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Single Stage Energy Conversion through RBFN Controller based Boost Type Vienna Rectifier for Wind Turbine System

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Abstract

This paper presents, a Radial Basis Function Network (RBFN) controller based boost type Vienna Rectifier, which is engaged in a single stage energy conversion in the wind turbine system (WTS). The boost type Vienna Rectifier converts AC into DC with an enhanced voltage of a 230V AC to 400V DC in a single stage conversion, along with the benefits of the low voltage stress across switches (50% of DC-link voltage), reduced harmonics, sinusoidal input current shaping, and improved power factor. This sort of AC/DC conversion is adequate for low voltage DC distribution, telecommunication systems, and data centers etc. This paper presents the comparative analysis of single stage Vienna Rectifier over two-stage energy conversion (Diode bridge rectifier + Boost converter) for 1kW wind turbine system and results are validated in MATLAB/Simulink.

1. INTRODUCTION

The wind turbine systems are gaining more attention due to rapid developments in low cost and highly efficient wind turbines design, generators and power conversion units. Generally, there are two types of wind turbine system employed, which are variable speed turbine system and fixed speed turbine system. The variable speed turbine system is more advantageous than fixed speed turbine system due to high efficiency, enhanced power quality [1, 2] and MPPT (Maximum Power Point Tracking) [3-5]. The PMSG (Permanent Magnet Synchronous Generator) [6, 7] is a most preferable mechanical to electrical energy conversion system, which is the best alternative over DFIG (Double Fed Induction Generator) to the small-scale [8] wind power systems.

In most of the cases, a two-stage conversion (Diode bridge rectifier + Boost converter) [9] is employed to convert generated AC from the WTS into DC, i.e. AC is converted into DC through the diode rectifier and the DC/DC power conversion is done by the boost converter to obtain the required voltage levels. Apart from this a single stage AC/DC power conversion is possible with enhanced voltage levels by the boost type Vienna Rectifier [10]. It is preferable to AC/DC power conversion where unidirectional power flow is adequate. The boost type Vienna Rectifier offers low voltage stress across switches up to 50% of DC-link voltage, reduced harmonics [11], power factor [12,13] near to unity, sinusoidal input current shaping [14] and enhanced power quality [15]etc. The Vienna Rectifier is invented by J.W. Kolar in the year of 1993 for AC/DC power conversion. In the present energy scenario, power loss reduction is one of the most significant parameters in the power transmission. Therefore, a 400V DC distribution [16] is more advancement in telecommunication systems [17] data centers and low voltage DC distribution [18] etc.

In this paper, a single stage energy conversion is presented through RBFN controller [19-22] based boost type Vienna Rectifier over a two-stage energy conversion with enhanced voltage level [23, 24] and reduced total harmonic distortion (THD) [25]. An intelligent neural network based RBFN

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controller is employed over conventional controllers such as sliding mode control [26, 27], model predictive control [28] and SVPWM (Space Vector Pulse Width Modulation) [29-31] etc, for a three switch Vienna Rectifier in order to achieve AC/DC conversion and required voltage level (230V AC to 400V DC) with a single stage conversion in a 1kW wind turbine system.

2. WIND TURBINE SYSTEM

The wind system mainly consists of turbine blades, gearbox and turbine generator, where the wind kinetic energy is converted into mechanical energy through low-speed turbine blades. The mechanical energy is then transformed into electrical energy by the turbine generator, which is connected to external power conversion unit to transform AC to DC for DC distribution and/or DC loads. The PMSG is a preferable alternator in the steam- turbine, gas-turbine, and small hydro turbine and wind turbine applications due to the effective performance of the machine even for the large input variations. And also the machine is very compact due to the absence of slip-rings, contact brushes and DC supply for the field excitation, when compared with the induction generators (IGs) and doubly-fed induction generators (DFIGs).

The turbine mechanical torque [1, 2] is expressed as,

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

Where ρ =Air density (kg/m3), C_p = Power Coefficient, A= Sweep area of turbine blades (m^2), β = Pitch angle (deg), v = Wind speed (m/s), ω =Rotor angular velocity (rad/sec) and λ = Tip-ratio. λ can be expressed as,

$$\lambda = \frac{\omega_m r}{v}\text{, where r = Rotor radius (m)} \tag{2}$$

Therefore, the mechanical power (P_m) developed by the turbine [1, 2] is taken as,

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

Similarly, the mechanical energy converts into electrical energy using PMSG at high speed and its mathematical modeling can also be derived.
The electrical energy (voltage) developed by the PMSG is [1, 2] 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 current and voltage respectively, L_d and L_q are the *d-q* axis inductance of generator, ψ_f = Magnetic flux (w_b), ω_e = Electrical speed of the generator, R_g= Generator resistance. The ω_e is [1, 2] 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 (T_{Elec}) produced by the generator is [1, 2] 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 [1, 2] 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 generation voltage is [25, 30] written as,

$$\left.\begin{aligned} E_{AN} &= E_m \sin(wt) \\ E_{BN} &= E_m \sin(wt - \frac{2\pi}{3}) \\ E_{CN} &= E_m \sin(wt + \frac{2\pi}{3}) \end{aligned}\right\} \quad (9)$$

3. MODEL DESCRIPTION

In this paper, a comparative performance analysis of two types of conversion units is presented. The first one is a two-stage conversion with diode bridge rectifier + boost converter unit and the second one is a single stage conversion unit with the boost type Vienna Rectifier. In both the cases, wind turbine system is considered as supply system and a neural network-radial basis function network is used for converter control based on the input data.

3.1. Two Stage Conversion

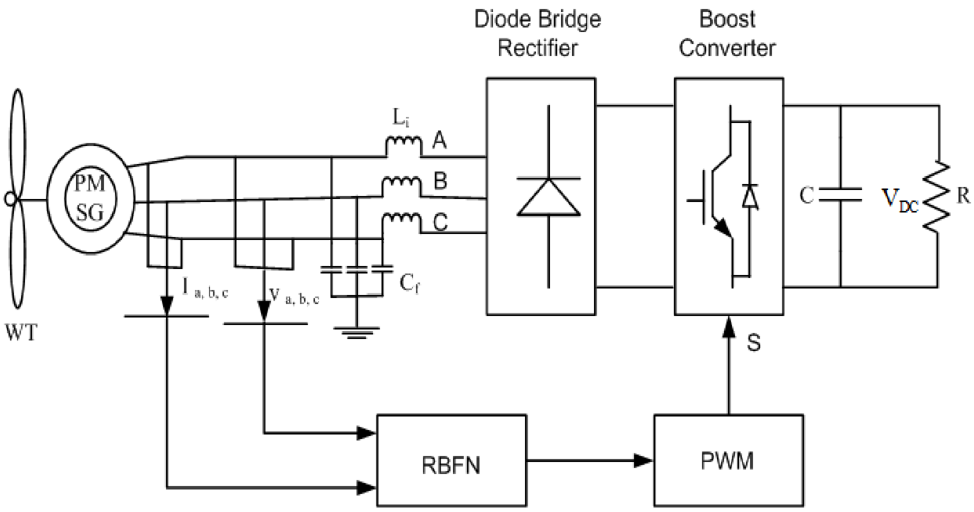

Figure1. *Model diagram of a two-stage conversion unit of WTS*

The block diagram of a two-stage conversion (Diode bridge rectifier + Boost converter) is depicted in Fig 1, which contains the wind conversion unit, bridge rectifier unit and boost converter unit etc. In this, the alternative current (AC) produced by the PMSG of WTS is connected to the diode bridge rectifier to convert into direct current (DC). Then the converted DC is step up to 400V DC through the boost converter with the proper switching signal generated by RBFN + PWM controller unit, where the controller output is the duty cycle (D). The duty cycle of the switch is predicted by the input and output voltage values of the boost converter, which is expressed as,

$$D = 1 - \frac{V_{in}}{V_{out}} \quad (10)$$

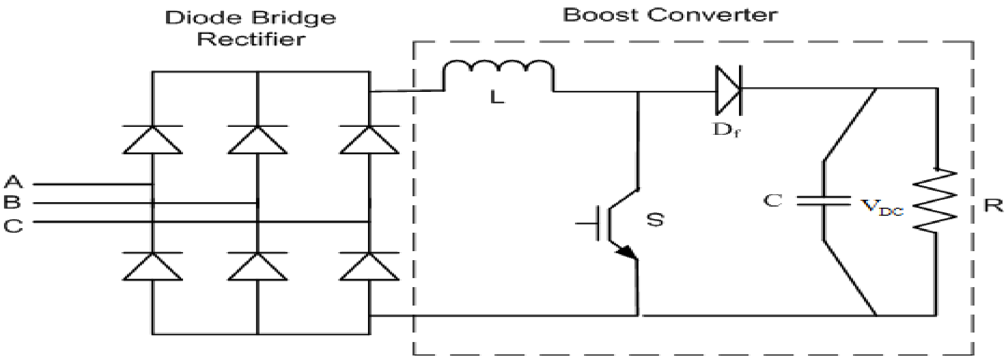

Figure2. *Two-stage conversion unit of WTS*

The conversion of energy takes two stages as shown in Fig 2, in which diode bridge rectifier (consists of 6-diodes) is used for AC/DC and boost converter (includes Switch-S, inductor-L, Diode-D_f and Capacitor-C) is used for DC/DC conversion. But this results in reduced power quality and only preferable for very low voltage AC/DC conversion systems. In another hand, for medium and high voltage conversion systems; the AC/DC conversion units are required with improved power quality, reduced harmonics, and low switching losses.

3.2. Proposed Single Stage Conversion

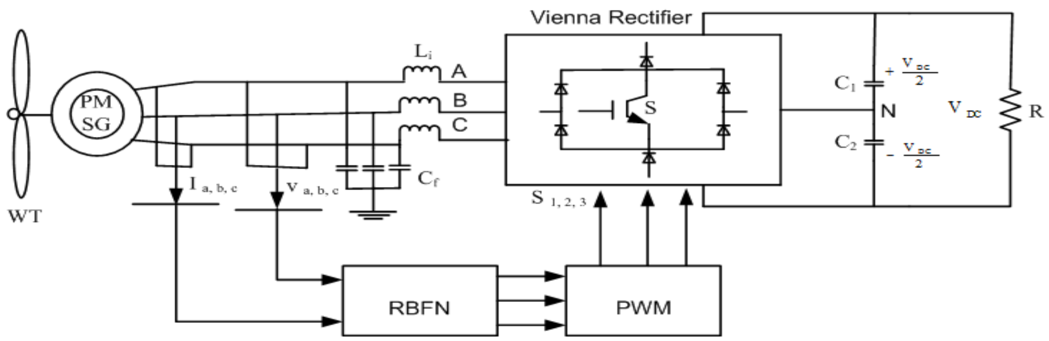

Figure 3. *Proposed single stage conversion unit of WTS*

In a single stage conversion (Vienna Rectifier) as shown in Fig 3, the alternative current (AC) produced by the PMSG of WTS is connected directly to the boost type Vienna Rectifier, where AC is converted into DC with an increased level of output voltage. The Vienna Rectifier is incorporated with three power switches and 18-diodes, the output capacitor is split into two as C_1 and C_2, therefore the total output voltage is the sum of the voltage across C_1 and C_2. This voltage control ensures the balanced output voltage and reduces 50% of the voltage stress across the switches.

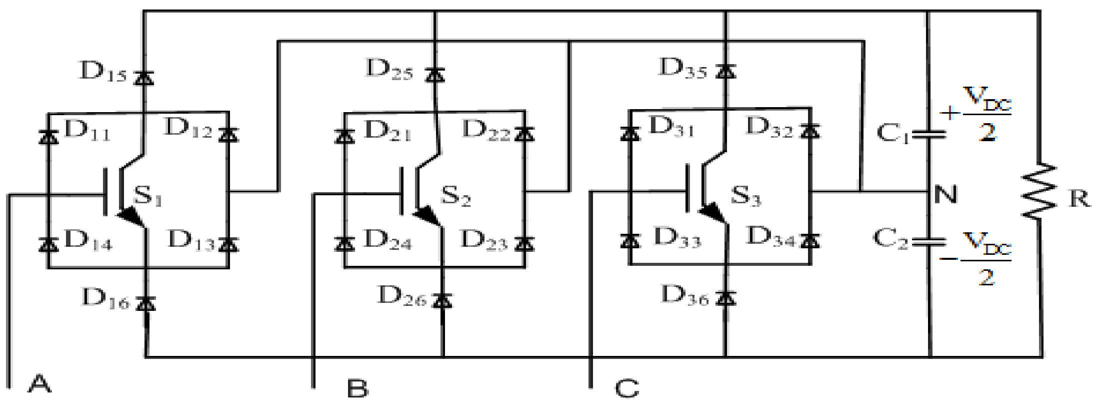

Figure 4.*Circuit diagram of Vienna Rectifier*

The proposed circuit is depicted in Fig 4, in which the circuit operation is explained for phase-A as follows; for S_1=0 (switch-OFF), the current flows through the diodes (D_{11}, D_{15}) from phase (A) to neutral (N) when I_A is positive and current flows through the diodes (D_{16}, D_{14}) from N to A when I_A is negative. Similarly for S_1=1 (switch-ON), the current flows through the switch S_1 (D_{11}-S_1-D_{13}) from A to N when I_A is positive and current flows the switch S_1 (D_{12}-S_1-D_{14}) from N to A when I_A is negative. In the manner, the circuit operation can be expressed for switch S2 and S3 i.e. for all three phase voltage and current equations. The triggering pattern of proposed circuit is shown in below Table 1 and the output voltage are represented as +1 ($+\frac{V_{DC}}{2}$) and -1($-\frac{V_{DC}}{2}$) with reference to the input terminal voltages ($V_{AN, BN, CN}$).

The state-space equations for the input side voltage of rectifier are [25, 30] written as,

$$\left.\begin{aligned} E_{AN} &= Ri_A + L\frac{di_A}{dt} + V_{AN} \\ E_{BN} &= Ri_B + L\frac{di_B}{dt} + V_{BN} \\ E_{CN} &= Ri_C + L\frac{di_C}{dt} + V_{CN} \end{aligned}\right\} \quad (11)$$

Where R= source resistance, L=source inductance and $E_{AN,\ BN,\ CN}$ = Vienna rectifier input 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 [25, 30] which can be written as the function of current and (ON-state) state of the switch].

$$\left.\begin{aligned} V_{AN} &= \frac{V_{DC}}{2}\,\mathrm{sgn}(i_A)(1-S_1) \\ V_{BN} &= \frac{V_{DC}}{2}\,\mathrm{sgn}\,(i_B)(1-S_2) \\ V_{CN} &= \frac{V_{DC}}{2}\,\mathrm{sgn}\,(i_c)(1-S_3) \end{aligned}\right\} \quad (12)$$

Where 'sgn' is the signum function of $i_{A,B,C}$ and the output capacitor voltage of the Vienna rectifier is split into V_{DC1} ($+\frac{V_{DC}}{2}$) and V_{DC2} ($-\frac{V_{DC}}{2}$) at C_1 and C_2 respectively. This voltage control ensures the balanced output and reduces to half of the DC – link voltage across the switches. Therefore, the DC – link capacitor voltage is [25, 30] written as,

$$\left.\begin{aligned} V_{DC} &= V_{DC1} + V_{DC2} \\ \Delta V &= V_{DC1} - V_{DC2} \end{aligned}\right\} \quad (13)$$

Table 1. *Switching Pattern*

S1	S2	S3	VAN	VBN	VCN
0	0	0	+1	-1	-1
0	0	1	+1	-1	0
0	1	0	+1	0	-1
0	1	1	+1	0	0
1	0	0	0	-1	-1
1	0	1	0	-1	0
1	1	0	0	0	-1
1	1	1	0	0	0

The current through the output capacitor is [25, 30] written as,

$$\left.\begin{aligned} i_{C1} &= C_1 \frac{d\,V_{DC1}}{dt} \\ i_{C2} &= C_2 \frac{d\,V_{DC2}}{dt} \end{aligned}\right\} \tag{14}$$

4. RBFN CONTROLLER

An artificial intelligent RBFN based controllers employed for the fast dynamic response over the conventional converter controllers. The conventional controllers are having more pitfalls such as complex in controller design, slow dynamic response and heavy components cost. It is a similar kind of network as the feedforward network, having both supervised and unsupervised phases. It is a three layer network called input layer, a hidden layer, and an output layer. The hidden layer activation functions are 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) to RBFN controller are voltage and current, and the output variable (y_k) is a duty cycle (D). The controller output as depicted in Fig 5 is given to the PWM (Pulse Width Modulation) pulse generator which generates the switching pattern for the Vienna Rectifier. The parameters considered for 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 [19-22] represented as,

$$net_i^{\,1} = x_i^{\,1}(N) \tag{15}$$

$$y_i^{\,1}(N) = f_i^{\,1}(net_i^{\,1}(N)) = net_i^{\,1}(N) \text{, where i=1, 2} \tag{16}$$

b) **Hidden layer:** In this, a Gaussian function is performed for each and every node i.e. RBFN is used as a membership function. The net input and output for the hidden layer is [19-22] represented as,

$$net_j^{\,2}(N) = (X - M_j)^T \sum_j (X - M_j) \tag{17}$$

$$y_j^{\,2}(N) = f_i^{\,2}(net_j^{\,2}(N)) = Exp(net_j^{\,2}(N)) \text{, j=1, 2.....9} \tag{18}$$

Where $M_j = [m_{1j} m_{2j} ....m_{ij}]^T$ = Mean

And standard deviation = $\sum_j = diag[\frac{1}{\sigma_{1j}^{\;2}} \frac{1}{\sigma_{2j}^{\;2}} .... \frac{1}{\sigma_{ij}^{\;2}}]^T$

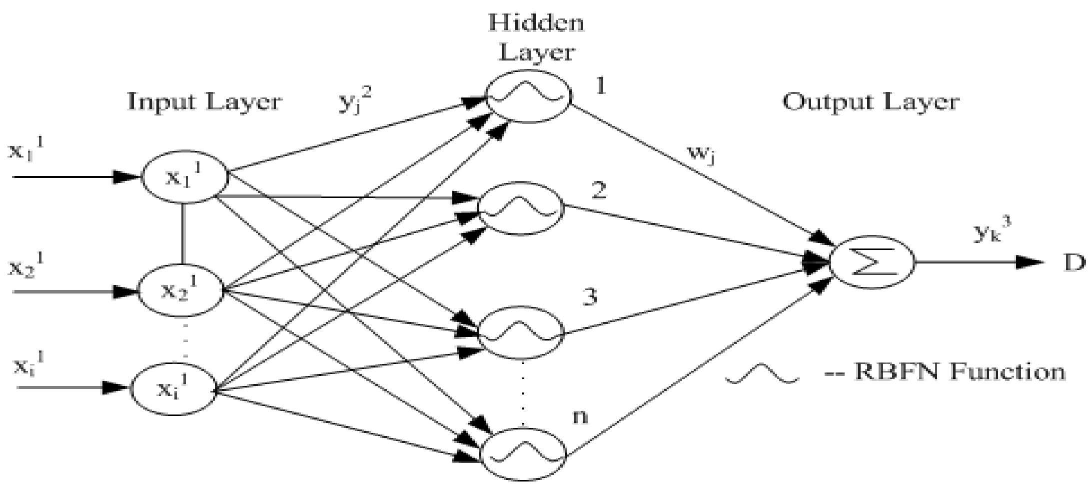

Figure 5.*Control model of RBF*

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 ∑ [19-22], therefore

$$net_k^3 = \sum W_j y_j^2(N) \quad (19)$$

$$y_k^3(N) = f_k^3(net_k^3(N)) = net_k^3(N) = D \quad (20)$$

Table 2. *Parameter configuration of RBFN*

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

5. RESULT ANALYSIS

In this paper, a 230V/1kW wind turbine system considered as an input source for both two-stage and single stage conversion units. Both the circuits are designed for 400V/1kW DC load from a 230V AC generated PMSG based WTS at base speed. The design parameters considered for both the cases are tabulated in Table 3, the wind input (m/s) and turbine speed (W_m) (pu) is shown in Fig6. The wind input data is considered as 9 m/s to 16 m/s and the corresponding output parameters of PMSG are taken as input data to train the RBFN controller. The three-phase peak voltage is taken for the Vienna Rectifier input from the PMSG as depicted in Fig 7. The resultant active power (P_{AC}), apparent power (P_{APP}) and reactive power (P_{Rec}) output of PMSG are shown in Fig 8.

Table 3*. Design parameters*

S. No	Circuit parameters	Ratings
1	Three phase input voltage ($V_{A, B, C}$)	230V
2	Maximum Output Voltage	400V
3	Power rating for wind unit	1kW
4	Input inductance ($L_i = L_{A, B, C}$)	10mH
5	Input filter capacitance ($C_f = C_{A, B, C}$)	100uF
6	DC-link capacitance ($C = C_1 + C_2$)	200 µF
7	Diode resistance (R_{ON})	0.001Ω
8	Load resistance (R)	160Ω
9	Maximum output power (P)	1kW

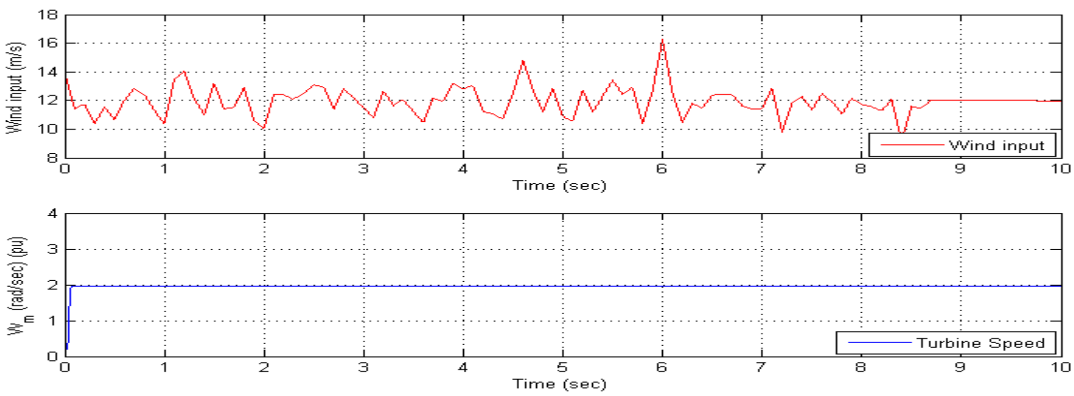

Figure 6. *Simulink results of wind input (m/s) and turbine speed (Wm) (pu)*

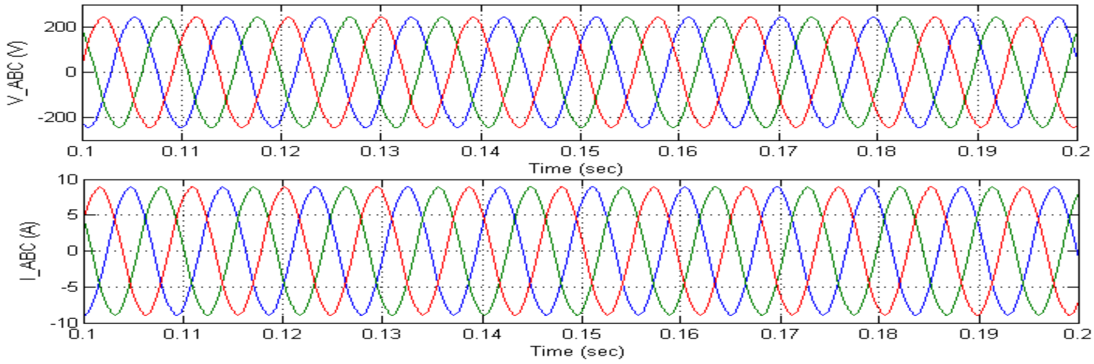

Figure 7. *Simulink results of three-phase supply of WTS*

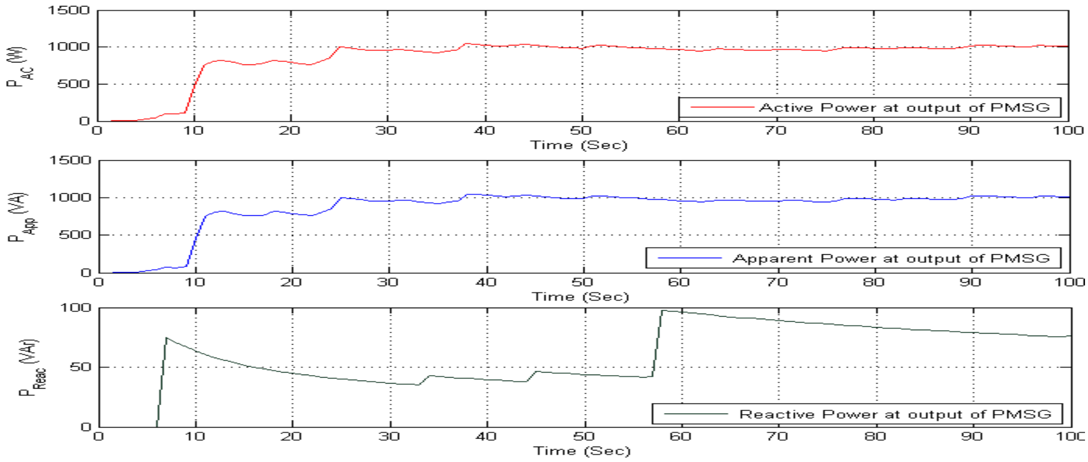

Figure 8. *Simulink results of output Active power (P_{AC}), Apparent power (P_{APP}) and Reactive power (P_{Rec}) of PMSG*

5.1 Result Analysis of A Two Stage Conversion

The circuit parameters as mentioned in Table 3, are considered for the performance analysis of a two-stage conversion system. The voltage across the DC-link capacitor is 377.9V, which is equal to the DC output voltage as shown in Fig 9. The resultant output DC voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) using RBFN controller for a two-stage conversion are depicted in Fig 10. The voltage (V_{sw}), current (I_{sw}) and power (P_{sw}) at the switch (S) are depicted in Fig 11, from which 1.428Wof power loss across the switch is noticed. Similarly, the source side %THD of WTS in a two-stage conversion is taken from the FFT (Fast Fourier Transform) window as shown in Fig.12.

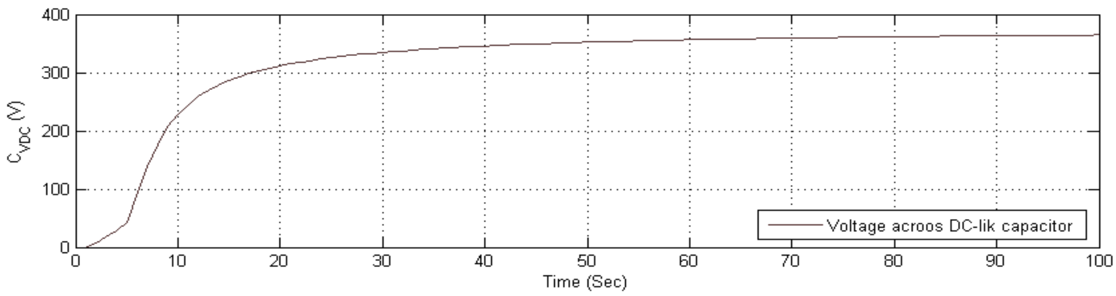

Figure 9. *Simulink result of DC-link voltage (C_{VDC})*

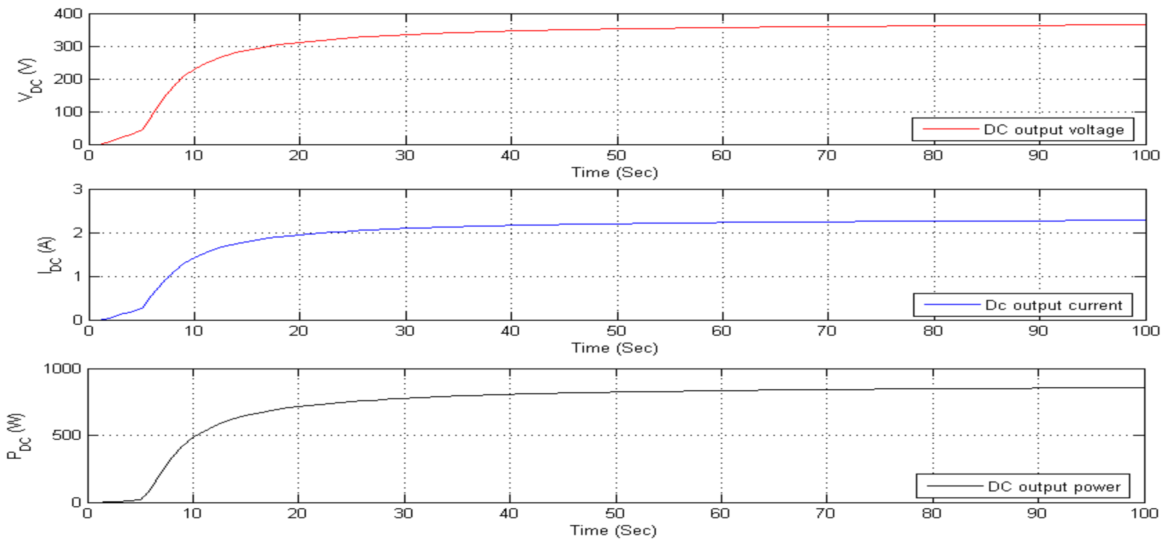

Figure 10. *Simulink results of output DC voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) using RBFN controller for a two-stage conversion*

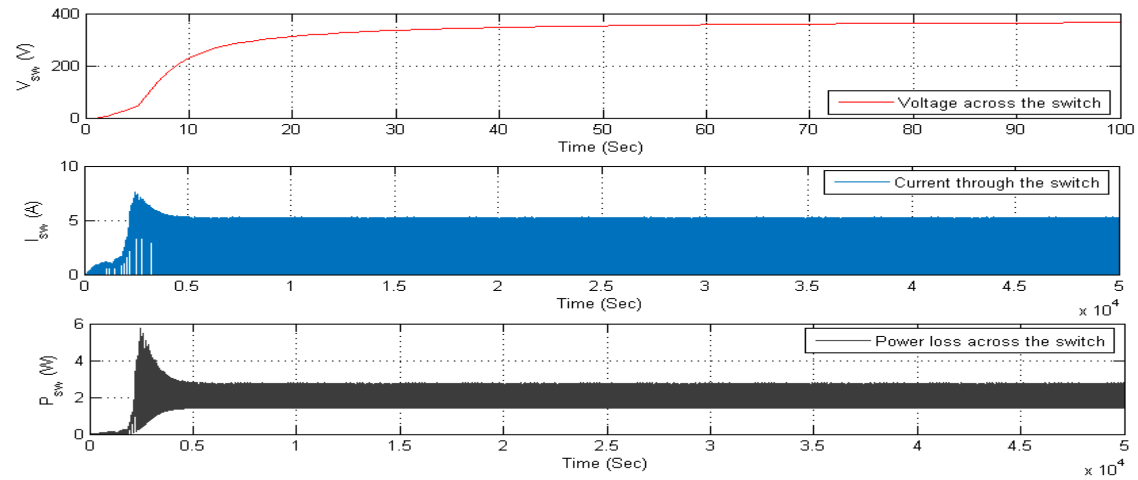

Figure 11. *Simulink results of voltage (V_{sw}), current (I_{sw}) and power (P_{sw}) at the switch (S)*

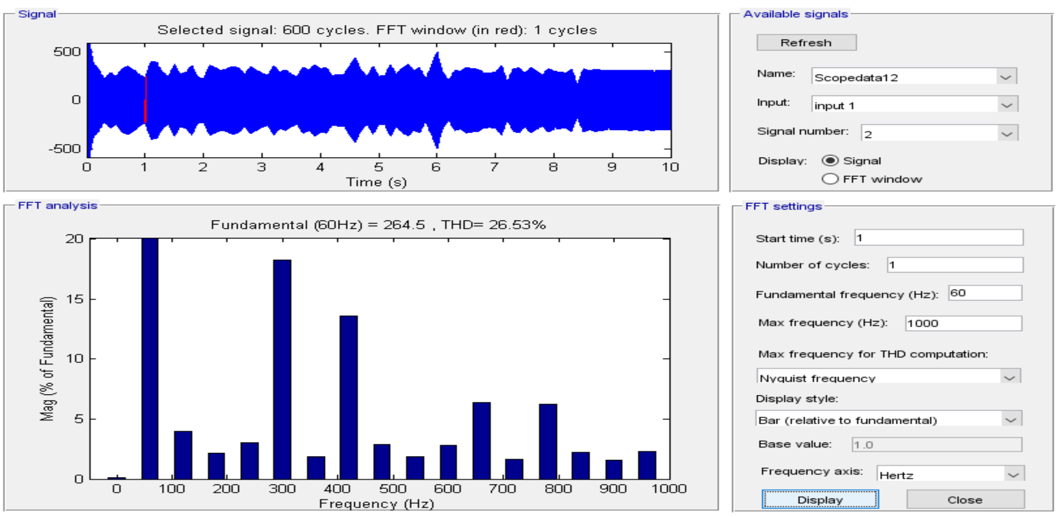

Figure 12. *FFT window of a two-stage conversion unit for source side %THD*

5.2 Result Analysis of A Single Stage Conversion

The performance analysis of a single stage conversion system is compared to the two-stage conversion system, and the resultant output DC voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) using RBFN controller for the Vienna Rectifier are depicted in Fig 13. The voltage across the DC-link capacitor is split into two voltages at capacitor C_1 and C_2as shown in Fig 14. This results in a reduction of voltage stress (186.7V) across the switch as depicted in Fig 15, from which 0.348W/phase of power loss across the switch is noticed. Whereas, in case of a two-stage conversion system, the voltage stress (377.9V) and the power loss (1.428W) across the switch are very high.

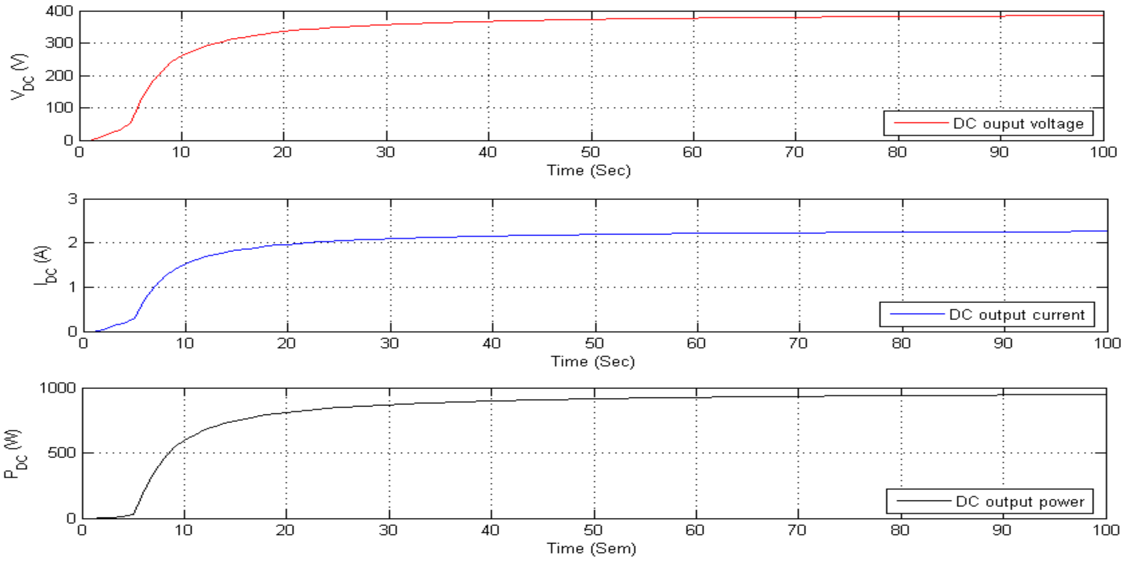

Figure 13. *Simulink results of output DC voltage (V_{DC}), current (I_{DC}) and power (P_{DC}) using RBFN controller for a single stage conversion*

Similarly, in case of a conventional SVPWM (Space Vector Pulse Width Modulation) controller based Vienna Rectifier, the voltage stress (278.2V) and power loss (0.778W/phase) across the switch are more when compared with RBFN controller based single stage conversion system. Therefore, the overall performance of a proposed single stage conversion in the wind turbine system is better than the conventional two-stage conversion and SVPWM based single stage conversion systems.

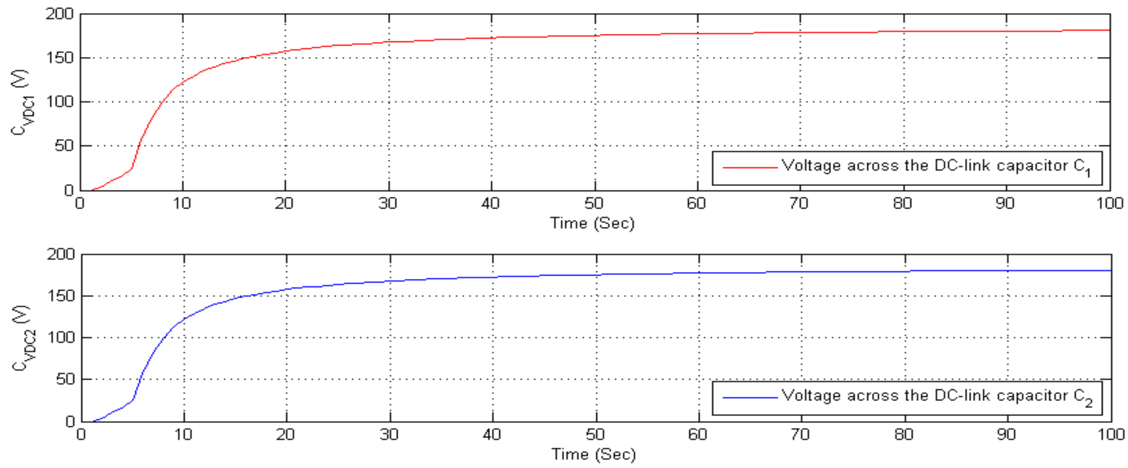

Figure 14. *Simulink results of DC-link voltage at C_1 and C_2*

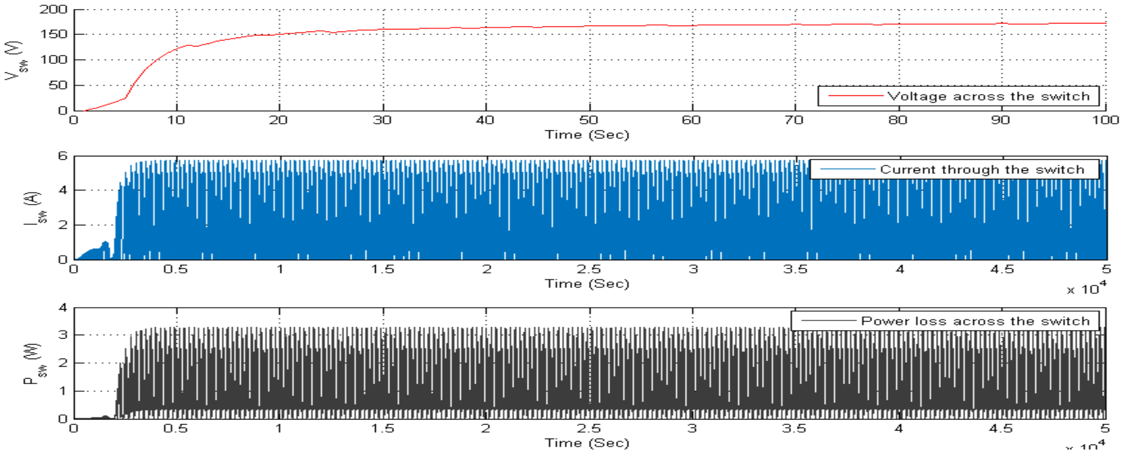

Figure 15. *Simulink results of voltage (V_{sw}), current (I_{sw}) and power (P_{sw}) at the switch (S_1)*

The source side %THD of WTS in a single stage conversion is taken from the FFT (Fast Fourier Transform) window as shown in Fig 16, which presents the extremely improved %THD of a single stage conversion system.

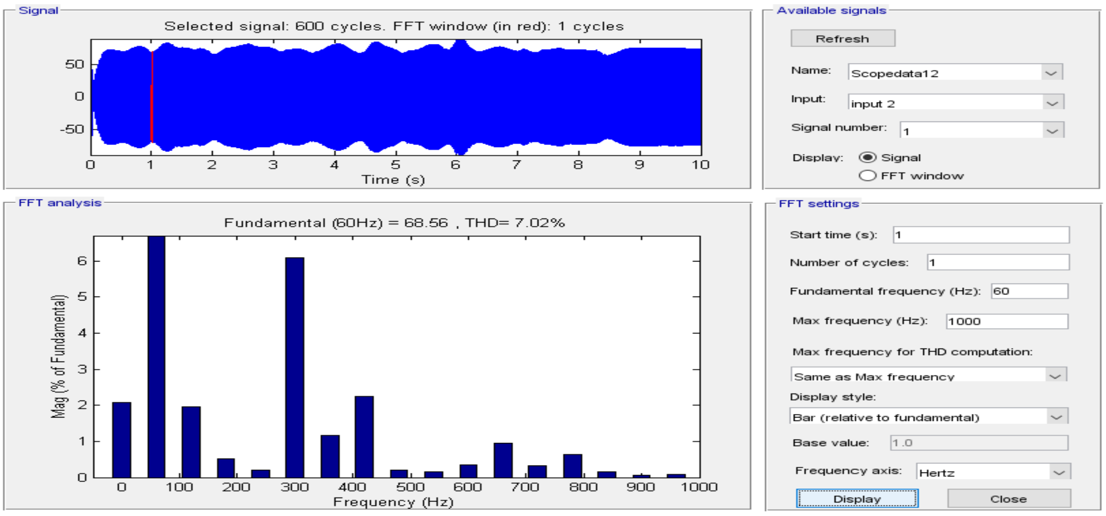

Figure16. *FFT window of a single-stage conversion unit for source side %THD*

6. CONCLUSION

This paper presents a single stage energy conversion through RBFN controller based boost type Vienna Rectifier over a two-stage conversion (Diode Bridge Rectifier + Boost converter). The comparative analysis shows that the single stage (Boost type Vienna Rectifier) conversion has better performance than the two-stage energy conversion system as tabulated in Table 4 and 5. The boost type Vienna Rectifier is essential for a unidirectional power flow with reduced total harmonic distortion, enhanced power factor, sinusoidal input current shaping, and low switching losses. An AC/DC conversion unit plays a vital role in the DC distribution, telecommunication, data centers, HVDC transmission, low voltage domestic DC loads and also high voltage DC loads of industrial applications.

Table 4. *Comparative result analysis of conversion units*

Power Conversion Topology	V_{DC} (V)	I_{DC} (A)	P_{DC} (W)	Source side % THD
Diode bridge Rectifier + Boost converter	377.9	2.357	888.7	26.53
Boost type Vienna Rectifier	397.3	2.332	982.8	7.02

Table 5. *Comparative voltage, current and power values per switch*

Power Conversion Topology	V_{sw} (V)	I_{sw} (A)	Power loss across the switch, P_{sw} (W)
Diode bridge Rectifier + Boost converter	377.9	0.00378	1.428
Boost type Vienna Rectifier	186.7	0.00187	0.348

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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