Comparative Analysis of RBFN and Fuzzy-SVPWM Controller Based Boost Type Vienna Rectifier for 1kW Wind Energy Conversion System

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Abstract

In this paper RBFN (radial basis function network) MPPT controller based 3-ϕ boost type Vienna Rectifier is designed for wind energy conversion system (WECS). The 3-ϕ boost type Vienna rectifier is accomplished to convert AC/DC conversion from the renewable energy systems of AC generating units and/or from AC mains. This kind of rectifiers is very impressive where a unidirectional power flow is adequate in the network with high power density. The AC/DC rectifier provides a sinusoidal input current, improved power factor and low ripple at the input side. An RBFN controller based proposed system configuration is designed for 1kW wind energy conversion system in MATLAB/Simulink with a step up voltage of 230 V to 400 V at a turbine base speed of 12 m/s and the results are validated. The performance analysis of an RBFN controller based circuit topology is compared with the fuzzy logic-based SVPWM (space vector pulse width modulation) controller.

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1 Introduction

The development of wind energy conversion systems is increasing very rapidly in renewable power generation due to improved technology in wind turbine design with low cost and less weight. The advancement in power converters makes the system very simple and low structures in renewable energy conversion. The maximum power tracking is feasible in the WECS based on the various optimal control algorithms developed by the researchers such as incremental conductance (IC), P&O (Perturbation & Observation) [1–3], fuzzy logic control (FLC) and adaptive neural network (ANN) etc [4–6]. The intelligent control MPPT techniques (FLC, ANN) are robust in nature and fast convergent in control of non-linear systems over the conventional control schemes (IC, P&O). In most of the WECS, variable speed wind turbines are preferable rather than the fixed speed turbines because of the better performance features for extreme wind variations [7]. The PMSG is a widely used generating system for WECS over the DFIG (Double Fed Induction Generator) due to higher efficiency and low power losses [8]. The virtual inertia controller introduced for the control of PMSG to maintain the dynamic frequency support [9] and clarify the fault ride through control of the PMSG. Similarly, direct torque control (DTC) and direct power control (DPC) techniques are widely used in WECS to track the maximum power based on different control algorithms [10–13]. The high altitude wind energy conversion is an advancement in the WECS over traditional wind turbine systems with reduced installation investment for small-scale [14, 15] power plants.

One of the most important areas in the WECS is AC/DC and DC/AC power conversion through advanced power converters topologies in order to supply to the end user load demand and/or main grid [16]. Apart from all the rectifier units proposed by the researchers in various papers, the Vienna Rectifier is a supply/grid side AC/DC converter to be used in WECS and/or AC mains to feed the DC loads where unidirectional power flow is absolutely necessary [17, 18]. The Vienna Rectifier is invented by J.W. Kolar in the year of 1993 for AC/DC conversion. It is become very popular over regular converters because of its merits like power factor correction [19, 20], input current shaping [20], total harmonic distortion (THD) reduction [22, 23]. Many control strategies are introduced to control the Vienna Rectifier like sliding mode, SVPWM, PMC (Predictive Model Control), hysteresis control and adaptive neural network control [22–29] techniques etc.

Aforementioned control strategies have few drawbacks in control structure such as high complexity, low convergence and poor efficiency. In order to compensate the pitfalls of the conventional control structures, artificial intelligent controllers [30–33] are preferred for converter control with fast convergence and high efficiency. In this paper, an intelligent neural network-RBFN controller based 3-ϕ 3-level unidirectional boost type Vienna Rectifier proposed over the typical SVPWM controller for 1kW WECS and the output voltage of 400V/1kW is connected to the resistive load. This kind of rectifier units more crucial for AC/DC conversion in DC distribution systems, DC microgrid and MV (medium voltage) DC distribution etc. The performance analysis of the Vienna Rectifier using an RBFN and fuzzy logic based SVPWM controller is carried out through the output results.

2 Model Description

The proposed design configuration consists of a wind turbine, PMSG and Vienna Rectifier with the capacitive filter as shown Figure 1. The wind turbines are two types, one is fixed speed and another one is variable speed. Generally, variable speed turbines are more advantageous than the fixed speed with improved power quality, high efficiency, and maximum power tracking. PMSG is a preferable high-speed generator for small-scale wind plants at

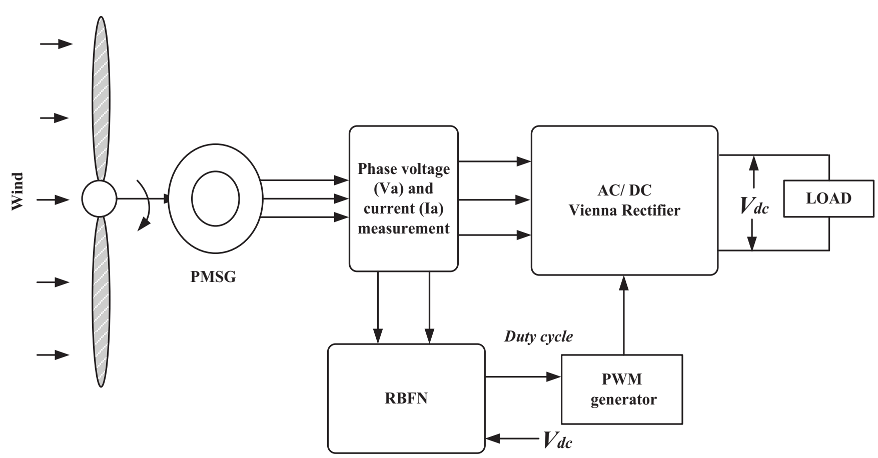

Figure 1 Proposed system configuration with RBFN controller.

all environmental conditions with less maintenance. The Vienna Rectifier is significant for AC/DC conversion with improved power factor, reduced harmonics, and low switching losses. Switching losses are greatly decreased in this type of rectifier due to reduced switching devices and mid-point circuit configuration. The capacitive filter section is used at the input side of the WECS which makes input current near to sinusoidal and reduces the input side current ripple. Similarly, a DC-link capacitor is connected at load side, which is split into two as C_1 and C_2, the total voltage across the load is V_{DC}.

2.1 Wind Energy Conversion System

The Wind Energy Conversion System is a wide range of technology used in distributed power generation, where the kinetic energy is transformed into mechanical energy through wind turbine and the mechanical energy is transformed into electrical energy by the PMSG. The power conversion rating of the system is decided by the design parameters and desired rating. The wind turbine and PMSG parameters considered in the system design are shown in Table 1. The speed and power characteristics of the turbine are shown in Figure 2, in which the maximum power achieved at turbine speed of 123 m/s for zero pitch angles.

The mechanical torque developed by the wind turbine is expressed as,

$$T_m = \frac{1}{2}\rho A C_p(\lambda, \beta)\nu^3 \frac{1}{\omega_m} \tag{1}$$

Where, ρ = Air density (kg/m^3), C_p = Power Coefficient, A = Sweep area of turbine blades (m^2), β = Pitch angle (deg), ν = Wind speed (m/s), ω = Rotor angular velocity (rad/sec) and λ = Tip-ratio. And λ can be expressed as,

$$\lambda = \frac{\omega_{m^r}}{\nu}, \quad \text{where r = Rotor radius(m)} \tag{2}$$

Table 1 Wind turbine system parameter

S.No	Wind Turbine System Parameters	Ratings
1	Maximum output power	1 kW
2	Wind base speed	12 m/s
3	Pitch angle	$0°$
4	Torque constant	1.8
5	Flux linkage	1.2 Wb-t
6	Stator phase resistance	3.07 Ω
7	Armature inductance	6.57 mH
8	PMSG Output voltage	230V

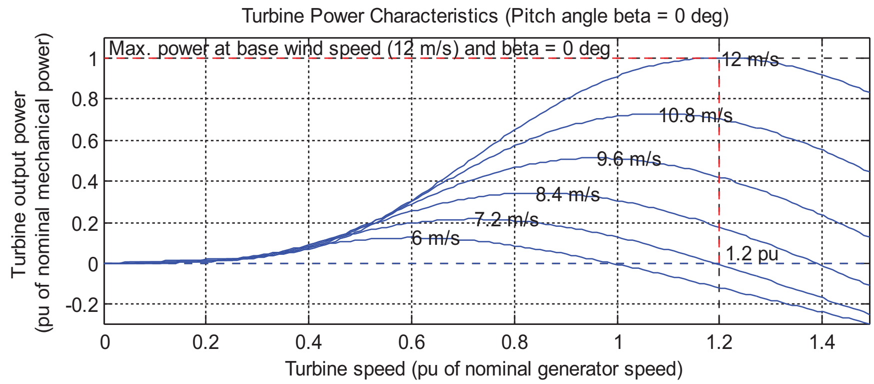

Figure 2 Turbine speed v/s power characteristics for zero pitch angle.

Similarly, the mechanical power developed by the wind turbine is expressed as

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta)\nu^3 \tag{3}$$

Similarly, the PMSG is an essential part in the field of small-scale wind energy conversion systems due to less weight (No gear-box) and high efficiency (due to the absence of field copper loss), in which the mechanical energy converts into electrical energy using PMSG at variable speed and the voltage equations of the PMSG are expressed as,

$$V_{gq} = (R_g + pL_q)i_q + \omega_e(L_d i_d + \psi_f) \tag{4}$$

$$V_{gd} = (R_g + pL_d)i_d - \omega_e L_q i_d \tag{5}$$

Where, i_d, V_{gd}, and $i_q V_{gq}$ are the d-q axis stator voltage and current respectively, L_d and L_q are the d-q axis inductance of generator, ψ_f = Magnetic flux (wb), ω_e = Electrical speed of the generator. The ω_e is expressed as

$$\omega_e = p_n \omega_m \tag{6}$$

Where, p_n = Number of pole pairs of the PMSG, ω_m = Mechanical angular speed. The electromagnetic torque produced by the generator is expressed as,

$$T_{Elec} = \frac{3}{2}[\psi_f i_q - (L_d - L_q)i_d i_q] \tag{7}$$

Therefore, the wind turbine dynamic model equation is expressed as,

$$J\frac{d\omega_m}{dt} = T_{Elec} - T_m - F\omega_m \tag{8}$$

Where J = moment of inertia & F = Viscous friction coefficient.

Three phase input voltage is written as,

$$\left.\begin{aligned} E_A &= E_m \sin(wt) \\ E_B &= E_m \sin\left(\mathrm{wt} - \frac{2\pi}{3}\right) \\ E_C &= E_m \sin\left(\mathrm{wt} + \frac{2\pi}{3}\right) \end{aligned}\right\} \tag{9}$$

2.2 Vienna Rectifier

The boost type Vienna Rectifier is a 3-ϕ 3-level unidirectional boost type converter with reduced switching devices, which makes low power loss across the switches. It consists of three switches i.e one switch in each phase, 18-diodes and two capacitors at output terminals as shown in Figure 3. Generally, this kind of rectifiers is used in AC generating supply systems and/or AC mains. The switching vectors are determined depending on the polarity of input currents. As shown in Figure 4a & 4b, for $S_1 = 0$ (switch-OFF) current flows through the diodes from phase to neutral when I_A is +ve and current flows through the diodes from neutral to phase when I_A is –ve.

Similarly, for $S_1 = 1$ (switch-ON) current flows through the switch S_1 from phase to neutral when I_A is +ve and current flows the switch S_1 from neutral to phase when I_A is –ve as shown in Figure 4c & 4d. In this way, circuit operation can be expressed for switch S_2 and S_3 i.e. for all three phase voltage and current equations.

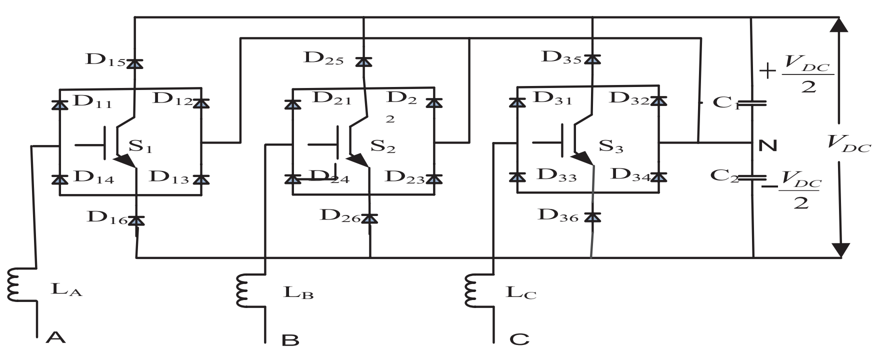

Figure 3 Circuit diagram of a 3-ϕ boost type Vienna rectifier.

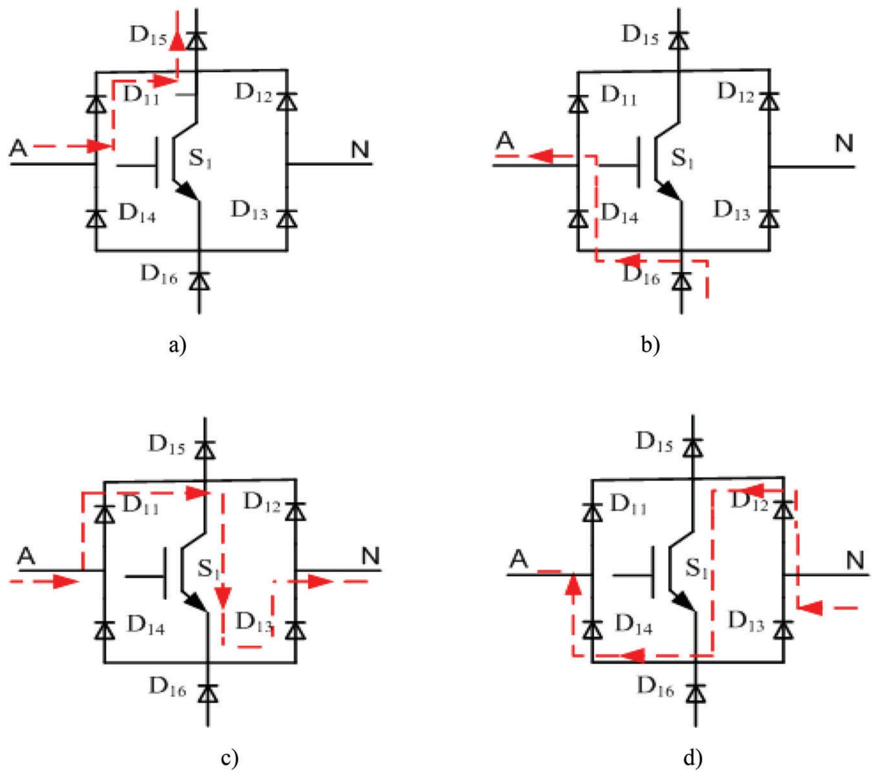

Figure 4 Current flow in the circuit when $S_1 = 0$ (Figure 4a: I_A+ve & Figure 4b: I_A-ve) and $S_1 = 1$ (Figure 4c: I_A+ve & Figure 4d: I_A-ve).

The state-space equations for the input side voltage of rectifier are written as,

$$\left.\begin{aligned} E_{AN} &= Ri_A + L\frac{di_A}{dt} + V_{AN} \\ E_{BN} &= Ri_B + L\frac{di_B}{dt} + V_{BN} \\ E_{CN} &= Ri_C + L\frac{di_C}{dt} + V_{CN} \end{aligned}\right\} \tag{10}$$

where, R = source resistance, L = source inductance and $E_{A,B,C}$ = Vienna rectifier terminal voltage which relies on the switching state and flow of current in the circuit. V_{AN}, V_{BN} and V_{CN} are the terminal voltages which can be written as the function of current and state of the switch.

$$\left.\begin{aligned} V_{\mathrm{AN}} &= \frac{\mathrm{V_{DC}}}{2}\mathrm{sgn}(i_A)(1-\mathrm{S_1}) \\ \mathrm{V_{BN}} &= \frac{\mathrm{V_{DC}}}{2}\mathrm{sgn}\ (\mathrm{i_B})(1-\mathrm{S_2}) \\ \mathrm{V_{CN}} &= \frac{\mathrm{V_{DC}}}{2}\ \mathrm{sgn}\ (\mathrm{i_c})(1-\mathrm{S_3}) \end{aligned}\right\} \tag{11}$$

Where, 'sgn' is the signum function of $\mathrm{I}_{A,B,C}$ and the Vienna rectifier output capacitor voltage is split into $+\frac{V_{DC}}{2}$ and $-\frac{V_{DC}}{2}$ at C_1 and C_2 respectively. This voltage control ensures the balanced output and reduces to 50% of the DC-link voltage across the switches.

3 Controllers

A comparative analysis of RBFN and Fuzzy-SVPWM control topologies is presented for the boost type Vienna Rectifier with voltage step-up of 230V to 400V in 1kW wind energy conversion system. RBFN controller is one of the finest control techniques with fast conversance and simple network structure. In other hands, the Fuzzy logic based SVPWM control strategy is very complex in design and operation with low conversance. In this section, the design and operation of both the controllers are explained for the boost type Vienna Rectifier control in the wind energy conversion system.

3.1 RBFN Controller

An intelligent artificial neural network is adapted to implement the proposed an RBFN control topology for the boost type Vienna Rectifier as shown in Figure 5. It is a three layer network called input layer, a hidden layer,

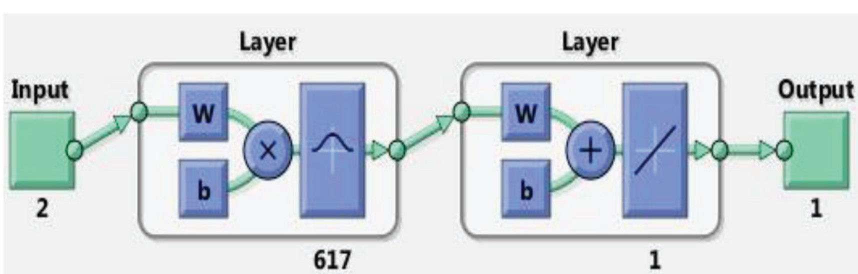

Figure 5 Control model of an RBFN.

Table 2 Parameter configuration of an RBFN

S.No.	Controller Parameters	Values/Methods
1	Input variables	$V_{A,B,C}$, $i_{A,B,C}$
2	Output variables	D (Duty cycle)
3	Hidden neurons (Maximum limit)	617
4	Training algorithm	OLS
5	Speed factor	0.03

and an output layer. The activation functions of hidden layer estimated by the distance between input vector and prototype vector. In the first step, the parameters which direct the basis function are estimated by unsupervised methods and in the second step, the final layer units are decided. The input variables ($x_i{}^1$) to an RBFN controller are voltage and current and the output variable ($y_k{}^3$) is a duty cycle (D). The parameters considered for an RBFN configuration are shown in Table 2.

a) Input layer: In this layer, the measured input variables are directly transmitted to next level through the nodes. The net input and output is represented as,

$$net_i^1 = x_i^1(N) \tag{12}$$

$$y_i^1(N) = f_i^1(net_i^1(N)) = net_i^1(N), \quad \text{where,} \quad i = 1, 2 \ldots n \tag{13}$$

b) Hidden layer: In this, a Gaussian function is performed for each and every node i.e an RBFN is used as a membership function. The net input and output for the hidden layer is represented as,

$$net_j^2(N) = (X - M_j)^T \sum_j (X - M_j) \tag{14}$$

$$y_j^2(N) = f_i^2(net_j^2(N)) = Exp(net_j^2(N)), j = 1, 2 \ldots ..9 \tag{15}$$

Where Mean $= M_j = [m_{1j} m_{2j} ....m_{ij}]^T$ and Standard deviation = $\sum_j = diag\left[\frac{1}{\sigma_{1j}^2}\frac{1}{\sigma_{2j}^2}.........\frac{1}{\sigma_{ij}^2}\right]^T$

c) Output layer: The overall output can be computed by the summation of all the inputs through the single node k, which is represented as $\sum$, therefore

$$net_k{}^3 = \sum W_j y_j{}^2(N) \tag{16}$$

$$y_k{}^3(N) = f_k{}^3(net_k{}^3(N)) = net_k{}^3(N) = D \tag{17}$$

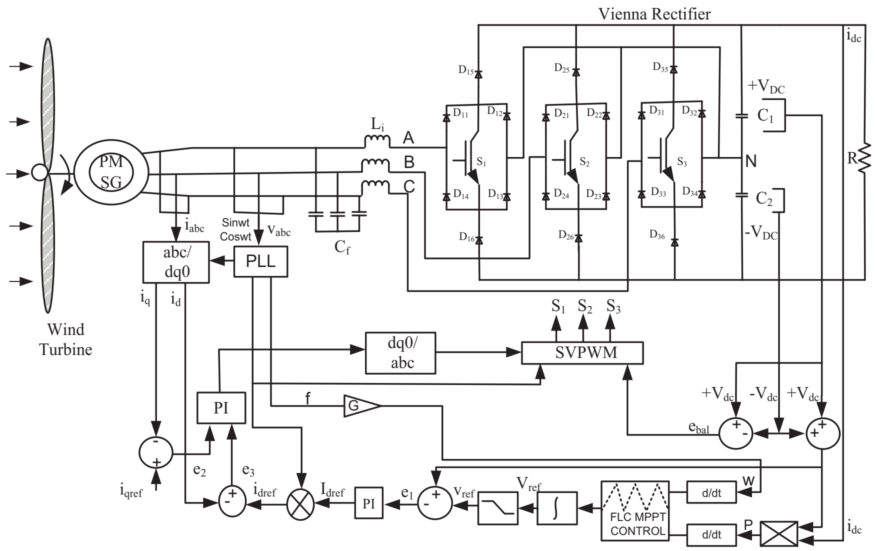

Figure 6 System configuration with fuzzy logic based SVPWM controller.

3.2 Fuzzy logic Based SVPWM Controller

The fuzzy logic based SVPWM controller is employed for control of boost type Vienna Rectifier, where fuzzy logic control works for MPPT and SVPWM engaged for pulse generation to the switches with a phase delay of 120° for each switch. The change in rotor speed of the PMSG and the change in power of the Vienna Rectifier are considered as the crisp data (input) to the fuzzy system. The output signal (crisp data) generated by of the fuzzy system is a d-axis reference current (i_{dref}), which is compared with the d-axis current (i_d) and given to the PI controller as shown in Figure 6, which results in tracing the accurate maximum power point. The control structure of the fuzzy logic control and SVPWM are explained in the following sections i.e. 3.2.i and 3.2.ii respectively.

i) Fuzzy Logic Control

The fuzzy logic control is a robust control technique used in non-linear system control for better accuracy. It consists of mainly three parts, Fuzzifier, Rule base and Defuzzifier as depicted in Figure 7. In the fuzzfier, the crisp data can be used as input and it converted into fuzzy data by means of fuzzification. The change in speed (dw/dt) and change in power (dp/dt) are the two input variables considered as crisp data. The output is governed by the

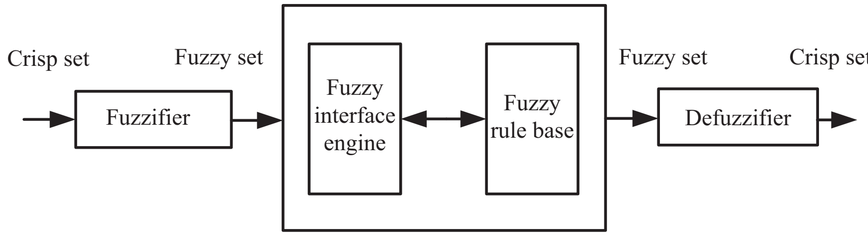

Figure 7 Model representation of fuzzy logic controller.

Table 3 Fuzzy rules for a change in power and speed

Change in Power (dp/dt) (pu)	Fuzzy Rules	Change in Speed (dw/dt) (pu)						
		NL	NM	NS	ZE	PS	PM	PL
	NL	NL	NL	NM	ZE	PM	PL	PL
	NM	NL	NM	NM	ZE	PM	PM	PL
	NS	NM	NM	NS	ZE	PS	PM	PM
	ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
	PS	PM	PS	PS	ZE	NS	NS	NM
	PM	PL	PM	PS	ZE	NS	NL	NM
	PL	PL	PL	PM	ZE	NM	NL	NL

rule base according to variations in input parameters. In the defuzzification, again the fuzzy data can be transformed into crisp data which is the output of the FLC.

The output reference current (i_{dref}) of FLC is compared with the supply d-axis current (i_d) and the resultant error will be given to the PI (Proportional-Integral) controller, which predicts the maximum power point tracking of WECS. The input and output parameters are expressed in seven linguistic labels as shown in Table 3, such as negative large (NL), positive large (PL), negative medium (NM), positive medium (PM), zero (ZE), negative small (NL) and positive small (PL). Similarly, the membership functions of FLC are represented in Figure 8 for input and output variables and also the rule base has represented in surface view as depicted in Figure 9.

ii) SVPWM Controller

The Vienna Rectifier switching pulses are triggered by the SVPWM current controller as shown in Figure 6. In this, the desired voltage vectors in the *d-q* frame for a 3-ϕ Vienna rectifier with eight switching patterns which finds a voltage space vector. The switching patterns are divided into six sectors excluding V_0 and V_7 with the same magnitude of $2/3V_{dc}$. Each of the voltage vectors can be synchronized by the adjacent vector of the

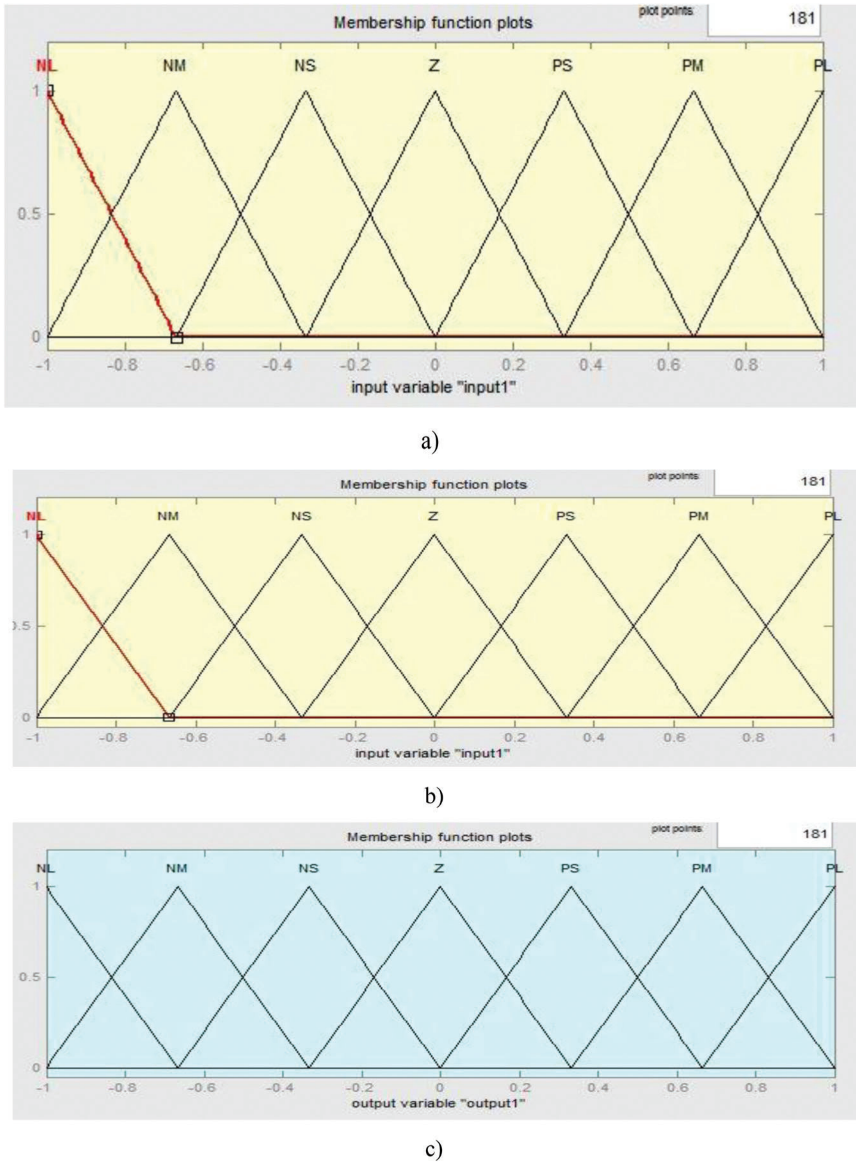

Figure 8 Membership functions: (a) input1-change in speed (pu)), (b) input2-change in power (pu) and (c) output-i_{dref} (pu).

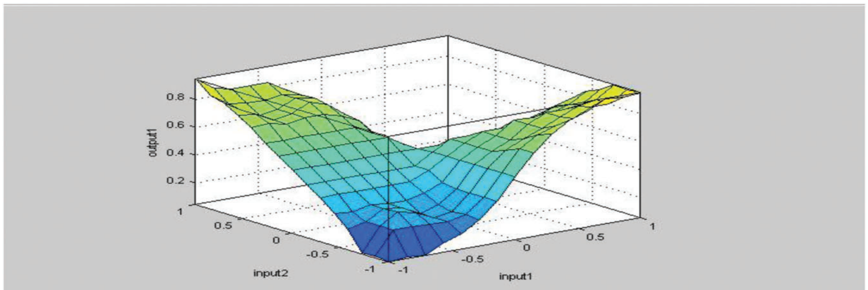

Figure 9 Representation of rule base in surface.

sector which minimizes the switching time and current harmonic distortion. In this the three-phase current abc (i_{ABC}) can be converted into (i_d & i_q) d-q frame which compared by the reference currents of i_{dref} and i_{qref}, an error signal is fed to the PI (Proportional-Integral) controller where the reference currents can be taken from the output voltage V_{DC} and V_{DCref}. Here i_d and i_q in d-q frame transformed into abc frame which is given to SVPWM controller where the desired switching pulses will be generated. The following equations are derived from the controller circuit. The mathematical equations of voltage and current in the stationary *d-q* frame are expressed as,

$$\left.\begin{aligned} C\frac{d\,V_{DC}}{dt} &= \frac{3}{2}\left(i_q S_q + i_d S_d\right) - i_L \\ L\frac{di_q}{dt} + \omega L i_d + R i_q &= E_q - V_{DC} S_q \\ L\frac{di_d}{dt} + \omega L i_q + R i_d &= E_d - V_{DC} S_d \end{aligned}\right\} \tag{18}$$

$$\left.\begin{aligned} V_d = E_d - \omega L i_q - L\frac{di_d}{dt} - R i_d = E_q - V_{DC} S_q \\ V_q = E_q - \omega L i_q - L\frac{di_q}{dt} - R i_q = E_d - V_{DC} S_d \end{aligned}\right\} \tag{19}$$

Where $V_d = V_{DC}S_d$ and $V_q = V_{DC}S_q$ are the part of AC voltages in the d-q frame. Similarly, the reference voltage is derived in the *d-q* frame as,

$$\left.\begin{aligned} V_{dref} = -\left(K + \frac{K_i}{S}\right)\left(i_{dref} - i_d\right) - \omega L i_q + E_d \\ V_{qref} = -\left(K + \frac{K_i}{S}\right)\left(i_{qref} - i_q\right) - \omega L i_d + E_q \end{aligned}\right\} \tag{20}$$

4 Result Analysis

The performance analysis of a 3-ϕ boost type Vienna rectifier is presented using RBFN and fuzzy logic based SVPWM current controller for a 1kW WECS. The circuit parameters considered for proposed system modeling are tabulated in Table 4 and the corresponding comparative results are presented in Table 5 and Table 6 respectively. In this a 230V AC is generated by the PMSG of wind energy conversion system is connected to a three-phase Vienna rectifier (1kW) through to meet the 400V/1kW system. For the proposed system configuration, the variable wind input data to be considered for RBFN and fuzzy system to train and control the entire system for desired output parameters. Figure 10 shows the variable wind input at the rotor blades of the turbine and rotor speed (pu). Similarly, Figure 11 shows the output three-phase voltage (V_{ABC}) and current (I_{ABC}) of the PMSG which is fed to the rectifier as input at a constant turbine speed of 12 m/s. The rectifier DC output voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) based on SVPWM are depicted in Figure 12. Similarly, the imbalanced DC-link voltage of the Vienna Rectifier is depicted in the Figure 13.

Table 4 Circuit parameters for base speed (12 m/s)

S.No	Circuit Parameters	Ratings
1	Three phase source voltage (peak)	230V
2	Maximum Output voltage	400V
3	The power rating of wind unit	1kW
4	Input inductance ($L_A = L_B = L_C$)	10mH
5	Input filter capacitance ($C_A = C_B = C_C$)	100uF
6	DC-link capacitance	200 μF
7	Diode resistance (R_{ON})	0.001Ω
8	Load resistance	160Ω
9	Maximum output power	1kW

Table 5 Comparative result analysis of Vienna Rectifier.

Rectifier Controller	V_{DC}(V)	I_{DC}(A)	P_{DC} (W)	Power Loss Across the Switch, P_L(W)/Phase
SVPWM	389.3	2.43	945.9	0.492
RBFN	397.3	2.47	982.8	0.348

Table 6 DC-link voltage of Vienna Rectifier

Rectifier Controller	V_{DC1}(V)	V_{DC2}(V)
SVPWM	186.5	207.2
RBFN	198.62	198.68

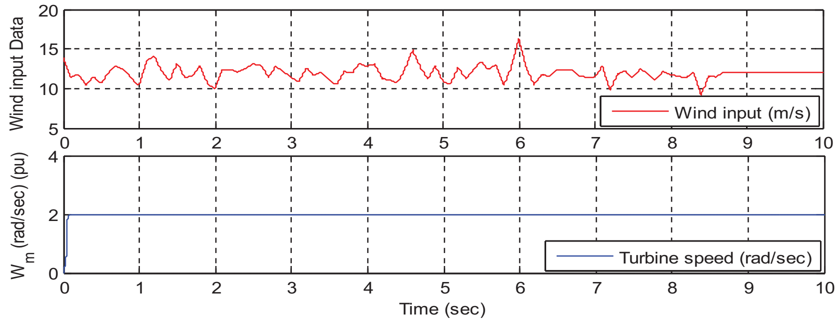

Figure 10 Simulation results of wind input and rotor speed (Wm) (pu).

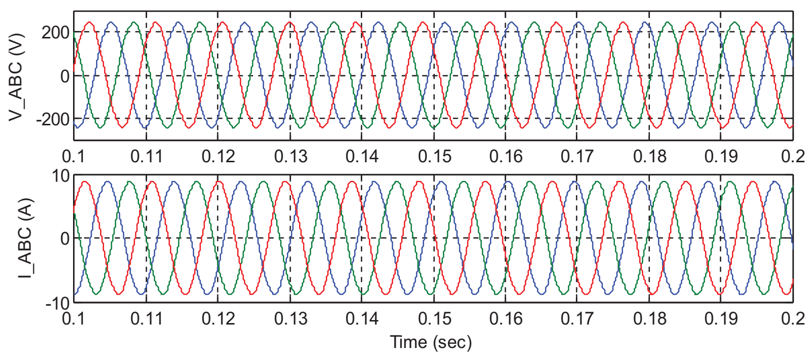

Figure 11 Simulink results of three-phase voltage (V_{ABC}) and current (I_{ABC}).

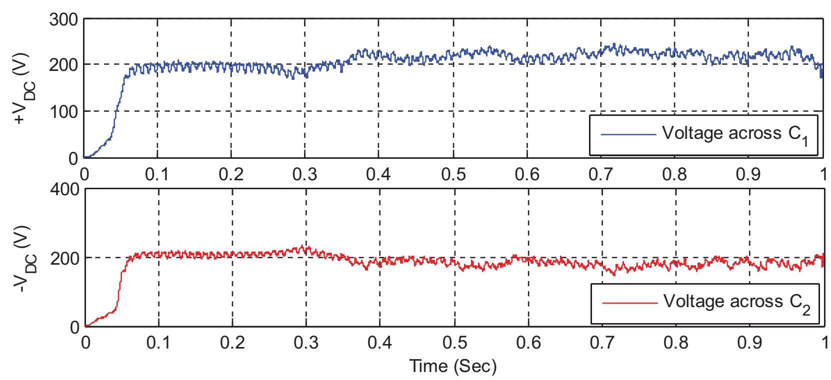

Figure 12 Simulation results of the voltage across the DC-link capacitors C_1 and C_2 using Fuzzy logic based SVPWM controller.

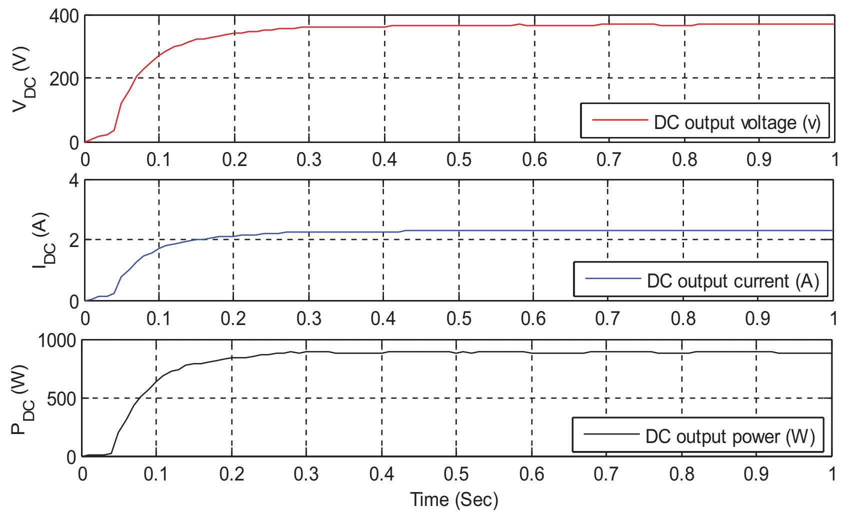

Figure 13 Simulation results of output DC voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) using SVPWM controller.

Aforementioned circuit parameters as in Table 4 are considered for RBFN controller based 3-ϕ proposed system configuration to meet the desired values. The rectifier DC output voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) based on RBFN are depicted in Figure 14. Similarly, the balanced DC-link voltage of the Vienna Rectifier based on RBFN control is depicted in the Figure 15. The output parameters of the system are taken for constant turbine speed of 12 m/s.

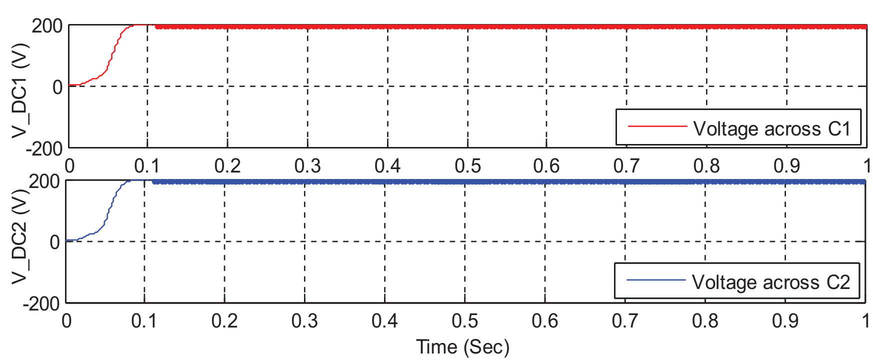

Figure 14 Simulation results of the voltage across the DC-link capacitors C_1 and C_2 using RBFN controller.

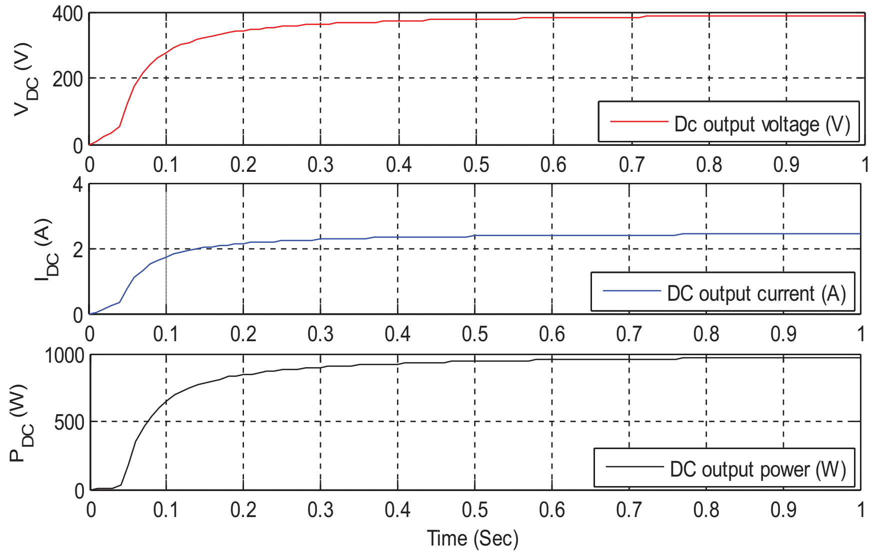

Figure 15 Simulation results of output DC voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) using RBFN controller.

5 Conclusion

In this paper, the novel boost type Vienna Rectifier is designed for 1kW wind energy conversion system with the fast dynamic response and reduced power losses. It has many advantages such as power factor correction, sinusoidal input current shaping and high efficiency etc. An artificial intelligent network based controller is used to control the Vienna Rectifier with proper switching pattern in order to get desired output variable. The performance analysis of an RBFN control based system is compared with the fuzzy logic-based SVPWM control technique and the better results are carried out through Matlab/Simulink for 230V to the 400V/1kW system at a base speed of the wind turbine. The Vienna Rectifier is a recommendable converter circuit for AC/DC power conversion where unidirectional power flow converters are essential like in DC distribution, telecommunication and data centers.

References

[1] Xia, Y., Ahmed, K. H., and Williams, B. W. (2011). A new maximum power point tracking technique for permanent magnet synchronous generator based wind energy conversion system. *IEEE Transactions on Power Electronics,* 26(12), 3609–3620.

[2] Reddy, D., and Ramasamy, S. (2017). A fuzzy logic MPPT controller based three phase grid-tied solar PV system with improved CPI voltage. In *2017 Innovations in Power and Advanced Computing Technologies (i-PACT),* (pp. 1–6). IEEE.
[3] Lu, C., Raghunathan, V., and Roy, K. (2011). Efficient design of micro-scale energy harvesting systems. *IEEE Journal on Emerging and Selected Topics in Circuits and Systems,* 1(3), 254–266.
[4] Chen, J., Chen, J., and Gong, C. (2014). On optimizing the transient load of variable-speed wind energy conversion system during the MPP tracking process. *IEEE transactions on industrial electronics,* 61(9), 4698–4706.
[5] Singaravel, M. R., and Daniel, S. A. (2015). MPPT with single DC–DC converter and inverter for grid-connected hybrid wind-driven PMSG–PV system. *IEEE Transactions on Industrial Electronics,* 62(8), 4849–4857.
[6] Wei, C., Zhang, Z., Qiao, W., and Qu, L. (2016). An adaptive network-based reinforcement learning method for MPPT control of PMSG wind energy conversion systems. *IEEE Transactions on Power Electronics,* 31(11), 7837–7848.
[7] OðÐuz, Y., Güney, Ý., and Çalýk, H. (2013). Power quality control and design of power converter for variable-speed wind energy conversion system with permanent-magnet synchronous generator. *The Scientific World Journal,* 2013.
[8] Mendis, N., Muttaqi, K. M., Sayeef, S., and Perera, S. (2012). Standalone operation of wind turbine-based variable speed generators with maximum power extraction capability. *IEEE Transactions on Energy Conversion,* 27(4), 822–834.
[9] Wang, Y., Meng, J., Zhang, X., and Xu, L. (2015). Control of PMSG-based wind turbines for system inertial response and power oscillation damping. *IEEE Transactions on Sustainable Energy,* 6(2), 565–574.
[10] Zhang, Z., Zhao, Y., Qiao, W., and Qu, L. (2014). A space-vector-modulated sensorless direct-torque control for direct-drive PMSG wind turbines. *IEEE Transactions on Industry Applications,* 50(4), 2331–2341.
[11] Shi, Y. T., Qi, K., Shu-juan, Q., De-hui, S., and Zheng-xi, L. (2014). Optimal control of PMSG wind energy convert system based on MPPT and ADRC control structure. In *2014 33rd Chinese Control Conference (CCC),* (pp. 6907–6912). IEEE.
[12] Zhou, Z., Scuiller, F., Charpentier, J. F., Benbouzid, M. E. H., and Tang, T. (2015). Power control of a nonpitchable PMSG-based marine current turbine at overrated current speed with flux-weakening strategy. *IEEE journal of oceanic engineering,* 40(3), 536–545.

[13] Singh, M., Khadkikar, V., and Chandra, A. (2011). Grid synchronisation with harmonics and reactive power compensation capability of a permanent magnet synchronous generator-based variable speed wind energy conversion system. *IET Power Electronics,* 4(1), 122–130.

[14] Adhikari, J., Prasanna, I. V., Ponraj, G., and Panda, S. K. (2017). Modeling, Design, and Implementation of a Power Conversion System for Small-Scale High-Altitude Wind Power Generating System. IEEE Transactions on Industry Applications, 53(1), 283–295.

[15] Lu, C., Park, S. P., Raghunathan, V., and Roy, K. (2012). Low-overhead maximum power point tracking for micro-scale solar energy harvesting systems. In *2012 25th International Conference on VLSI Design (VLSID)*, (pp. 215–220). IEEE.

[16] Kolar, J. W., and Friedli, T. (2013). The essence of three-phase PFC rectifier systems—Part I. *IEEE Transactions on Power Electronics,* 28(1), 176–198.

[17] Chen, H., and Aliprantis, D. C. (2010). Induction generator with Vienna rectifier: Feasibility study for wind power generation. In *2010 XIX International Conference on Electrical Machines (ICEM),* (pp. 1–6). IEEE.

[18] Krahenbuhl, D., Zwyssig, C., and Kolar, J. W. (2011). Half-controlled boost rectifier for low-power high-speed permanent-magnet generators. *IEEE Transactions on Industrial Electronics,* 58(1), 5066–5075.

[19] Islam, M. H., and Razzak, M. A. (2016). Design of a modified Vienna rectifier for power factor correction under different three phase loads. In *2016, 5th International Conference on Informatics, Electronics and Vision (ICIEV* (pp. 764–770). IEEE.

[20] Ramasamy, S., and Reddy, D. (2017). Design of a Three-phase Boost Type Vienna Rectifier for 1kW Wind Energy Conversion System. *International Journal of Renewable Energy Research (IJRER),* 7(4), 1909–1918.

[21] Leibl, M., Kolar, J. W., and Deuringer, J. (2017). Sinusoidal Input Current Discontinuous Conduction Mode Control of the VIENNA Rectifier. *IEEE Transactions on Power Electronics,* 32(11), 8800–8812.

[22] Foureaux, N. C., Oliveira, J. H., de Oliveira, F. D., Cardoso Filho, B. D. J., and de Faria, R. S. (2015). Command Generation for Wide-Range Operation of Hysteresis-Controlled Vienna Rectifiers. *IEEE Transactions on Industry Applications,* 51(3), 2373–2380.

[23] Adhikari, J., Prasanna, I. V., and Panda, S. K. (2017). Reduction of Input Current Harmonic Distortions and Balancing of Output Voltages of the

Vienna Rectifier under Supply Voltage Disturbances. *IEEE Transactions on Power Electronics,* 32(7), 5802–5812.

[24] Ma, H., Xie, Y., Sun, B., and Mo, L. (2015). Modeling and direct power control method of Vienna rectifiers using the sliding mode control approach. *Journal of Power Electronics,* 15(1), 190–201.

[25] Zhang, M., Li, B., Hang, L., Tolbert, L. M., and Lu, Z. (2012). Performance study for high power density three-phase Vienna PFC rectifier by using SVPWM control method. In *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC),* (pp. 1187–1191). IEEE.

[26] Ma, H., Xie, Y., Yang, Y., and Shi, Z. (2014). Voltage Balance control of Vienna-type rectifier using SVPWM based on 60 Coordinate System. In *2014 17th International Conference on Electrical Machines and Systems (ICEMS)*, (pp. 3187–3191). IEEE.

[27] Rajaei, A., Mohamadian, M., and Varjani, A. Y. (2013). Vienna-rectifier-based direct torque control of PMSG for wind energy application. *IEEE transactions on industrial electronics,* 60(7), 2919–2929.

[28] Adhikari, J., Prasanna, I. V., and Panda, S. K. (2016). Voltage oriented control of the three-level Vienna rectifier using vector control method. In *2016 IEEE Applied Power Electronics Conference and Exposition (APEC),* (pp. 9–16). IEEE.

[29] Li, X., Sun, Y., Wang, H., Su, M., and Huang, S. (2017). A Hybrid Control Scheme for three-phase Vienna Rectifiers. *IEEE Transactions on Power Electronics,* 33(1), 629–640.

[30] Lin, W. M., Hong, C. M., Ou, T. C., and Chiu, T. M. (2011). Hybrid intelligent control of PMSG wind generation system using pitch angle control with RBFN. *Energy Conversion and Management,* 52(2), 1244–1251.

[31] Reddy, D., and Ramasamy, S. (2018). Design of RBFN Controller Based Boost Type Vienna Rectifier for Grid-Tied Wind Energy Conversion System. *IEEE Access,* 6, 3167–3175.

[32] Saravanan, S., and Babu, N. R. (2016). RBFN based MPPT algorithm for PV system with high step up converter. *Energy conversion and Management,* 122, 239–251.

[33] Reddy, D., and Ramasamy, S. (2017). Single Stage Energy Conversion through an RBFN Controller based Boost Type Vienna Rectifier in the Wind Turbine System. *Gazi University Journal of Science*, 30(4), 253–266.

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