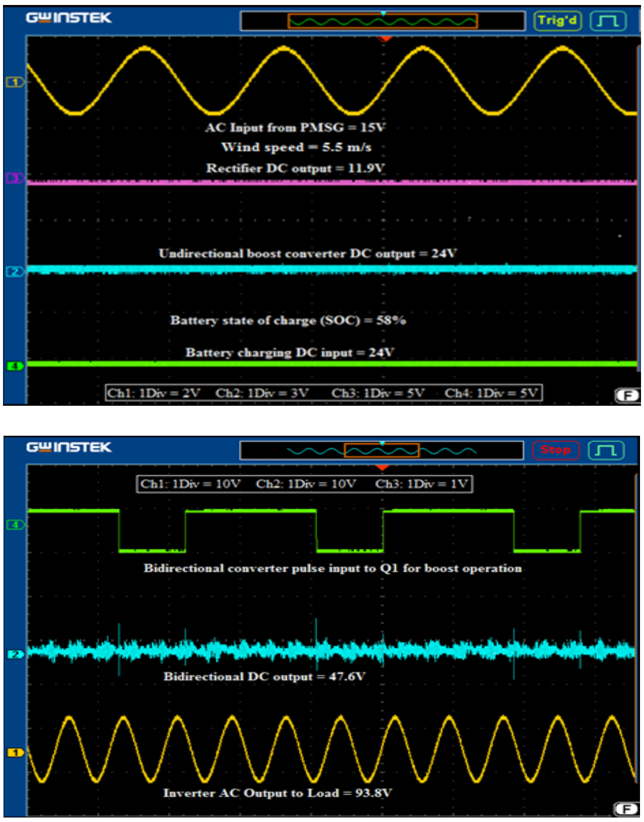


Figure 10. Hardware output result

The BDC again boost up the input 24V constant DC voltage into 48V DC voltage, and finally, an inverter converts 48V DC voltage into 98V AC voltage the value is nearly doubled and given to load. The source is given to both battery and load so, this mode of operation is called wind sourced battery-load mode. Real time output values from PMSG are 15V AC, its rectified into 11.9V DC and supplied to the UDC. The UDC maintains constant 24V DC, and again it supplied to charge the battery and also provided to BDC. The BDC output 47.6V DC is step-up and converts to AC using an inverter. The inverter output 93.8V is given to the load.

The output is taken at when the wind speed is at 7m/s. When compared to wind speed at 5.5 m/s there are some parameters changed. The BDC again boost up the input 24V constant DC into 48V DC, and finally, an inverter converts 48V DC into AC then the value nearly doubled and given to load. The source is provided to battery and load so, this mode of operation is called wind sourced battery-load mode. Real time output values from PMSG are 15V AC, its rectified into 11.9V DC and supplied to the UDC. The UDC maintain constant 24V DC and is provided to charge the battery and also supplied to BDC. The BDC output 48 DC is step-up and converts to AC using an inverter.

The inverter output 98V is as given to the load.The experimental platform of overall system consists of a boost converter and bi-directional converter with PMSG. The performance of the unidirectional boost and bi-directional converters are controlled by DSPIC30F4011 controller with PID control structure. Inverter is controlled by ANFIS controller.

Table 2. Output results

Conversion stages	Simulation results		Hardware results	
	Linear load	Non-Linear load	Linear load	Non-Linear load
PMSG Output	22	22	15	16
Rectifier output	20	20	11.9	12
UDC Output (V)	24	23.9	23.9	23.8
UDC Output (I)	4	4	4.2	4.11
Battery Output (V)	4	4	4.1	4.1
Battery Output (V)	24	24	23.9	23.6
BDC Output (V)	48	48	47.3	46.8
BDC Output (I)	25	2.45	2.3	2.41
Inverter Output (I)	2	2.1	1.7	1.9
Inverter Output (V)	98	97.3	93.8	92.7
THD (%)	2.57	4.35	7.65	9.35

The hardware result values verified with simulation results. Its outputs are almost equal to the simulation result. The system has a robust performance under all the modes. The THD values are obtained in simulation is below 5% and hardware results are below 10%.

6. CONCLUSION

In this paper, bidirectional converter operation plays an important role for mode changing operation and its five modes of operation were analysed. Wind energy is the main input sources from renewable energy, based on this source level the operations are divided into five modes and also these modes based on state of charge in battery. The electrical energy conversion system consists of a unidirectional boost converter and bidirectional converter operates four modes in boost operation and one mode in a buck operation. Simulink model of whole system including unidirectional DC-DC boost converter, bidirectional DC-DC converters were developed for wind energy electrical system and simulation results were obtained in MATLAB/SIMULINK. Real time implementation of whole system including speedgoat real time target machine, bidirectional DC-DC converters controlled by DSPIC30F4011 were developed for wind energy electrical system and real-time results were obtained. A variety of operating conditions from different inputs were analysed. The system has a robust performance under mode changing while input wind speed changes. The hardware results of the proposed model were verified with simulation results. The mode changing operation is effectively done in both simulation and real-time platforms.

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