Design of a Three-phase Boost Type Vienna Rectifier for 1kW Wind Energy Conversion System

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Abstract- This paper accords a novel 3-ϕ (three-phase) boost type Vienna rectifier for AC/DC power conversion. The proposed circuit topology is employed for the power conversion of AC into DC with the enhanced output voltage and reduced switching losses. It is a preferable front side conversion unit for AC power generated renewable energy systems and also for AC input fed DC applications. Vienna rectifier is adequate where a unidirectional power flow is essential in the system with high power density and low voltage stress across the switches. The AC to DC Vienna Rectifier provides approximately a unity PF (Power Factor), sinusoidal input current and low THD (Total Harmonic Distortion) at the supply side. İn this paper, the Vienna Rectifier is engaged in the conversion of a 230V AC to 400V DC with 50% reduction of voltage stress across the switches. The SVPWM (Space Vector Pulse Width Modulation) controller based proposed circuit topology is designed for 1kW PMSG (Permanent Magnet Synchronous Generator) wind energy conversion system (WECS) in MATLAB/Simulink and results are validated.

Keywords- Wind Energy Conversion System (WECS), PMSG, Vienna Rectifier, DC-link voltage, SVPWM Controller.

1. Introduction

In the existing energy scenario, the lossless power distribution is at most dominant aspect due to a consistent shortage of fossil fuels. The distributed energy recourses (DERs) are made effectively utilized among the natural resources due to enormous advancement in power electronic converters. Various power conversion systems have been developed by the researchers to track and convert the energy from the renewable energy resources i.e. from wind, solar, fuel cell and tidal etc. The AC/DC converter topologies are proposed by the researchers on diode bridge rectifiers, six-pulse controlled bridge rectifiers and three-level neutral point clamped (NPC) rectifiers [1] etc. But the switching losses and input current harmonic distortions are increases as the number of active power switches increases in the circuit. The researchers have proposed a hybrid Cuk-SEPIC converter strategy [2] to reduce the switching losses. But the number of passive elements are more in the circuit which reduces the overall efficiency of the system. The interleaved boost converter topologies are proposed in [3] in order to reduce the ripple current and increase the voltage gain. But the interleaved boost converter is incorporated with the coupled inductor topology which reduces the overall efficiency and makes the system bulky and costly. In order to overcome these issues, a 3-ϕ boost type Vienna rectifier is presented to rectify and regulate the supply voltage of AC system. Similarly, power factor correction (PFC) [4], high power density, low voltage stresses across the switch [5], harmonic reduction [6, 7, 8], voltage balance [9] and overall conversion efficiency are the possible considerations to enhance the system performance by the Vienna rectifier. The Z-source inverter with DVR (Dynamic Voltage Restorer) and resonant fault current limiter circuit topologies have proposed for power quality improvement and protection of DERs in [10, 11] respectively. A half-controlled bridge rectifier is used for a 3-ϕ system based on PWM (pulse width modulation) control strategy [12], as it's integrated with the low power high-speed permanent magnet synchronous generator (PMSG) [13, 14, 15] the controlling of overall system at higher speed is a considerable factor to achieve a stable system operation. The electrical spring control strategy is proposed [16, 17] for the renewable energy sources with battery storage when there is a deficit in power generation due to environmental changes.

A 3-ϕ three switch buck type PWM rectifier [18, 19], is preferred with combined EMI (Electromagnetic

Interference) filter design concept to avoid the noise disturbance produced by the supply system and/or surrounding unit components, the design of EMI filter section with large inductors and capacitors makes the system very complex and so that the size of the filter design need to be minimized with the design modifications [20]. A closed loop 12-pulse rectifier is used with EMI filter [21, 22, 23], for low input current distortions, where the control of voltage cannot be possible by the diode rectifier unit. A 5kW 3-ϕ PFC (power factor correction) buck type rectifier is modeled [24, 25], for 400V DC distribution system which can step down to 48V for low voltage applications like data centers and telecommunications [26, 27] etc.

Similarly, ultra-flat magnetic components with PCB (Printed Circuit Board) integrated core are explained [28], for future low voltage & high power density appliances such as LED drivers, screen power sources, and ultra-flat conversion devices. In [29] the diode rectifier with the current injected network (CIN) and current injected device (CID) at the input side reduces the overall performance because of power dissipation in CIN resistors. Apart from all the issues in conversion system, a Vienna rectifier with SVPWM current control strategy [30, 31] is initiated in this paper to minimize the power loss across switches, to improve the input current near to sine wave, to maintain the power factor at unity and reduced THD.

2. Proposed Model Description

The proposed model is carried out primly by the WECS and Vienna rectifier unit as shown in Fig.1, where the kinetic energy is transformed into mechanical energy and then it is converted into electrical energy of AC form by the WECS. The generated AC voltage can be converted into DC voltage by the Vienna rectifier by enhancing the voltage level at the output side which is connected to DC load of required rating and/or to the DC distribution system.

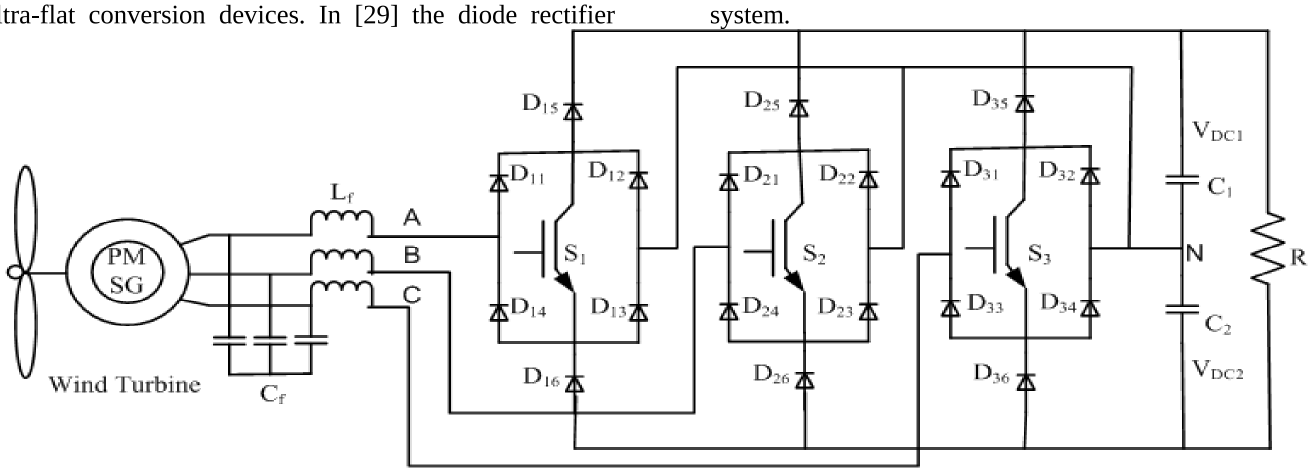

Fig.1 Proposed circuit model of a 3-ϕ boost type Vienna Rectifier

2.1 *Wind energy conversion system*

In the process of effective energy production, the chief criterion is to fulfill the power demand of end users with the low cost. Power can be produced by the available renewable and non-renewable resources of distinct forms. Apart from conventional resources, many renewable resources are available in nature; one of them is wind energy which plays a crucial role in the power system. In this system, the kinetic energy is transformed into mechanical energy and then it is converted to electrical energy. WECS consists of the mechanical gearbox with two or more blades connected, which transforms low rotational wind turbine speed to high rotational PMSG speed. A PMSG is connected to the mechanical gearbox which transforms mechanical energy into electrical energy. The mechanical power output characteristics of the wind turbine for the different speed input at zero pitch angle are shown in Fig.2.

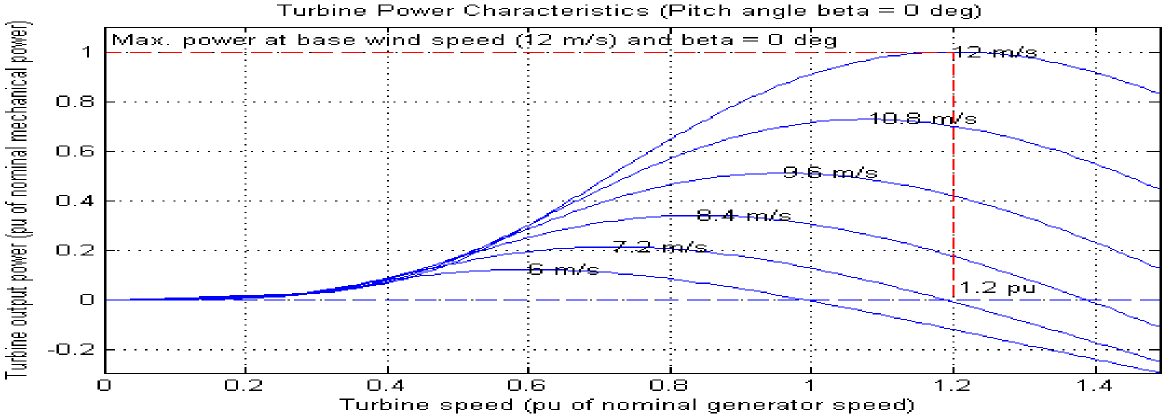

Fig.2 Speed vs power characteristics of the wind turbine

A) Wind Turbine Modeling

The wind turbine can transform kinetic energy into mechanical energy at variable speed and the torque developed by the turbine will be derived from the mathematical modeling. The wind turbine and PMSG parameters considered in the system design are shown in Table.1. The mechanical torque (T_m) produced by the wind turbine is expressed as,

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

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,

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

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

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

B) PMSG Modeling

The mechanical energy is converted into electrical energy using PMSG at high speed and fed to the AC/DC and/or AC/DC/AC converters for the DC utility and/or AC mains. The mathematical modeling of PMSG can be derived from machine parameters. The electrical energy (voltage) developed by the PMSG is expressed as,

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

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

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 (wb) and R_g refers to the resistance of the generator (Ω).

ω_e is the electrical speed of the generator. The ω_e is expressed as

$$\omega_e = p_n \omega_m \quad (6)$$

The electromagnetic torque (T_{Elec}) of the PMSG is expressed as,

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

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

$$J\frac{d\omega_m}{dt} = T_{Elec} - T_m - F\omega_m] \quad (8)$$

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

Three phase input voltage is written as,

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

Table. 1: Wind turbine unit parameters

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

2.2 Vienna Rectifier (AC/DC converter)

The Vienna Rectifier is an advantageous unidirectional PFC (power factor correction) rectifier with less number of active power switches, sinusoidal input current, and balanced output DC-link voltage, low voltage stress across switches, high switching operation and high efficiency. The boost type rectifier is used for the wind, microturbines, low voltage DC (LVDC), high voltage DC distribution (HVDC) and AC mains at the front side for higher voltages of 400V-750V-1500V. It consists of 3-switches and 18-diodes with DC-link capacitor at the output. The current flow in the circuit depends on the switching pattern, as mentioned in Table.2. As shown in Fig.3a & 3b, for S_1=0 (switch-OFF) current flows through the diodes from phase to neutral when is I_A +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 +ve and current flows the switch S_1 from neutral to phase when I_A is –ve as shown in Fig.3c & 3d. 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.

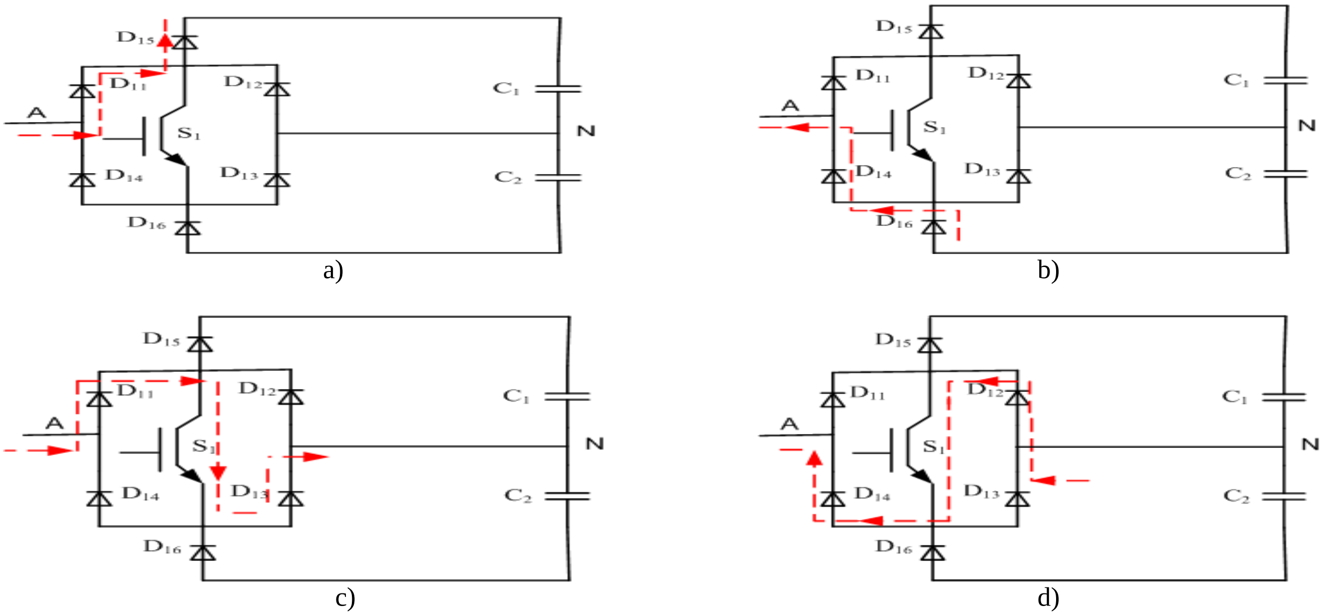

Fig.3 Current flow in the circuit when S_1=0 (Fig3a: I_A +ve & Fig3b: I_A -ve) and S_1=1 (Fig3c: I_A +ve & Fig3d: I_A -ve)

Table.2: Switching Pattern

S_1	S_2	S_3	V_{AN}	V_{BN}	V_{CN}	Charge	Discharge
0	0	0	$+\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	C_1, C_2	-
0	0	1	$+\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	0	C_1, C_2	-
0	1	0	$+\frac{V_{DC}}{2}$	0	$-\frac{V_{DC}}{2}$	C_1	C_2
0	1	1	$+\frac{V_{DC}}{2}$	0	0	C_1	C_2
1	0	0	0	$-\frac{V_{DC}}{2}$	$-\frac{V_{DC}}{2}$	C_1, C_2	-
1	0	1	0	$-\frac{V_{DC}}{2}$	0	C_2	C_1
1	1	0	0	0	$-\frac{V_{DC}}{2}$	C_1	C_2
1	1	1	0	0	0	-	C_1, C_2

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

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

where, *R*= source resistance, *L*=source inductance and $E_{A,B,C}$ = terminal voltage of Vienna rectifier which depends 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.

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

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 written as,

$$\left.\begin{aligned} V_{DC} &= V_{DC1} + V_{DC2} \\ \Delta V &= V_{DC1} - V_{DC2} \end{aligned}\right\} \quad (12)$$

The current through the output capacitor is written as,

$$\left.\begin{aligned} i_{C1} &= C_1 \frac{d\,V_{DC1}}{dt} \\ i_{C2} &= C_2 \frac{d\,V_{DC2}}{dt} \end{aligned}\right\} \quad (13)$$

3. SVPWM Controller

The SVPWM current controller as shown in Fig.4 is used to generate the desired voltage vectors in the *d-q* frame for a three-phase Vienna rectifier with eight switching patterns which finds a voltage space vector. The switching patterns can be 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 sector which minimizes the switching time and current harmonic distortion. In this the three-phase current abc (i_{ABC}) can be transformed into (i_d & i_q) *d-q* frame which compared by the reference currents of i_{dref} and i_{qref} , an error signal is given 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 stationary *d-q* frame are expressed as,

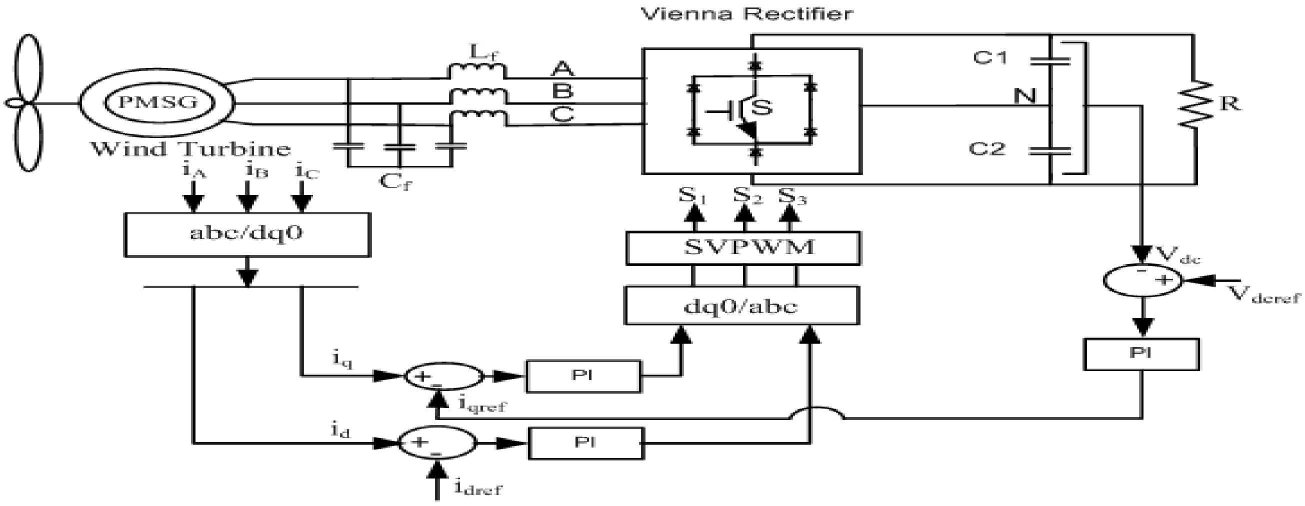

Fig.4 Proposed model of an SVPWM based three phase boost type Vienna Rectifier

$$\left.\begin{aligned} C\frac{d\,V_{DC}}{dt} &= \frac{3}{2}(i_q S_q + i_d S_d) - i_L \\ L\frac{di_q}{dt} + \omega L i_d + R i_q &= E_q - V_{DC} S_q \\ L\frac{di_d}{dt} + \omega L i_q + R i_d &= E_d - V_{DC} S_d \end{aligned}\right\} \quad (14)$$

$$\left.\begin{aligned} V_d &= E_d - \omega L i_q - L\frac{di_d}{dt} - R i_d = E_q - V_{DC} S_q \\ V_q &= E_q - \omega L i_q - L\frac{di_q}{dt} - R i_q = E_d - V_{DC} S_d \end{aligned}\right\} \quad (15)$$

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, reference voltage is derived in *d-q* frame as,

$$\left.\begin{aligned} V_{dref} &= -(K + \frac{K_i}{S})(i_{dref} - i_d) - \omega L i_q + E_d \\ V_{qref} &= -(K + \frac{K_i}{S})(i_{qref} - i_q) - \omega L i_d + E_q \end{aligned}\right\} \quad (16)$$

4. Result Analysis

A 3-ϕ boost type Vienna rectifier is presented based on SVPWM current controller for a 1kW WECS. The parameters considered for the system modeling are shown in Table.3. In this, the maximum of 230V is generated by the PMSG of WECS, which is connected to three phase Vienna rectifier (1kW) through a filter capacitor. The switches are operated as per the sequence of pulse generation for the desired output of the rectifier i.e. to get the 400V DC from 230V AC input. Fig.5 shows the generated switching pulses for the switches S_1, S_2 and S_3 and Fig.6 shows the given wind input to the turbine blades with the variation of 8m/s to 16m/s and turbine speed in rad/sec (pu). Similarly, Fig.7 shows the results of turbine speed (Wm) (rad/sec), mechanical torque (Tm), phase voltage (V_A) and phase current (I_A). The 3-ϕ voltage (V_{ABC}) and current (I_{ABC}) input are given to rectifier from WECS are shown in Fig.8.

Table.3: Proposed circuit parameters

S.No	Circuit parameters	Ratings
1	Three phase input voltage	230V
2	Maximum output voltage of Vienna Rectifier	400V
3	Input inductance (L_A=L_B=L_C)	10mH
4	Input filter capacitance (C_A=C_B=C_C)	100uF
5	DC-link capacitance ($C_1 + C_2$)	200µF
6	Diode resistance (R_{ON})	0.001Ω
7	Load resistance (R)	160 Ω
8	Maximum output power	1kW

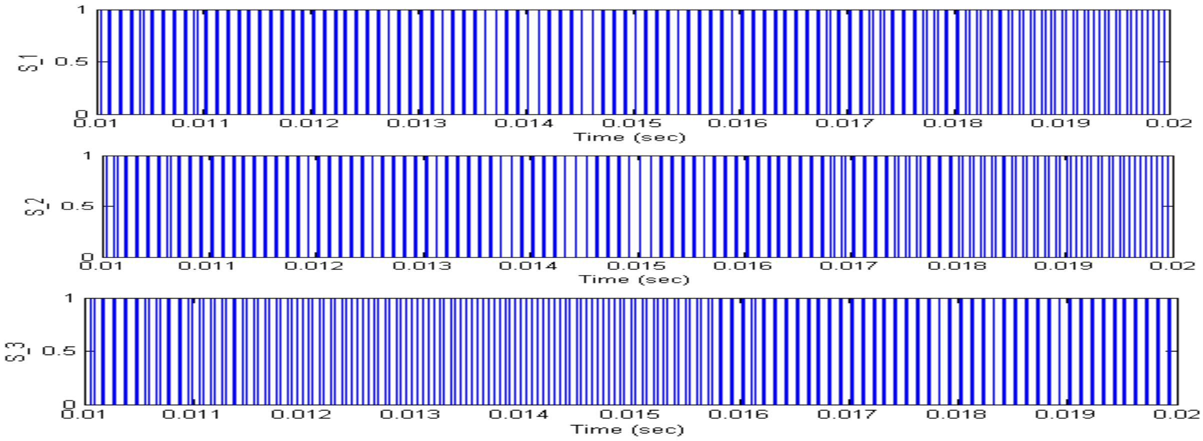

Fig.5 Switching pulses ($S_{1, 2, 3}$) generated by the SVPWM controller

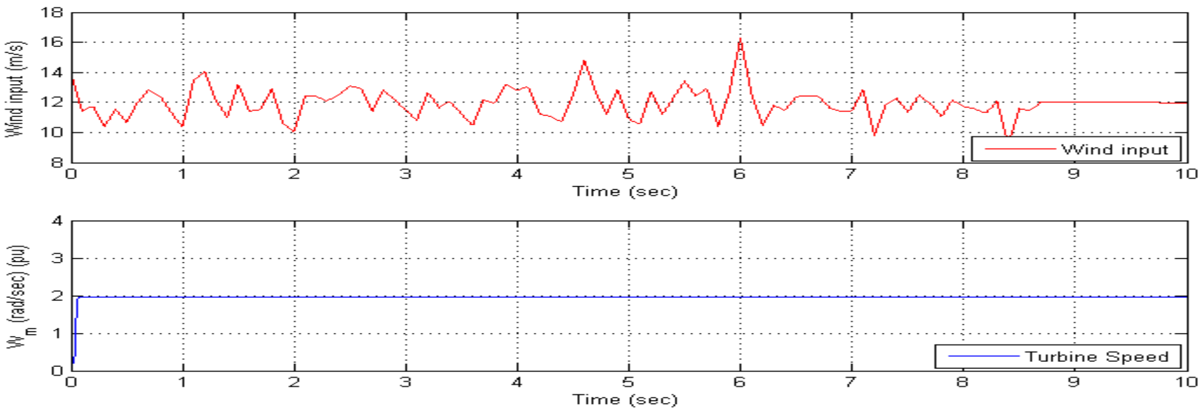

Fig.6 Simulation results of wind input and rotor speed (Wm) (pu)

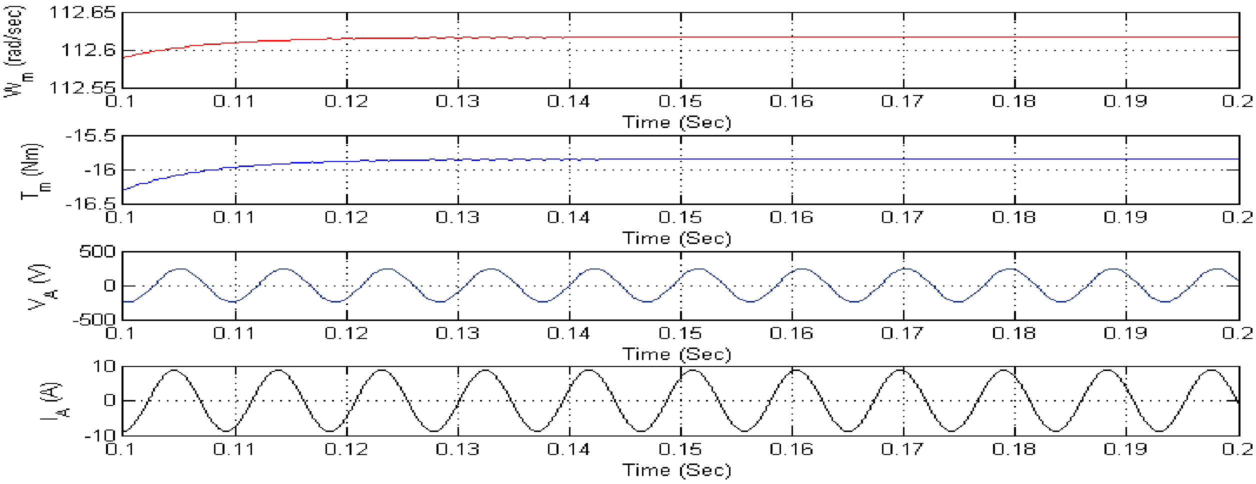

Fig.7 Results of turbine speed (Wm) (rad/sec), mechanical torque (Tm), phase voltage (V_A) and phase current (I_A)

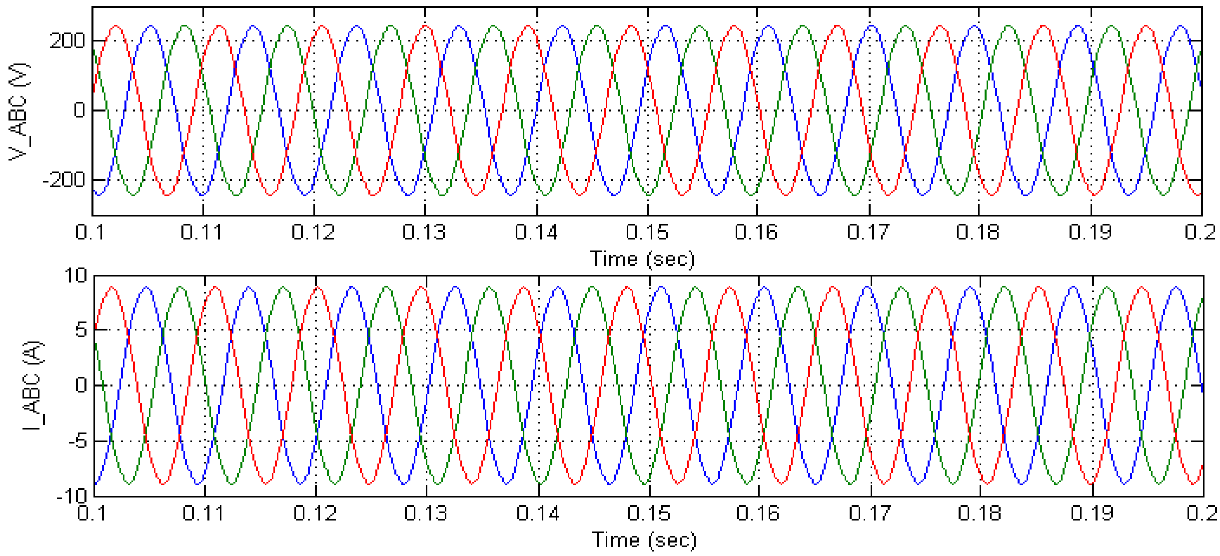

Fig.8 Simulation results of three phase voltage (V_{ABC}) and current (I_{ABC})

The output active power (P_{AC}), apparent power (P_{APP}) and reactive power (P_{Reac}) of the PMSG are shown in Fig.9, which states the maximum power generation from the PMSG even for low-speed wind turbines in the small-scale WECS. The output of the AC/DC converters is mainly depended on the DC-link capacitors, which is maintained at a constant value even for large input variations as shown in Fig.10. Similarly, the desired output waveforms of the proposed rectifier are depicted in Fig.11 for DC output voltage (V_{DC}), current (I_{DC}) and power (P_{DC}). And one of the main desirable parameters is voltage stress and power loss across the switches, which results in the high-efficiency power conversion of the converter. The voltage across the switches is reduced to half of the DC-link voltage which results in reduced switching losses, and the voltage (V_{SW}), current (I_{SW}) and power (P_{SW}) waveforms are plotted for the switch S_3 as shown in Fig.12 and similar to the other the switches.

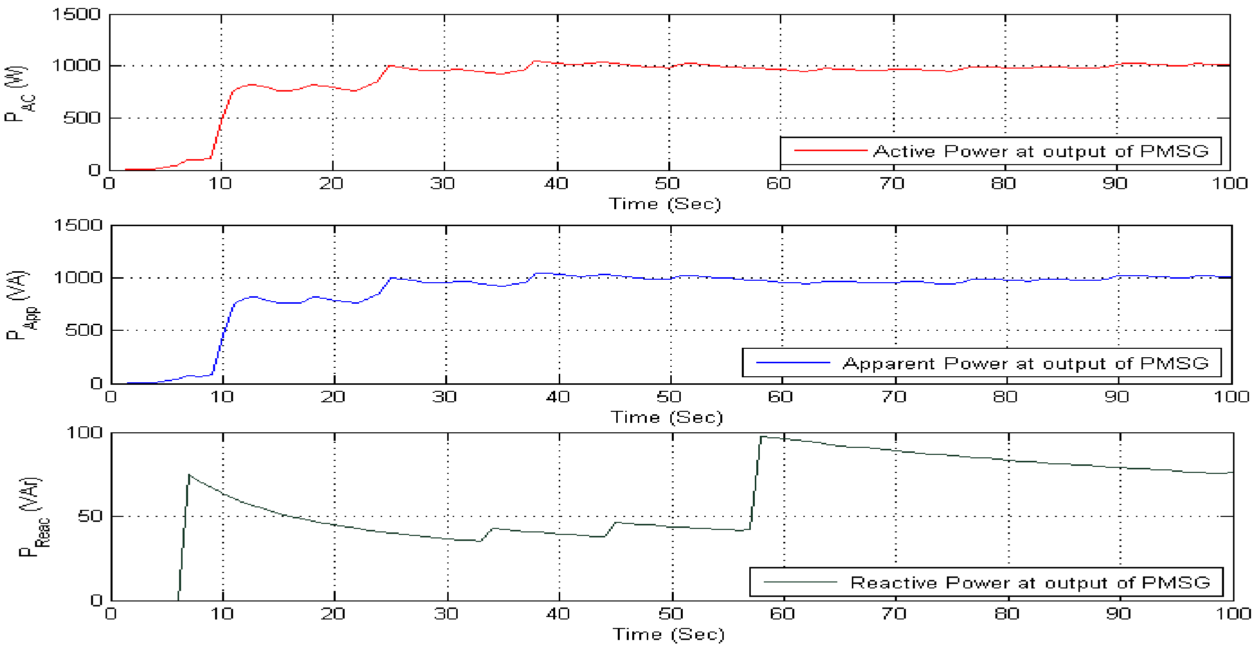

Fig.9 Simulation results of Active power (P_{AC}), Apparent power (P_{APP}) and Reactive power (P_{Reac}) at output of PMSG

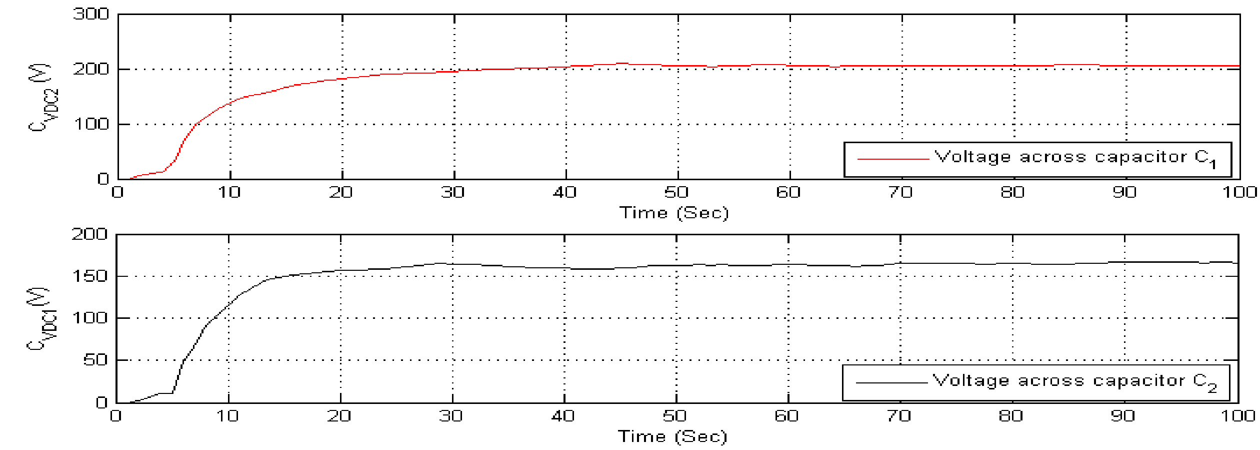

Fig.10 Simulation results of voltage across the DC-link capacitors C_1 and C_2

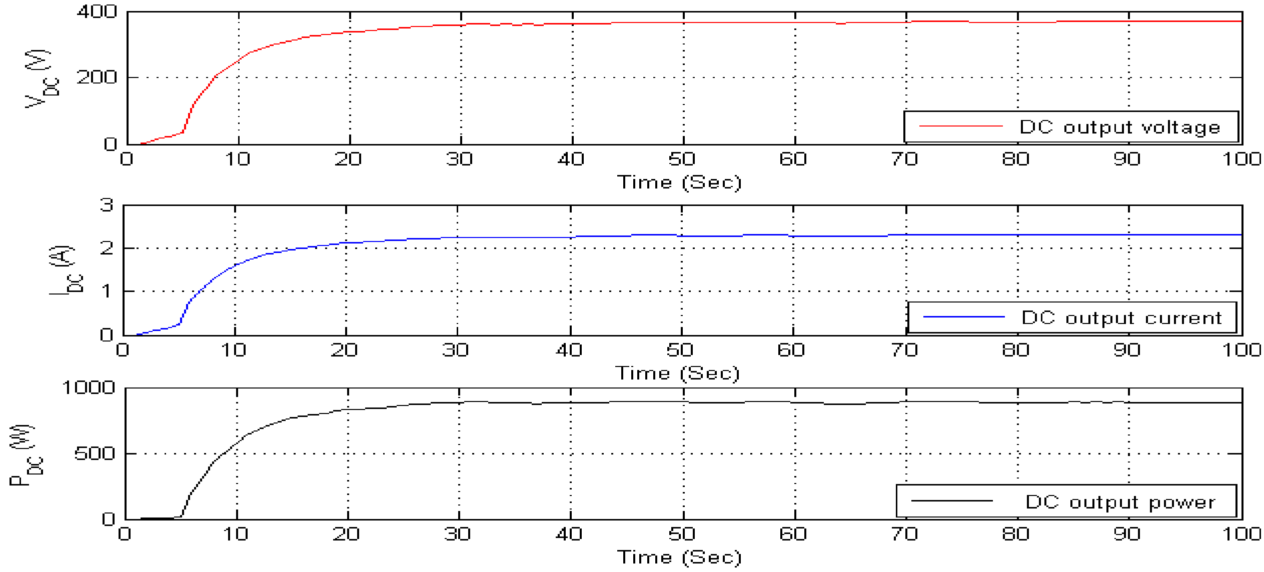

Fig.11 Simulation results of DC output voltage (V_{DC}), current (I_{DC}) and power (P_{DC})

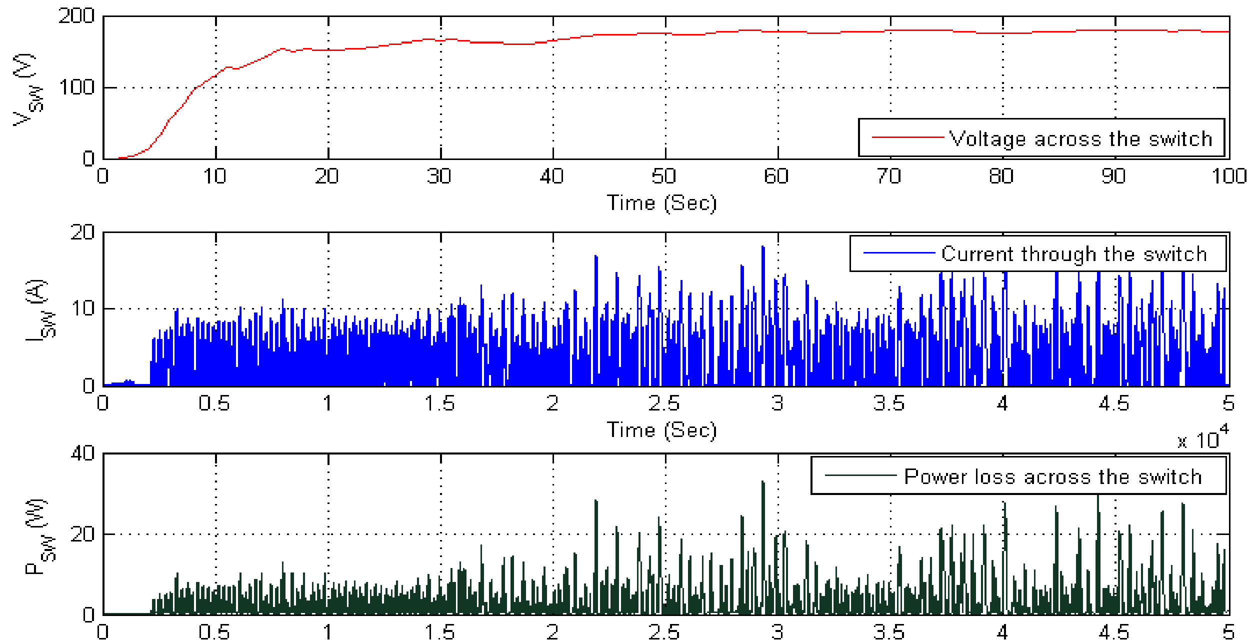

Fig.12 Simulation results of voltage (V_{SW}), current (I_{SW}) and power (P_{SW}) at switch S_3

5. Conclusion

In this paper, the SVPWM current controller based boost type Vienna rectifier is proposed for a 1kW PMSG wind conversion energy conversion system with reduced switching components. The rectifier circuit minimizes the switching power losses and cost of the conversion unit. It also reduces the THD, input current shaping to sinusoidal, maintains the power factor approximately unity. Vienna rectifier is preferred at front side conversion unit for AC power generated renewable energy systems and/or AC mains. This kind of AC/DC conversion unit is very applicable for data centers, telecommunications, UPS (uninterruptible power supply), LVDC distribution systems and AC mains etc. The desired output parameters obtained by the Vienna Rectifier are tabulated in Table.4, which states the performance of the proposed circuit topology.

Table.4: Results obtained by the Vienna Rectifier

S.No	Circuit parameters	Results
1	Power rating of WECS	IkW
2	DC output Voltage	368.2V
3	DC output Current	2.302A
4	DC output Power	883.2W
5	Voltage across the capacitor C_1	238.7V
6	Voltage across the capacitor C_2	172.7V
7	Voltage across the switch	278.2V
8	Current throgh the switch	0.00278A
9	Power loss across the switch	0.774W

References

[1] Leibl M, Kolar JW, Deuringer J. Sinusoidal Input Current Discontinuous Conduction Mode Control of the VIENNA Rectifier. IEEE Transactions on Power Electronics. 2017 Nov;32(11):8800-12.

[2] Kumar K, Babu NR, Prabhu KR. Design and Analysis of an Integrated Cuk-SEPIC Converter with MPPT for Standalone Wind/PV Hybrid System. International Journal of Renewable Energy Research (IJRER). 2017 Mar 22;7(1):96-106.

[3] RAMASAMY S, Abishri P, Umashankar S. Review of Coupled Two and Three Phase Interleaved Boost Converter (IBC) and Investigation of Four Phase IBC for Renewable Application. International Journal of Renewable Energy Research (IJRER). 2016 Jun 18;6(2):421-34.

[4] Islam MH, Razzak MA. Design of a modified Vienna rectifier for power factor correction under different three phase loads. In Informatics, Electronics and Vision (ICIEV), 2016 5th International Conference on 2016 May 13 (pp. 764-770). IEEE.

[5] Adhikari J, Prasanna IV, Panda SK. Voltage oriented control of the three-level Vienna rectifier using vector control method. In Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE 2016 Mar 20 (pp. 9-16). IEEE.

[6] Foureaux NC, Oliveira JH, de Oliveira FD, Cardoso Filho BD, de Faria RS. Command Generation for Wide-Range Operation of Hysteresis-Controlled Vienna Rectifiers. IEEE Transactions on Industry Applications. 2015 May; 51(3):2373-80.

[7] Adhikari J, Prasanna IV, Panda SK. Reduction of Input Current Harmonic Distortions and Balancing of Output Voltages of the Vienna Rectifier under Supply Voltage Disturbances. IEEE Transactions on Power Electronics. 2017 Jul;32(7):5802-12.

[8] Li X, Sun Y, Wang H, Su M, Shoudao H. A Hybrid Control Scheme for three-phase Vienna Rectifiers. IEEE Transactions on Power Electronics. 2017 Jan 30.

[9] Lee JS, Lee KB. Performance analysis of carrier-based discontinuous PWM method for Vienna rectifiers with neutral-point voltage balance. IEEE Transactions on Power Electronics. 2016 Jun;31(6):4075-84.

[10] Kasa S, Ramasamy S. Photovoltaic Fed Dynamic Voltage Restorer with Voltage Disturbance Mitigation Capability Using ANFIS Controller. International Journal of Renewable Energy Research (IJRER). 2016 Jan 1;6(3):825-32.

[11] Mekalathur HK. An improved Resonant Fault Current Limiter for Distribution System under Transient Conditions. International Journal of Renewable Energy Research (IJRER). 2017 Jun 18;7(2):547-55.

[12] Krahenbuhl D, Zwyssig C, Kolar JW. Half-controlled boost rectifier for low-power high-speed permanent-magnet generators. IEEE Transactions on Industrial Electronics. 2011 Nov;58(11):5066-75.

[13] Hu KW, Liaw CM. Development of a wind interior permanent-magnet synchronous generator-based microgrid and its operation control. IEEE Transactions on Power Electronics. 2015 Sep;30(9):4973-85.

[14] Rajaei A, Mohamadian M, Varjani AY. Vienna-rectifier-based direct torque control of PMSG for wind energy application. IEEE transactions on industrial electronics. 2013 Jul;60(7):2919-29.

[15] Tiwari R, Babu NR. Fuzzy Logic Based MPPT for Permanent Magnet Synchronous Generator in wind Energy Conversion System. IFAC-Papers Online. 2016 Jan 1;49(1):462-7.

[16] Cherukuri SH, Saravanan B. An overview of selected topics in smart grids. Frontiers in Energy. 2016 Dec 1;10(4):441-58.

[17] CHERUKURI SH. Performance analysis of electric spring in reducing the power drawn from the supply system during generation uncertainties. International Journal of Renewable Energy Research (IJRER). 2015 Dec 24;5(4):1133-45.

[18] Heldwein ML, Nussbaumer T, Kolar JW. Common mode modeling and filter design for a three-phase buck-type pulse width modulated rectifier system. IET power electronics. 2010 Mar;3(2):209-18.

[19] Monroy-Morales JL, Hernández-Ángeles M, Campos-Gaona D, Peña-Alzola R, Ordonez M, Mérida W. Modeling and control design of a Vienna rectifier based electrolyzer. In Power Electronics for Distributed Generation Systems (PEDG), 2016 IEEE

7th International Symposium on 2016 Jun 27 (pp. 1-8). IEEE.

[20] Boillat DO, Krismer F, Kolar JW. EMI Filter Volume Minimization of a three-phase, Three-Level T-Type PWM Converter System. IEEE Transactions on Power Electronics. 2017 Apr;32(4):2473-80.

[21] Biela J, Hassler D, Schönberger J, Kolar JW. Closed-loop sinusoidal input-current shaping of 12-pulse autotransformer rectifier unit with impressed output voltage. IEEE Transactions on Power Electronics. 2011 Jan;26(1):249-59.

[22] Nishida Y, Ohyama H, Pejovic P, Kolar JW. three-phase harmonic reducing diode rectifier. In Power Electronics and Motion Control Conference (EPE/PEMC), 2012 15th International 2012 Sep 4 (pp. LS3e-3). IEEE.

[23] Kolar JW, Friedli T. The essence of three-phase PFC rectifier systems—Part I. IEEE Transactions on Power Electronics. 2013 Jan;28(1):176-98.

[24] Stupar A, Friedli T, Minibock J, Kolar JW. Towards a 99% efficient three-phase buck-type PFC rectifier for 400-V DC distribution systems. IEEE Transactions on Power Electronics. 2012 Apr;27(4):1732-44.

[25] Soeiro TB, Vancu F, Kolar JW. Hybrid active third-harmonic current injection mains interface concept for DC distribution systems. IEEE Transactions on Power Electronics. 2013 Jan;28(1):7-13.

[26] Lee JS, Lee KB. A Novel Carrier-Based PWM Method for Vienna Rectifier With a Variable Power Factor. IEEE Transactions on Industrial Electronics. 2016 Jan;63(1):3-12.

[27] Lee JS, Lee KB. Carrier-based discontinuous PWM method for Vienna rectifiers. IEEE Transactions on Power Electronics. 2015 Jun;30(6):2896-900.

[28] Marxgut C, Muhlethaler J, Krismer F, Kolar JW. Multi objective optimization of ultra flat magnetic components with PCB-integrated core. IEEE Transactions on Power Electronics. 2013 Jul;28(7):3591-602.

[29] Darijevic M, Jankovic M, Pejovic P, Kolar JW, Nishida Y. three-phase rectifiers with suboptimal current injection and improved efficiency. IET Power Electronics. 2014 Apr;7(4):795-804.

[30] Yao W, Zhengyu L, Zhang M, Lin Z. A novel SVPWM scheme for Vienna rectifier without current distortion at current zero-crossing point. In Industrial Electronics (ISIE), 2014 IEEE 23rd International Symposium on 2014 Jun 1 (pp. 2349-2353). IEEE.

[31] Zhang Y, Gui X, Yang M, Xu D. Comparison of Direct Current Control and Direct Power Control Using SVPMW Modulation. In Instrumentation and Measurement, Computer, Communication and Control (IMCCC), 2014 Fourth International Conference on 2014 Sep 18 (pp. 936-940). IEEE.