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Analysis and Implementation of Improved Performance of Triplen Harmonic Injection for Vienna Rectifier

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Abstract

This article is a study on the analysis of harmonics reductions and load voltage control for Vienna Rectifier (VR) with help of the Triplen Harmonic Injection (THJ) and the proportional integral controller (PIC). The sinusoidal PWM is the easiest modulation technique for AC-DC rectifiers to comprehend; however, it is not capable of entirely using the accessible DC bus source voltage. In order to enhance the load voltage regulation and harmonics reductions of the VR, PIC and THJ PWM methods are developed. The performances of the designed PWM methods as well as the PIC are validated at different operating conditions by developing models using MATLAB/Simulink as well as real experimental models. Simulation and experimental results are presented to show the effectiveness of the designed control methods.

Keywords, *Vienna Rectifier, Triplen Harmonic Injection, Proportional Integral Controller*

1. Introduction

Nowadays, the power electronic converters are extensively used in most of the control applications. These are front end converters, which draw non-sinusoidal current from the power supply because of their non-linear nature which may cause power quality problems and can affect the customer super sensitive equipment malfunctioning, equipment failure, and increasing system losses. The AC power is easy to generate and transmit everywhere, but consumer requires DC power also in addition to utilizing the batteries. But batteries do not produce high efficiency and the cost is more when the power electronic converter based AC to DC power conversion is used. Still, these kinds of conversion draws non-sinusoidal flow of current, which will affect the quality of the power to deteriorate. In order to solve this problem, the filter capacitors are applied at the front end. But since the cost of filters is high this may increase the overall cost of the system.

Further, the research extends towards the power factor correction also (PFC) by applying converters without filter. The Vienna Rectifier (VR) rectifies the unregulated AC input power into an output DC power without drawing non- sinusoidal current from its three phase source; three switch configured system, which is a three level topology. It has the advantage of introducing small source current harmonics in comparison with other converters. The harmonic current is the one of the major issues in the traditional uncontrolled and controlled bridge rectifiers widely applied by the consumer which is presented in [1]. The PFC for AC-DC based boost converter topology is implemented in [2].

However, this method has been extended to three-phase usage by connecting a three-phase diode bridge rectifier and a single switch boost DC-DC converter working in discontinuous conduction mode (DCM). It has demerits such as more conduction losses, large switching voltage stresses, and radio interference emission problems resulting in the

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requirement of a large input filter .Voltage and current waveforms improvements have reduced the harmonic distortion and the characteristics of the multilevel converters are used to improve the waveforms of the power electronic circuits. PWM based single stage three phase boost type VR is developed in [4].

The space vector modulation (SVM) based VR is designed to obtain the optimum power density using three phase power model has been well addressed in [5]. Three phase three level boost type VR was designed to work under the unity power factor (UPF) with minimum current has been harmonics has demonstrated in [6]. The PWM based on single carrier wave is designed for VR and it generated small Total Harmonics Distortion (THD) on the load side compared to the two levels PWM based rectifiers. The VR can easily obtain the higher efficiency because of small voltage stress on the devices and the small ON/OFF losses [7].

The performance of VR using the unbalance grid characteristic is explained for the elimination of ripples in the input side [8]. Renewable energy as a source for VR is implemented and its performance has been analyzed in [9]. Performance of VR in unbalanced load conditions using SVM over wide range of load change is dealt in [10]. Power quality improvement using VR is utilized and the converter has the ability to compensate the reactive power flow in power system as well as controlling input current harmonics [11-15]. The above mentioned techniques used to reduce can be solved by the Triplen Harmonic Injection (THJ) in conjunction with proportional integral controller (PIC).This paper is to explore on harmonics reduction analysis and load voltage regulation for VR. The performance of the VR with control methods prepared is implemented using both the MATLAB/Simulink and prototype models in [14].

2. Operation of Vienna Rectifier

The whole power diagram model of the VR is shown in Figure 1 and the operation of the VR is explained below. If the line current i_a is positive, and the controlled switch Q_a is in on-state, the voltage across the converter pole “A” and the dc-bus mid-point “N” (i.e., V_{AN}) is zero. The current flow direction for this case is depicted in Figure 2 (a). Suppose the line current i_a is positive, and the controlled switch Q_a is in closed state, then, the voltage across V_{AN} is $V_{dc}/2$ (refer to Figure 2 (b)). Likewise, if the line current i_a is negative, the voltage V_{AN} will be $-V_{dc}/2$ if the switch Q_a is in **off** state and zero if the switch Q_a is in **on** state (see Figure 2 (d)). Similarly, this working principle is extended to phase legs “B “as well as “C”. The small signal model of the VR has been reported in [12]. Now, the final model of this VR can be expressed as (1)

$$\begin{gathered}\dot{x}=A.x+B.u+E.\omega \\ y=C.x+D.u\end{gathered} \tag{1}$$

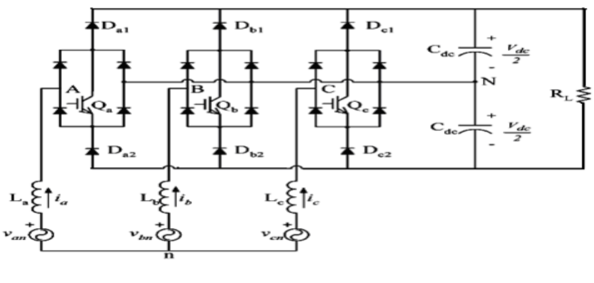
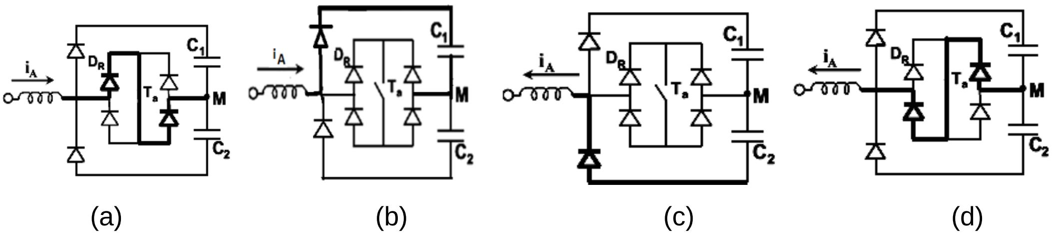


Figure 1. Complete Power Circuit Model of Vienna Rectifier



(a) (b) (c) (d)

Figure 2. Conduction Paths for Phase-Leg a When: (A) the Line Current is Positive, and the Controlled Switch is on; (B) the Line Current is Positive, and the Controlled Switch is Off; (C) the Line Current is Negative, and the Controlled Switch is Off; and (D) the Line Current is Negative, and the Controlled Switch is on

Where,

$$A=\begin{pmatrix} 0 & \omega & 0 & -\frac{v_s\sqrt{2}}{LV_o} \\ -\omega & 0 & 0 & \frac{\omega I_s\sqrt{2}}{LV_o} \\ 0 & 0 & -\frac{2}{C_oR_o} & 0 \\ \frac{3v_s\sqrt{2}}{C_oV_o} & -\frac{3\sqrt{2L\omega I_s}}{C_oV_o} & 0 & 0 \end{pmatrix},\ E=\begin{pmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

$$B=\begin{pmatrix} -\frac{V_o}{2L} & 0 & 0 \\ 0 & -\frac{V_o}{2L} & 0 \\ 0 & 0 & \frac{\alpha\sqrt{2I_s}}{LV_o} \\ \frac{3\sqrt{2I_s}}{2C_o} & 0 & 0 \end{pmatrix}$$

$$C=\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad (2)$$

3. Controller Design of Vienna Rectifier

In this section the detailed controller design for VR is presented and is given in Figure 3. The load voltage V_o is measured, and is compared with the reference voltage V_{oref} using a comparator and the difference output gives the voltage error signal. This error is applied to the PIC, which produces the control signal. This control signal is multiplied with a three phase Triplen Injection harmonic signals, and its three phase control signals are compared with the output of PI controller. These give the three phase reference current signals, which are again compared with the measured three phase line currents by using the comparators. These comparators produce the three phase error currents which are processed through hysteresis current controllers to generate the PWM pulses for each phase of the VR switches. This generated PWM currents for each phase is again logical AND operated with a fixed frequency PWM pulse generator and then, the output of the logical AND operator gives the PWM pulses for each phase to control the harmonics as well as to regulate the load voltage.

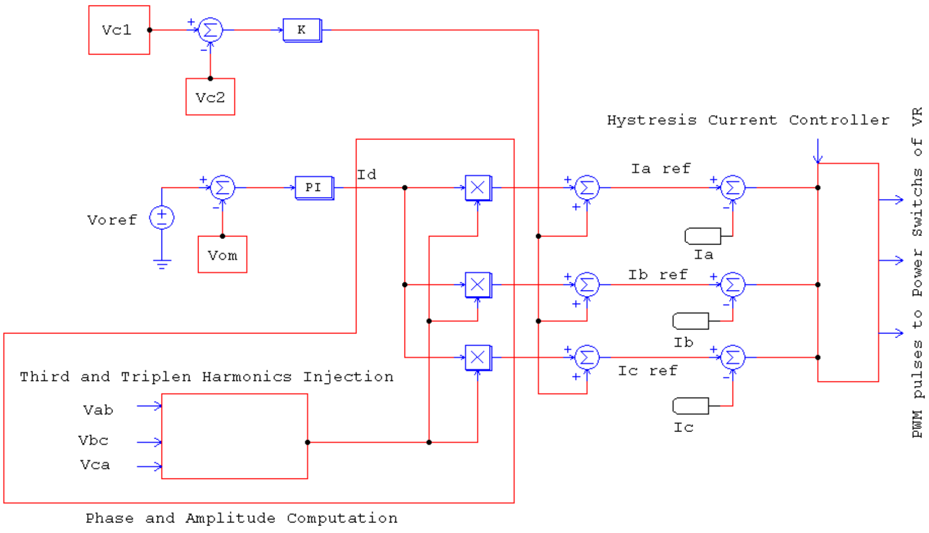


Figure 3. Control Diagram of Three Phase VR Circuit.

3.1. Third Order Harmonics

Third Order Harmonics are the odd multiples of the 3^{rd} harmonic of the fundamental component (50 or 60 Hz): 3rd, 9th, 15th, 21st. etc. Preferably, in a balanced three phase system, the phase currents are pure sine waves and the neutral current is the sum of all the three phase signals which are

$$\begin{aligned} I_a &= T \sin 3\omega t \\ I_b &= T \sin 3(\omega t + 120) \\ I_c &= T \sin 3(\omega t - 120) \end{aligned} \qquad (3)$$

Where,

T is constant which modulates the magnitude of the signal.

Therefore the neutral current I_n is

$$I_n = I_a + I_b + I_c = 3T \sin 3\omega t \qquad (4)$$

The I_n is thrice times the third harmonic phase current magnitude, which is also true for other Triplen Harmonics like multiples of three.

The main problem in the SPWM (Sinusoidal Pulse width modulation) is inability to completely use the obtainable DC bus source voltage. This kind of problem is neutralized by Triplen Harmonic Injection (THJ) PWM method which enhances the VR performance.

Let us consider a waveform consisting of a fundamental component (refer to Figure 4)

$$y = \sin\theta + A \sin 3\theta \qquad (5)$$

The maximum quantity of y can be determined by substituting the values found for ‘sin’ term in equation (5) where, $\theta = \omega t$ and A is a parameter to be maximized at the same time keeping the peak magnitude of y(t) unity.

The peak quantity of y(t) is derived by setting its derivative with respect to θ equal to null. Thus,

$$\frac{dy}{d\theta} = \cos\theta + 3A\cos 3\theta = \cos\left(12A\cos^2\theta - (9A-1)\right) = 0 \tag{6}$$

The maximum and minimum of the waveform occur at the conditions

$$\cos\theta = 0 \text{ and } \cos\theta = \sqrt{(9A - \frac{1}{12A})} \tag{7}$$

This gives

$$\sin\theta = 1 \text{ and } \sin\theta = \sqrt{(1 + \frac{3A}{12A})} \tag{8}$$

The maximum quantity of y will be calculated by substituting the values obtained for sinθ in (5) and it is shown in the following trigonometric identity (9)

$$\sin\theta = 3\sin\theta + 4\sin^3\theta \tag{9}$$

The maximum value for A is that value, which minimizes by and will be obtained by differentiating for by with respect to A and equating the result to null. Then, it can be expressed as equation (8)

$$\frac{dy}{d\theta} = -(2) - \left(\frac{1}{1} + 3A\right)\sqrt{\left(\frac{1-3A}{12A}\right)} \tag{10}$$

Next, by summating these third harmonic generations, a 15.5% improvement in the magnitude of the fundamental of the three phase voltages is obtained. Injecting a 3^{rd} harmonic component to the fundamental component gives the three phase modulating waveforms for VR and they can be expressed as in (11).

$$V_{an} = \frac{2}{\sqrt{3}}\left(\sin\omega t + \frac{1}{6}\sin(3\omega t)\right)$$

$$V_{bn} = \frac{2}{\sqrt{3}}\left(\sin(\omega t - \frac{2\pi}{3}) + \frac{1}{6}\sin(3\omega t)\right)$$

$$V_{cn} = \frac{2}{\sqrt{3}}\left(\sin(\omega t + \frac{2\pi}{3}) + \frac{1}{6}\sin(3\omega t)\right)$$

Where, $\theta = \omega t$ (11)

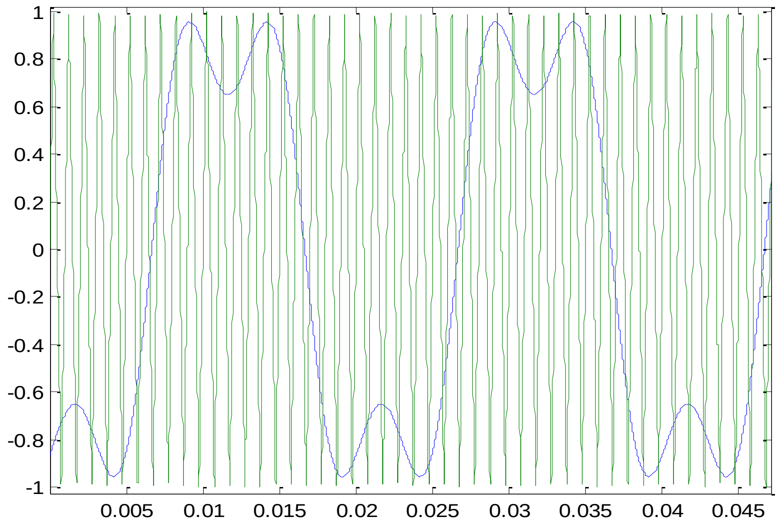


Figure 4. Reference and CarrieraSignals of Third Harmonics

The THIPWM is implemented in the same manner as the SPWM, that is, the reference waveforms are compared with their triangular waveforms. As a result, the amplitude of the reference waveforms does not exceed the DC supply voltage $V_{dc}/2$, but the fundamental component is higher than the supply voltage V_{dc}. As mentioned above, this is approximately15.5% higher in amplitude than the normal sinusoidal PWM. Consequently, it provides a better utilization of the DC supply voltage. The three reference voltages and triangular waveforms of a three-phase THPWM produce the following output phase voltages $V_{aN,}$ $V_{bN,}$ $V_{cN.}$ This technique is a variation of the previously discussed Third-Harmonic Injection technique discussed in Section 2.1.

3.2. Triplen Harmonics Injection (THI)

The THI is obtained by injecting additional harmonics in the reference waveform apart from the Third Harmonics. The resulting flat-topped waveform (refer to Figure 4) also allows over-modulation while improving even further the resulting frequency spectra of the ac-term and dc-term. The analytical expression for the reference waveforms can be derived from the addition of other Triplen Harmonics as expressed by (12)

$$Y=1.15\sin(\omega t) + 0.27\sin(3\omega t)-0.029\sin(9\omega t) \tag{12}$$

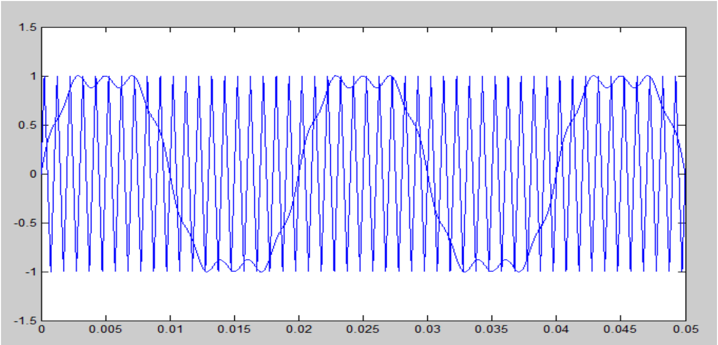


Figure 5. Reference and Carrier Signals of Triplen Harmonics

3.3. Design of Output Voltage Controllers

The PIC and PI controllers are used for load voltage regulations and voltage balancing of the output capacitors C_1 and C_2 of the VR circuit. The PIC and PI controllers' parameters of VR are obtained by using the Ziegler-Nichols second method. This method is applied to the model of the VR circuit in (1), which gives the controller parameters Kp= 0.6, Kcr= 3; Hence Ki= 2Kp/Pcr= 0.00014 [13].

4. Results and Discussions

The performances of the simulation and experimental results of the VR using designed controllers are discussed. Figure 6.The laboratory prototype model is performed on the VR circuit with its specifications as listed in Table 1. The control circuit is implemented in digital platform field programmable gate arrays (FGPA). The parameters of the power circuits are as follows:

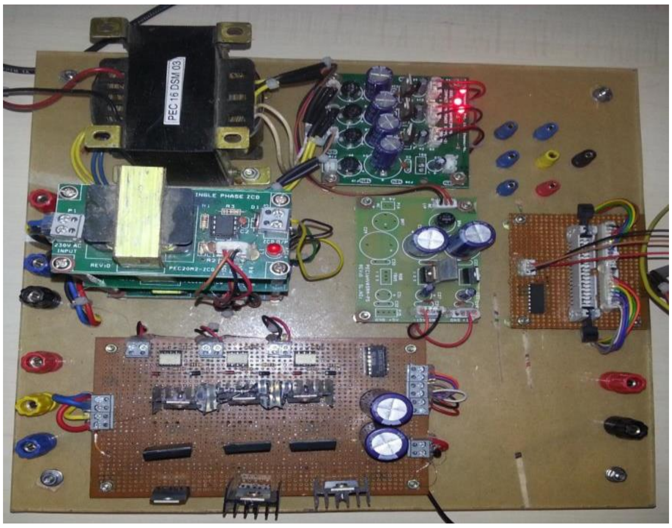


Figure 6. Main Circuit of Vienna Rectifier

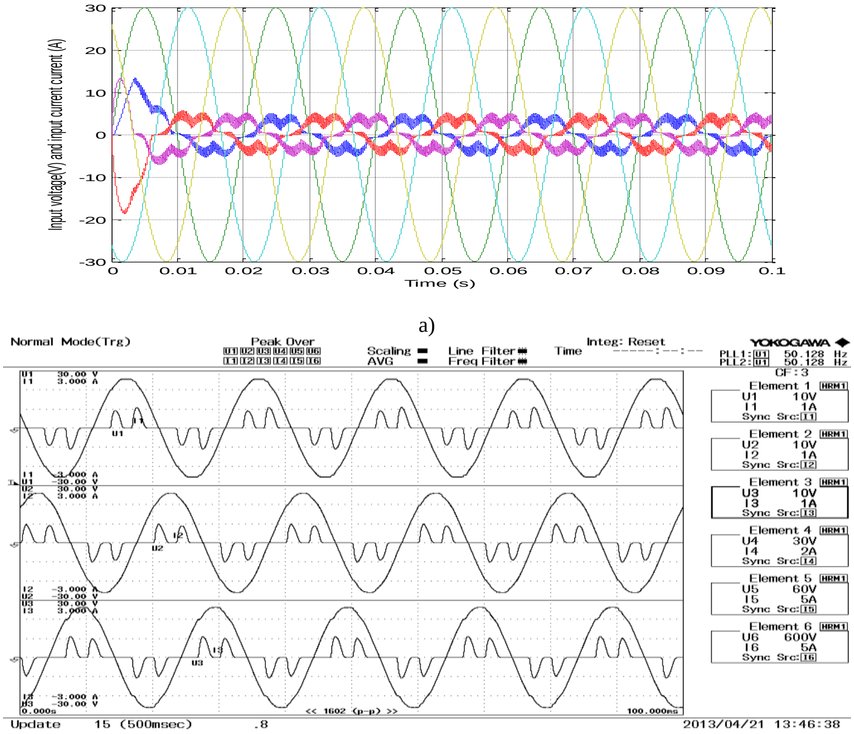
Q a, b, c	IRFN 540 (MOSFET);
D_{a1} To D_{c1}	FR306 (Diodes);
C_1 C_2	400 µF/500V (Electrolytic and plain polyester type);
$L_{a,b,c}$	10µH/10A (Ferrite Core)

Table 1. Specifications of the Vr Circuit

Parameters name	Symbol	Value
Input Voltage	V_{in}	30 V (Peak)
Output Voltage	V_o	82V
Inductor	La Lb Lc	10µH
Capacitors	C1 and C2	400 µF
Nominal switching frequency	fs	100kHz
Load resistance	R	51.25Ω
Output power	P_o	131.2W
Input power	P_{in}	135W

Efficiency	η	97.03%
Average output current	I_o and I_{in}	1.6A & 4.5A
Duty ratio	d_1 and d_2	0.5
Peak to Peak Inductor Current Ripple	Δ_{iL}	15% of I_{in}
Peak to Peak Output Capacitor Ripple Voltage	ΔV_o	0.5V

Figures 7(a) and 7(b) show the simulated and experimental results of the VR circuit without THJ method. From these Figures, it is found that the source currents have non-sinusoidal signals and contain more harmonics with reduced power factor. Figure8. Indicates the simulated phase a of the VR circuit without THJ technique.



a)

(b)

Figure 7. Three Phases Input Voltage and Input Current of VR Circuit without THJ, (A) Simulation, (B) Experimental

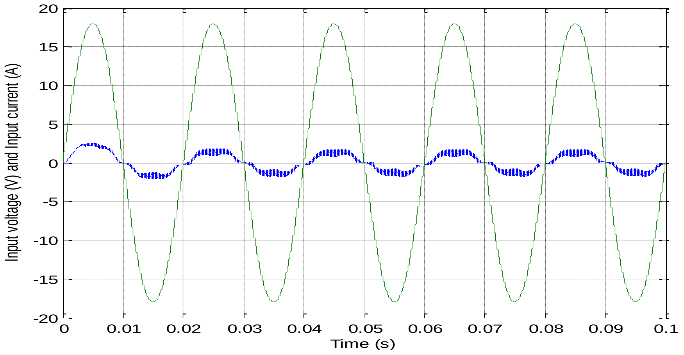
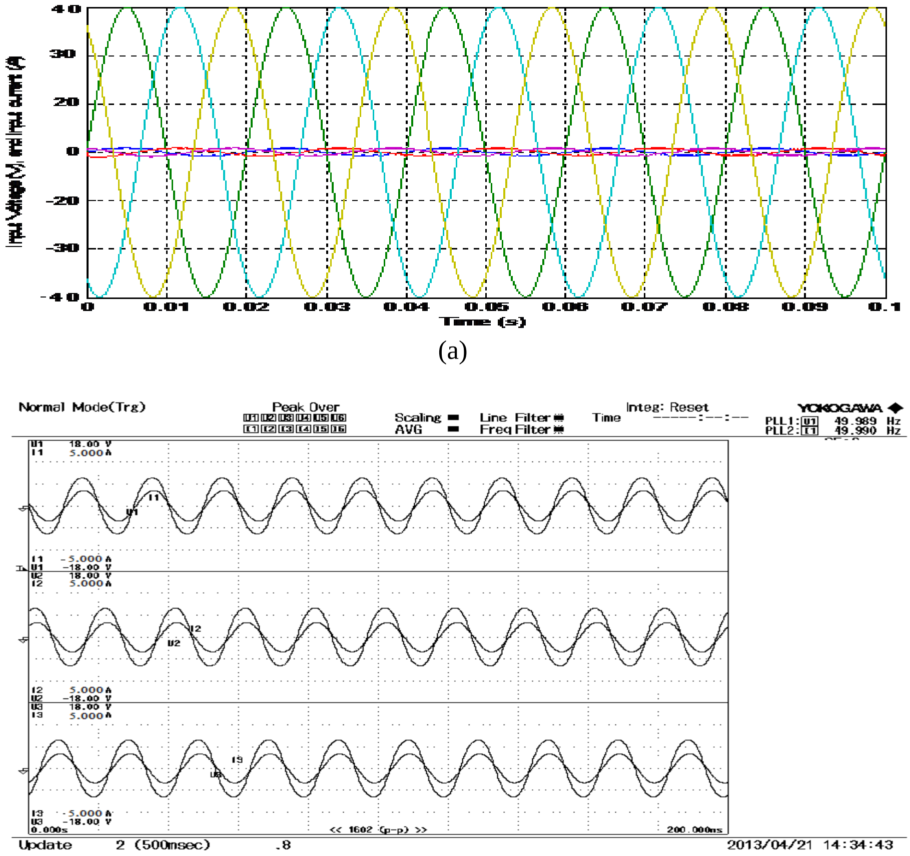


Figure 8. Simulated Input Voltage and Input Current of VR Circuit without THJ (Phase-A).

Figures 9(a) and 9(b) show the simulated and experimental results of the VR circuit using THJ method. From these Figures, it is found that the source current and voltage have sinusoidal in-phase waveforms and contain little harmonics with improved power factor. Fig. 10 indicates the simulated phase-a source of the VR circuit with THJ technique. Figures11 and 12 illustrate the simulated and experimental results of the output voltage of the VR circuit using THJ PWM method. It is clearly found that the output and load voltages have negligible overshoots and quick settling time using this method. Figures13 shows the experimental reference signals used in the generation of THJ method. Figure14 illustrates that the output voltage has a harmonic distortion of 5.719



(a)

(b)

Figure 9. Three Phases Input Voltage and Input Current of VR Circuit with THJ, (A) Simulation, (B) Experimental

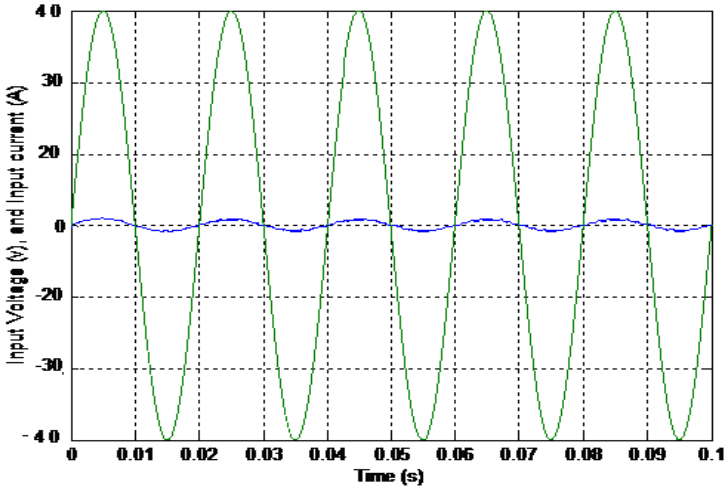


Figure 10. Input Voltage and Input Current of VR Circuit Using THJ (Phase-A)

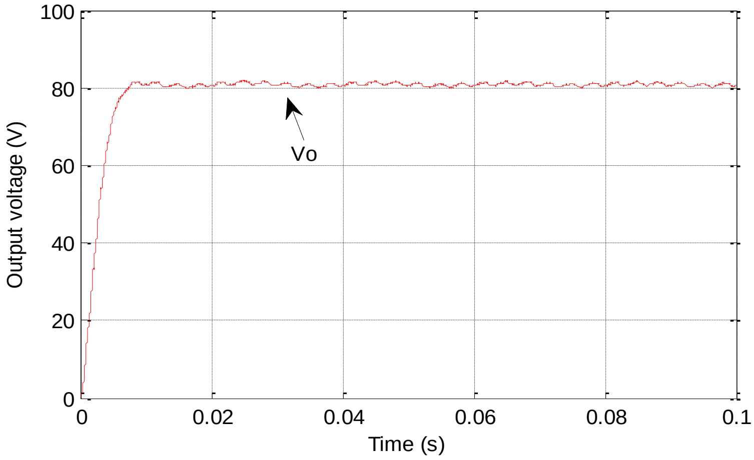


Figure 11. Simulated Output Voltage of VR Circuit Using THJ

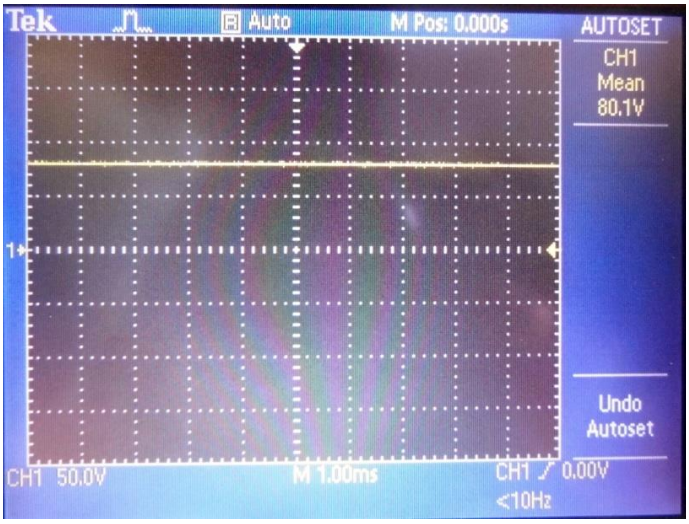


Figure 12. Experimental Output Voltage of VR Circuit Using THJ

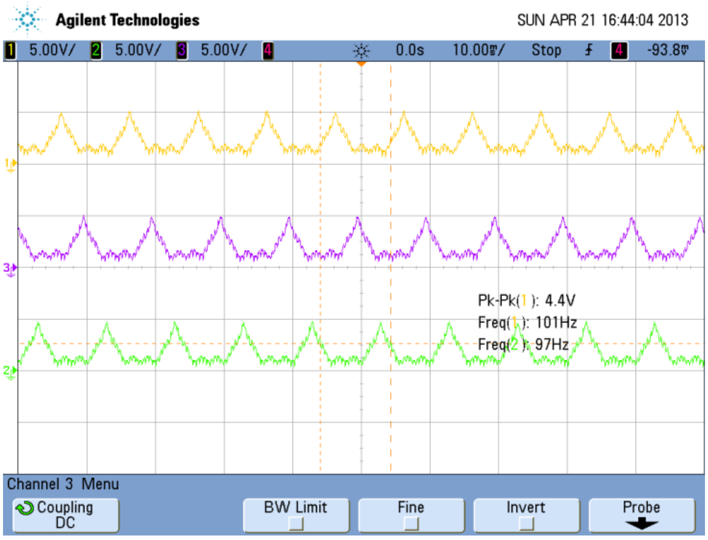
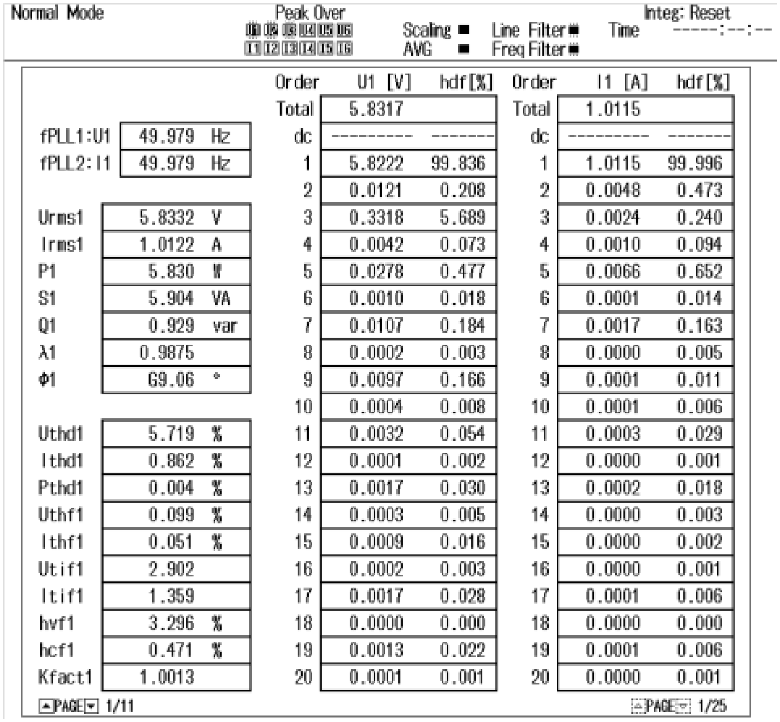


Figure 13. Experimental Reference Signals of THJ for VR Circuit


Normal Mode
Peak Over U1 U2 U3 U4 U5 U6 I1 I2 I3 I4 I5 I6
Scaling ■ AVG ■
Line Filter ■ Freq Filter ■
Integ: Reset
Time -----:--:--

fPLL1:U1	49.979	Hz
fPLL2:I1	49.979	Hz
Urms1	5.8332	V
Irms1	1.0122	A
P1	5.830	W
S1	5.904	VA
Q1	0.929	var
λ1	0.9875	
Φ1	G9.06	°
Uthd1	5.719	%
Ithd1	0.862	%
Pthd1	0.004	%
Uthf1	0.099	%
Ithf1	0.051	%
Utif1	2.902	
Itif1	1.359	
hvf1	3.296	%
hcf1	0.471	%
Kfact1	1.0013	

Order	U1 [V]	hdf[%]	Order	I1 [A]	hdf[%]
Total	5.8317		Total	1.0115	
dc	---------	-------	dc	---------	-------
1	5.8222	99.836	1	1.0115	99.996
2	0.0121	0.208	2	0.0048	0.473
3	0.3318	5.689	3	0.0024	0.240
4	0.0042	0.073	4	0.0010	0.094
5	0.0278	0.477	5	0.0066	0.652
6	0.0010	0.018	6	0.0001	0.014
7	0.0107	0.184	7	0.0017	0.163
8	0.0002	0.003	8	0.0000	0.005
9	0.0097	0.166	9	0.0001	0.011
10	0.0004	0.008	10	0.0001	0.006
11	0.0032	0.054	11	0.0003	0.029
12	0.0001	0.002	12	0.0000	0.001
13	0.0017	0.030	13	0.0002	0.018
14	0.0003	0.005	14	0.0000	0.003
15	0.0009	0.016	15	0.0000	0.002
16	0.0002	0.003	16	0.0000	0.001
17	0.0017	0.028	17	0.0001	0.006
18	0.0000	0.000	18	0.0000	0.000
19	0.0013	0.022	19	0.0001	0.006
20	0.0001	0.001	20	0.0000	0.001

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Figure 14. Harmonic Details of Phase Voltage

5. Conclusions

In this paper, the analyses of the harmonics reduction and the load voltage regulation for VR through THJ (Triplen Harmonic Injection) cum PIC (Proportional Integral Controller) ~~has~~ have been successfully demonstrated using both the MATLBA/Simulink and the prototype models. The key contribution of this paper is the VR control algorithm which is implemented using FGPA. The performance characteristics of the VR using THJ controllers are obtained at different regions of operation. The designed control has produced an improved power factor, reduced harmonics, and excellent load voltage regulation. Simulation and experimental results are presented to show the effectiveness of the proposed THJ controllers.

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