



## HIGH QUALITY RECTIFIERS WITH REDUCED THD FOR ENHANCED MAINS POWER QUALITY - VIENNA WITH SYNCHRONOUS LOGIC

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### ABSTRACT

A synchronous logic control based three-phase boost unity power factor rectifier unit that works as an interface to ensure high energy efficiency by reducing reactive power consumption, as well as to maintain a constant DC-bus voltage. This paper discusses the determination of performance characteristics of Vienna rectifier topology with the synchronous logic based control. Furthermore this enabled the design and development of a three-phase active converter system that was built and tested with the inputs and output. This paper also describes the Vienna Rectifier's power stage and synchronous logic control technique, with particular emphasis on finding differences between real prototype results and the simulation results. The design and experimental performance of a three-phase PWM rectifier with a power output of 3 kW is presented. The real prototype results confirm with the simulation results.

**Keywords:** Vienna rectifier, synchronous logic control, multi-level converter.

### 1. INTRODUCTION

There is growing awareness about line pollution and deteriorating power factor due to all prevailing inductive and non-linear loads. Utilities are as much concerned as the users. Passive power factor correction techniques like bulky line chokes with bulky capacitor filters are neither convenient nor economical; they need bulky components and are not adaptive to changing needs. Even though there are many low power and low cost applications, this draws non-sinusoidal current from the mains, which makes it inadequate for high power applications due to the strict regulations on conducted EM (electromagnetic) interference, as well as the high current stress on components. The input current must be actively sinusoidal shaped by using either a boost type front-end converter or by complex EM filtering for high power applications. The cost and size associated with EM filters make it a non preferred solution. In addition to lowering power bill to the consumers, improved power factor also contributes towards conservation of energy and helps in reducing air pollution, by virtue of less fossil fuel required for generating same amount of electrical power. Other resultant advantages are lower  $I^2R$  losses, steady terminal Voltages, reduced system capacity and reduced cable and switchgear sizes. Active PFC (Power Factor Correction) front ends also help meet the IEEE 519-92, IEC-555 and European EN 61000-3-2 standards for allowable harmonic contents of mains.

For medium power converters, many standard and proved applications with single-phase PFC are available. In most cases the front-end is usually a single-switch non-isolated boost topology that boosts the unregulated mains input to a voltage higher than the rectified line voltage. The current drawn from the mains source is in phase with the mains voltage (effectively sinusoidal) by controlling the switch. Although many solutions were offered for Single-phase power factor

correction, Three-phase active power factor correction was seldom considered.

Many high power equipments derive electrical power from Three-phase mains, incorporating an active Three-phase PFC front end can contribute significantly in improving overall power factor, reducing line pollution, lowering component stresses and reducing component size (e.g. the filter capacitor). The zero phase angle, between the mains voltage and the current, translates into a high power factor which, in turn, ensures that the source is not loaded reactively. Here one quadrant, three-phase, six-switch, three-level topology is used. Input current waveforms are controlled by six switches and the output is a positive split DC rail. The input stage of these power supply systems can be realized with either a modular topology using a star connection or delta-connection of single-phase boost rectifier modules with individual DC output voltages, or a direct three-phase rectifier topology, such as the Vienna Rectifier, where the DC output voltage is common to all phases. This topology mentioned is also known as the VIENNA rectifier and most of the current research focuses on this type of rectifier and its variants. The three-level structure of the Vienna Rectifier results in low blocking voltage stress on the power semiconductors and small input inductor volume. Therefore, the Vienna Rectifier is the ideal choice for the implementation of a high power, unity power factor rectifier that also has a high power density. This approach achieves three-phase power factor correction and reduced current harmonics and also offers many advantages and convenient, user-friendly features.

Amongst them are:

- a) Continuous sinusoidal input currents that allow compliance with the low-frequency harmonic limits defined in the technical report IEC 61000-3-4 for any power range, with unity power factor and extremely low distortion;



- b) No need for a neutral wire; reduction in voltage stress and switching losses of power semiconductors by almost 40%;
- c) Immunity towards variation or unbalance in mains three-phase voltages or absence of one of the phases;
- d) Wide mains voltage range: 160VAC to 520 VAC;
- e) Very low conducted common-mode EMI/RFI; very high efficiency of the order of 97.5%, for high power levels of about 30 kW and nominal input line voltage and
- f) Short circuit immunity to failure of control circuit.

The Vienna Rectifier topology can be implemented with either three switches or six switches. In this design, a six switch Vienna Rectifier (see Figure-1) is selected as it has lower conduction losses since the phase current flows through only one diode in each phase during the switch conduction and it is guaranteed that the switch voltage is clamped to half the output voltage.

The rectifier presented in this paper uses the most advanced synchronous logic control that can be used as an interface for three-phase AC sources and a DC-bus. The paper enables the confirmation of performance characteristics of VIENNA based rectifier topologies in the real world applications. This paper describes the Vienna Rectifier's power stage and synchronous logic control techniques, with particular emphasis on finding differences between real prototype results and the simulation results.

Furthermore this enables the design and development of an equivalent three-phase active rectifier (converter) system that is built and tested with the inputs and output. The results confirm the theoretical analysis. The rectifier is designed to operate over a wide line-to-line input voltage range of 160 to 520 VRMS, with a nominal input voltage of 400 VRMS and nominal power output of 3 kW. For an output voltage of 900 V and a power of 3 kW, the input phase current is approximately 4.5 A RMS. This paper presents the design and experimental results of a new forced air cooled, three-phase, six-switch PWM Vienna Rectifier that is designed to deliver 3 kW of output power. The complete paper is organized as follows: Section 2 explains design strategy of Vienna Converter. Section 3 discusses details of the converter analysis. The simulation results, comparison and discussion are presented in Section 4. Details on the experimental performance, such as the input currents and respective harmonics, output voltage, load current, mid-point voltage and input voltages are given in Section 5. The overall converter system performances with the synchronous logic control implementation are concluded in Section 6. The various papers and literature searched and referred in completing this paper are listed in Section 7.

## 2. DESIGN (EXAMPLE)

In this section, the design example of a converter is presented which is having the following specifications:

Input voltage:  $u_{NR} = 230V_{rms}$   
 Output power:  $P_o = 3 \text{ kW}$

Estimated converter efficiency (%):  $\eta = 93\%$

The design procedure is as follows:

- (a) Choose a suitable sinusoidal switching pattern for the Inverter three-phases. Enough lead angle range accommodated in order to keep the output voltage constant even under reduced load conditions. It is necessary to control the switch on-time, to comply with the technical report IEC61000-3-4, also at very high input mains voltage.
- (b) Select the switching frequency of the Bi-Directional switches (Transistors and Diodes) based on the type (MOSFET or IGBT) and voltage and current for the specified load  $P_o$ . The selected switching frequency is 50 kHz.
- (c) Select the Boost diodes for positive and negative sides based on the voltage, current and power for the specified load  $P_o$ .
- (d) Calculate the input filter inductance value needed for the specified input power  $P_{in} = P_o/\eta$ .
- (e) Calculate the input filter capacitance value needed for the specified input power  $P_{in}$ .
- (f) Calculate the input main inductance value needed for the specified input power and selected constant switching frequency.
- (g) Calculate the output storage capacitance value needed for the specified output power, required ripple and ride through time needed.
- (h) Verify the input current harmonic content at various output power levels with R, RL (fixed) and RL (variable) loads.
- (i) Verify system efficiency at various output power levels with R, RL (fixed) and RL (variable) loads.

## 3. CONVERTER ANALYSIS

The proposed three-phase high-quality rectifier is shown in Figure-1.

As we can see, it is formally topologically similar to the Vienna rectifier the output capacitors are C1 and C2. sR, sS, sT are bi-directional switches which can be built by using one switch and a diode bridge rectifier each or two switches and two diode rectifiers each. All these components are switched in such a manner that it reduces EMI and losses and allows for the utilization of smaller magnetics, thus saving cost and improving converter reliability. Moreover, the input inductors are standard high-frequency low-cost powdered iron-core or ferrite-core type.

Input current and capacitor voltage waveforms are calculated in the line half period, assuming the following conditions:

- Balanced three-phase input voltages;
- Voltages V1 and V2 across the two output capacitors C1 and C2 satisfying the following inequality:  $0 < V1, V2 < V_o$ ;
- Constant output voltage  $V_o$ ;

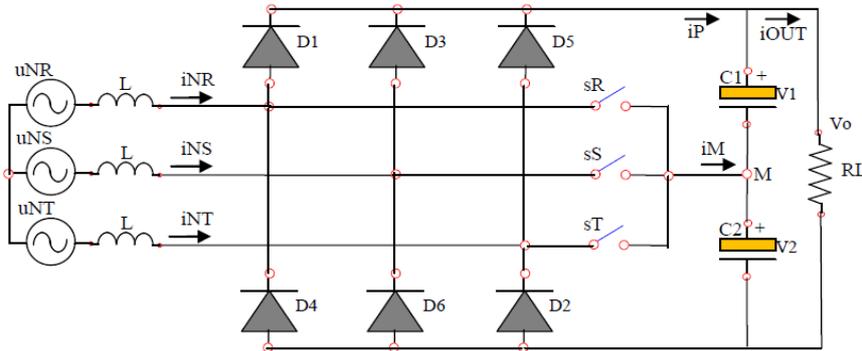


Figure-1. Scheme of the proposed three-phase high-quality rectifier.

**A. PLL control**

A new control technique is proposed which uses a three-phase PLL (phase lock loop) and incorporates the capability of instantaneously detecting a mains phase angle variation, and therefore is able to provide the appropriate compensation signal. The slew rate for the PLL is adjusted as 0.1HZ per second. The total tracking range has been fixed at 6% positive and 6% negative.

**B. Synchronous logic control**

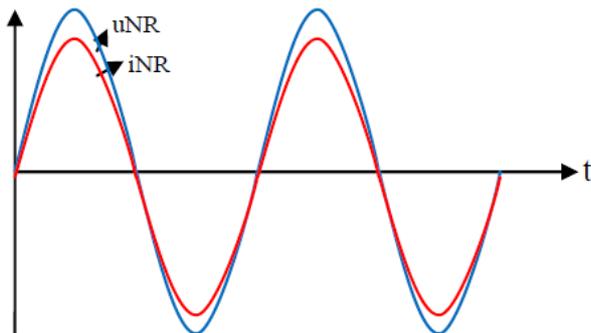


Figure-2(a). Input voltage and current wave forms of Vienna rectifier at unity power factor operation.

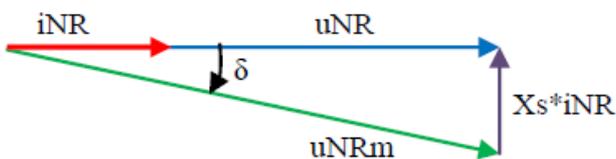


Figure-2(b). Rectifier operation of the Vienna rectifier at unity power factor.

**4. SYSTEM SIMULATION**

At nominal power level, it is possible to keep the output voltage constant for input under voltage situations also provided the input current is kept under the limits of the source capacity. In this case the switches on-time must be increased, increasing the boost effect. It is possible to compensate for input over-voltages provided the difference in potential of the peak source voltage is reasonably lower than the output voltage. Eventually some harmonics can be above the limits for input over voltages, but the measurement test applies only for the rated voltage.

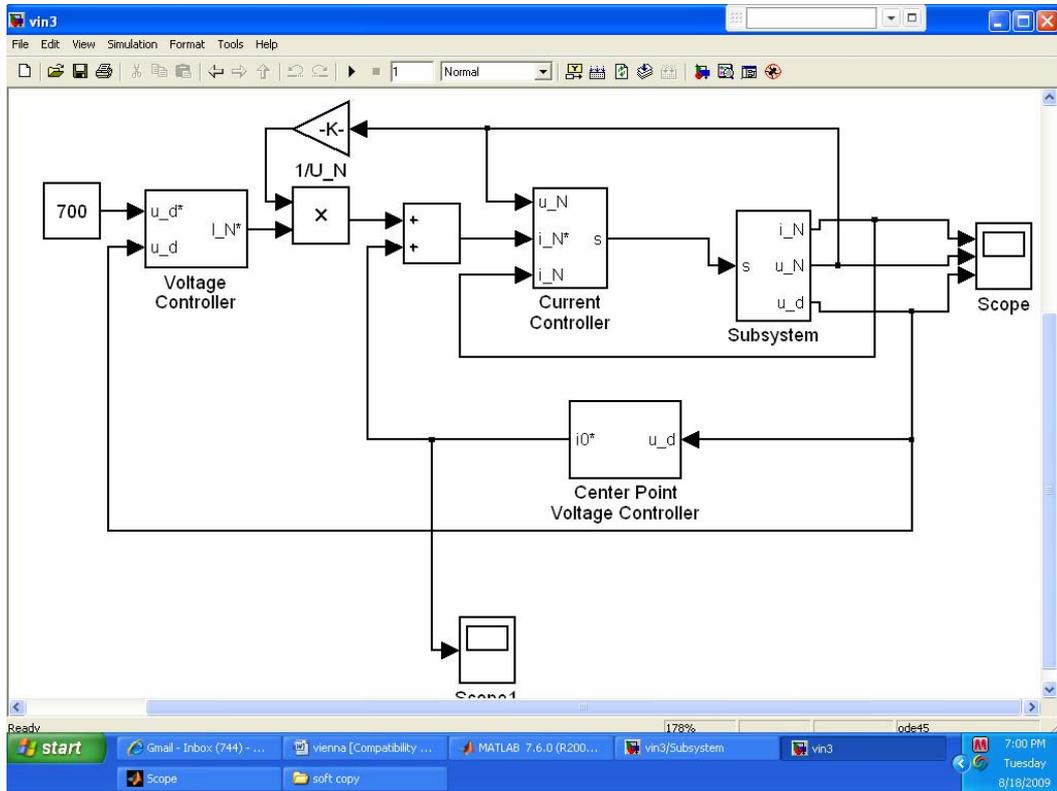
The major benefit of this converter, as compared to the simple bridge rectifier with capacitor, is the reduction of the input current harmonic content. Since this converter is suitable for high power applications, take the harmonic limits described in the technical report IEC 61000-3-4 as reference: “Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A per phase”.

Simulations have been performed in order to verify the input current harmonic content at different power levels (keeping the output voltage constant). Tabulated results by changing the loads on the output with R, RL and RL variable type and presented in the following Figures. The control strategy has enough lag and lead angle “δ” to keep the output voltage stable, while keeping constant their sinusoidal PWM switching pattern.

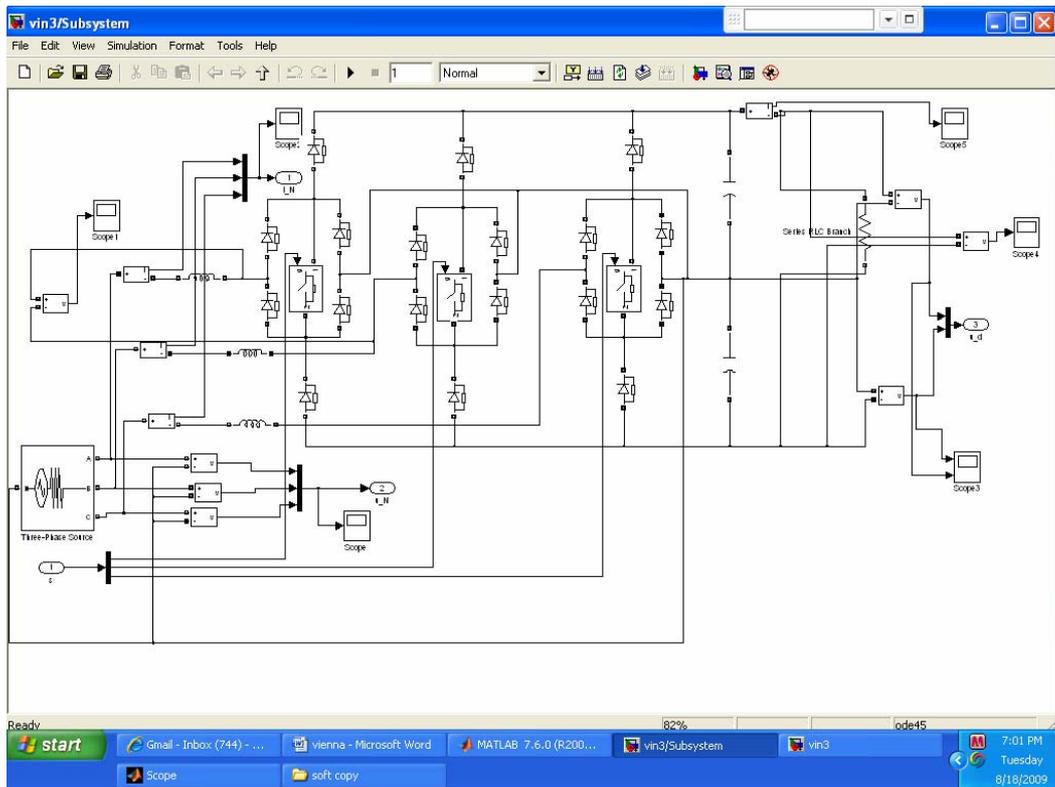
The simulation, at nominal conditions, gives an average output voltage of 899V, and the input current harmonics spectrum is much lower than the required levels as per the statutory requirements. The simulation and its results are shown in Figure-3 and Figure-4 respectively with Resistive (R) Load. The input current is,  $i_{NR} = 4.77A$  (corresponding to 3kW) at 232V input voltage, only harmonics 5th, 7th, 11th, 13th, and 17th, are considered. Third and its multiples are negligible to consider.



**A. Simulation**



**Figure-3(a).** Vienna rectifier voltage controller.



**Figure-3(b).** Vienna rectifier main circuit.

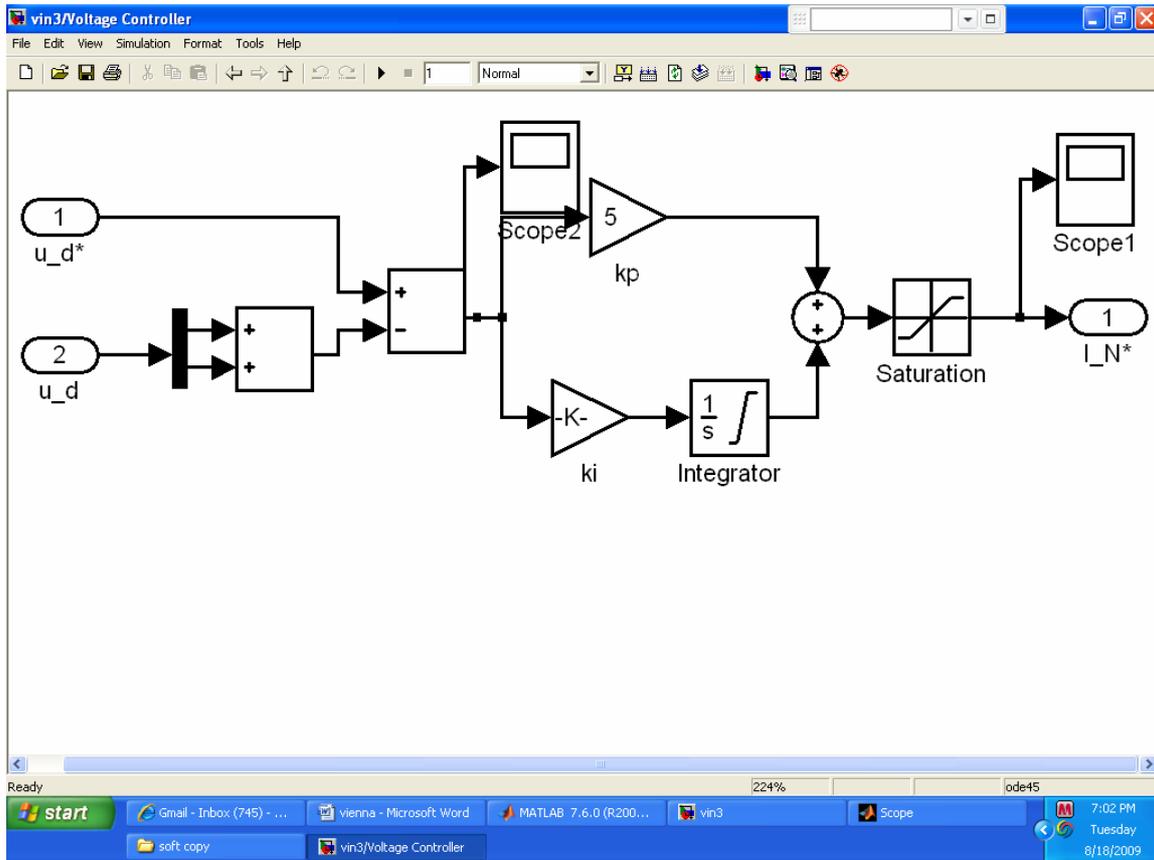
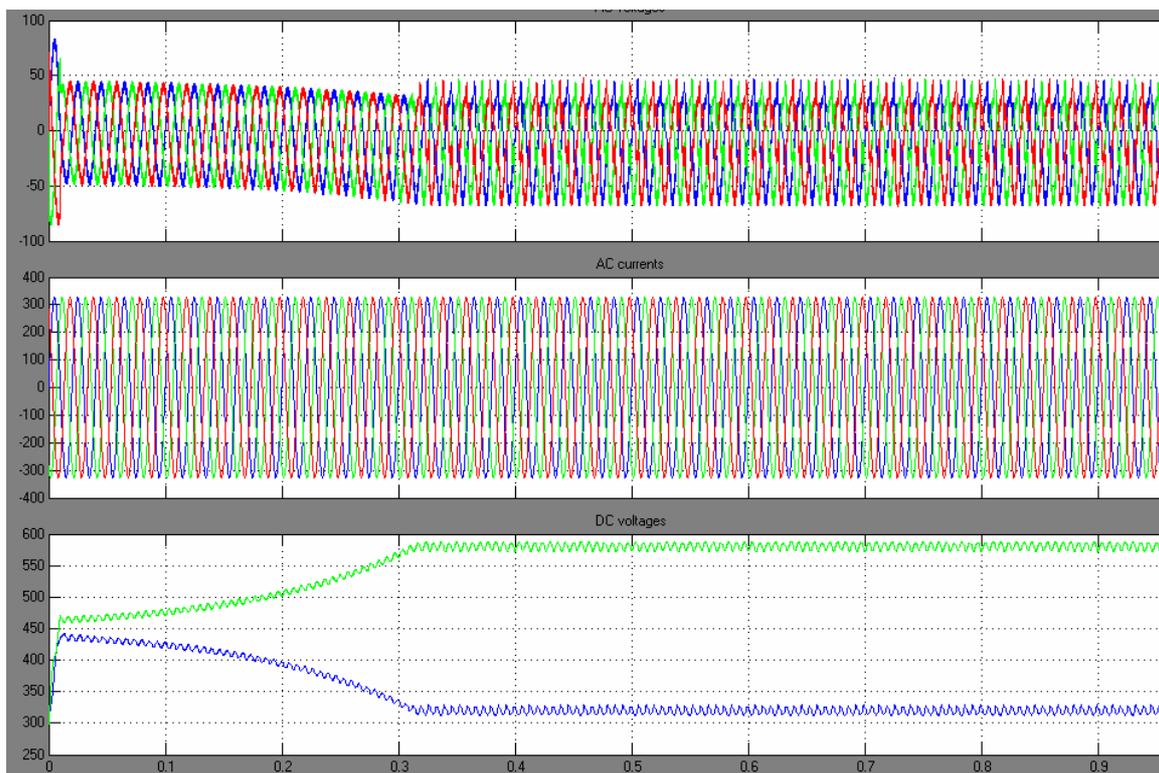


Figure-3(c). Vienna rectifier with PI controller (Synchronous Logic).

**B. Simulation results**



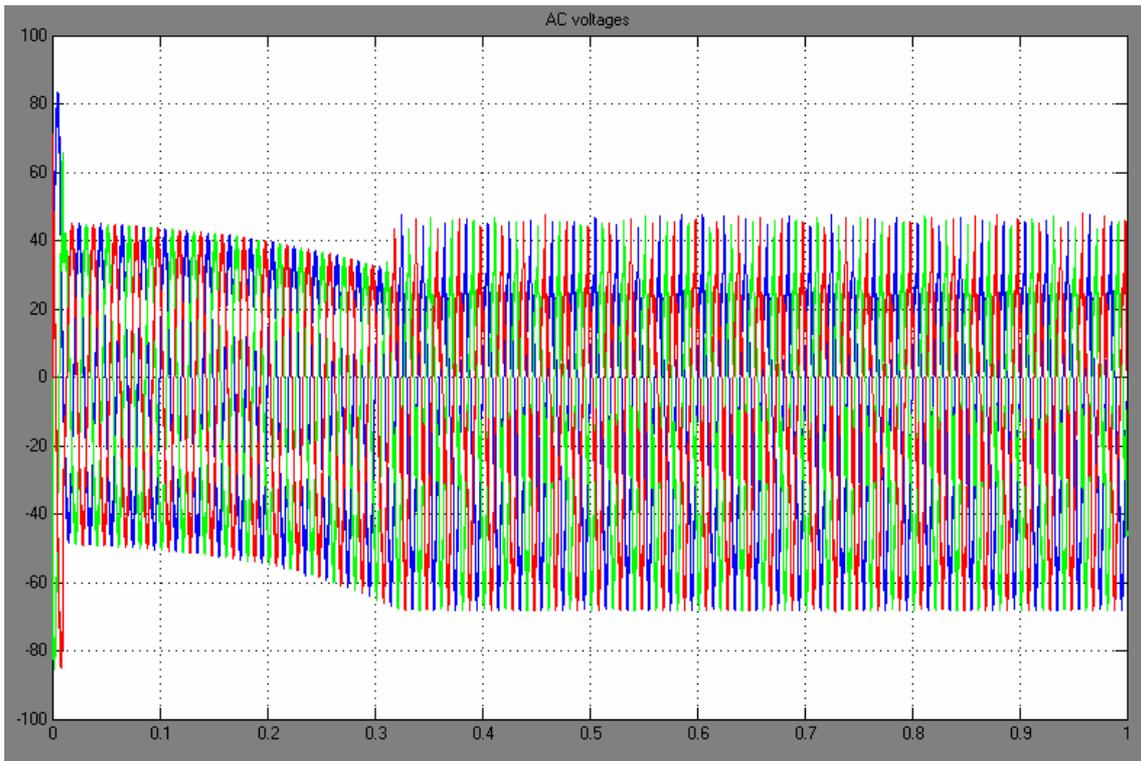
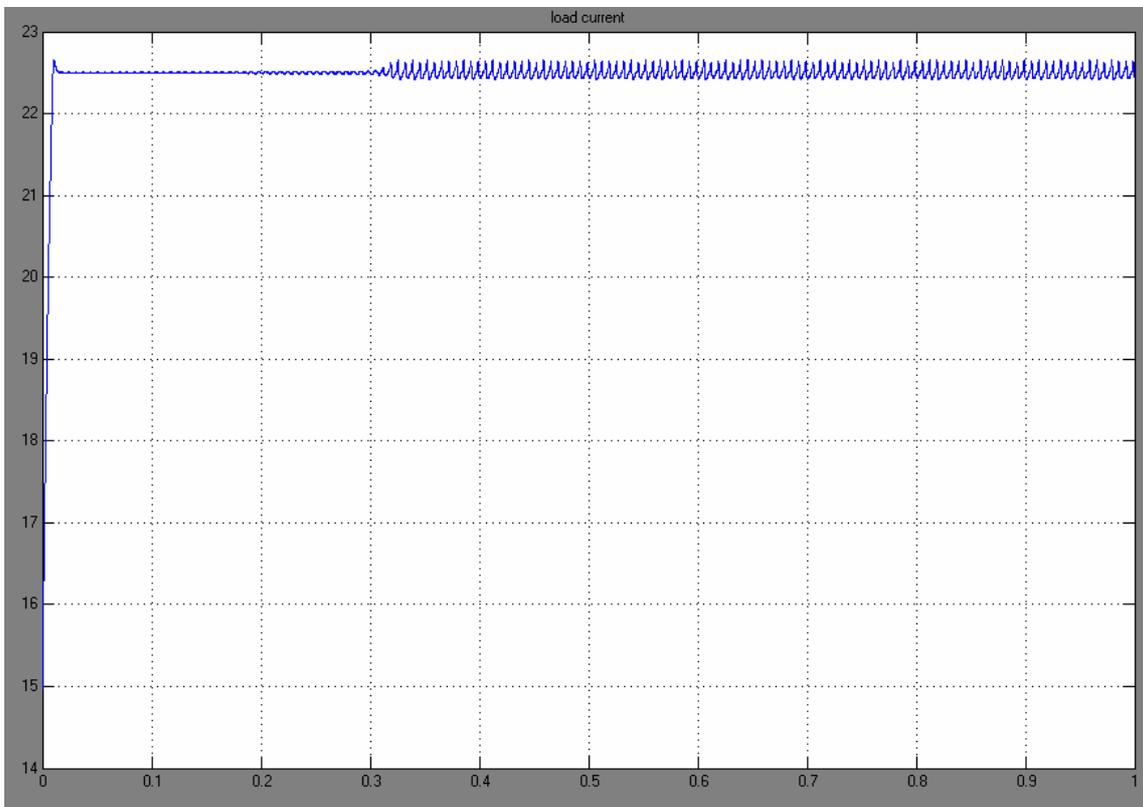


Figure-4(a). Vienna rectifier input voltages, output capacitor voltages and center point voltage.



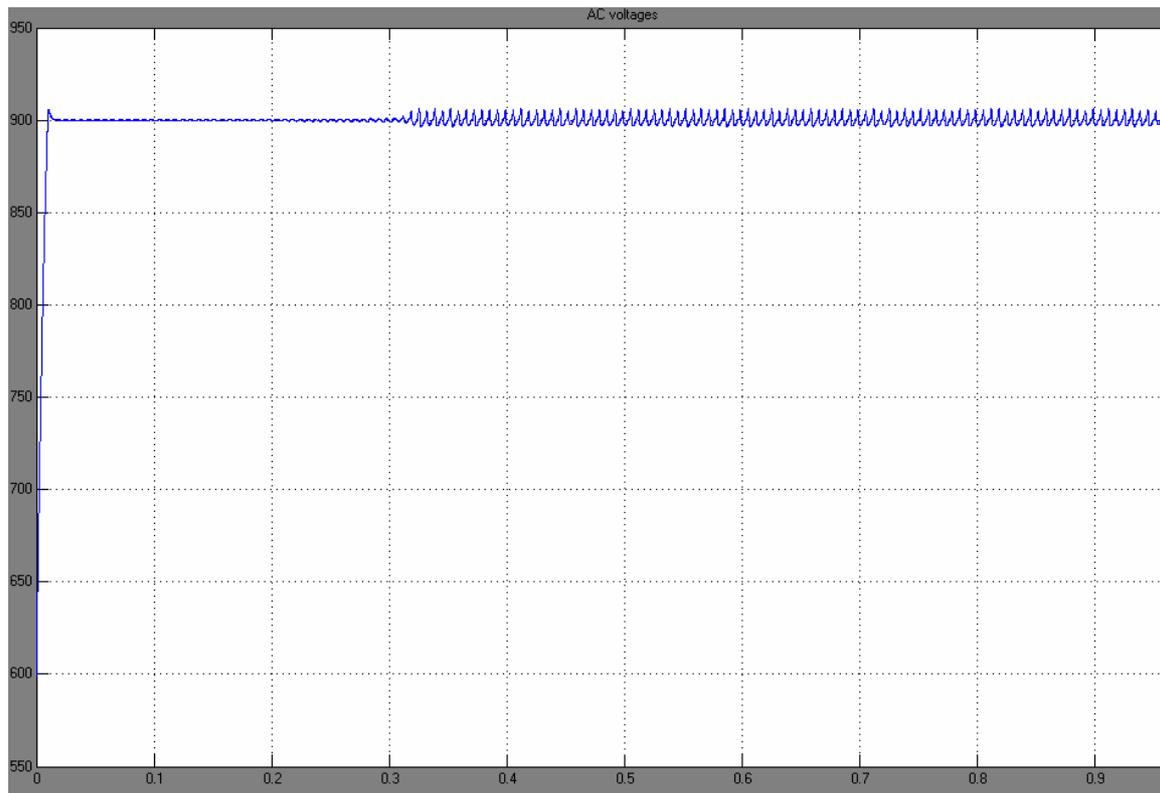


Figure-4(b). Vienna rectifier load current and voltage.

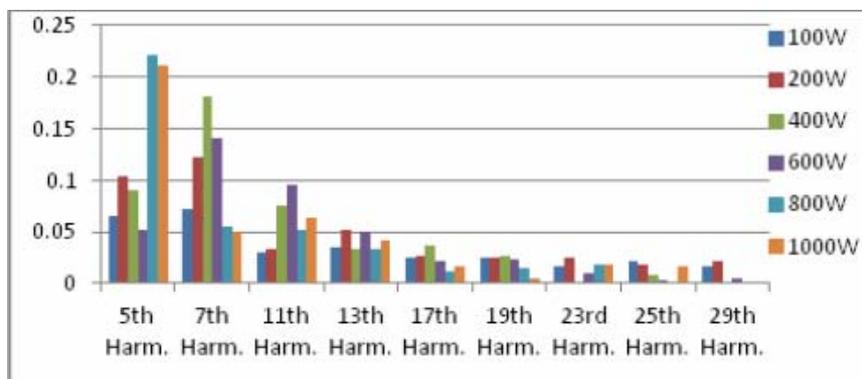


Figure-4(c). Simulation results of input current harmonics at different resistive load levels.

## 5. EXPERIMENTAL RESULTS

In order to verify the concept, a prototype of a three-phase VIENNA rectifier with proposed control approach using synchronous logic with line current sensing was built with following specifications: Input voltage 230VAC; Output voltage: 900VDC and Output power 3 kW.

The VIENNA rectifier used in the experiment is shown in Figure-1. The real proto-type setup is shown in Figures 5(a), power section and 5(b), logic section. The power supply, some line filters and output load sections are not shown due to space constraints. The experimental set-up with appropriate components chosen is as follows: three-phase Input filter inductance, Input filter

capacitance; main inductance; Output Capacitance, Fast Recovery Diodes, the three main bi-directional switches sR, sS and sT are implemented with two IGBT s in series with two FRDs (Fast Recovery Diodes) in series as shown in Figure-5(c). The output load resistance R is 270 ohm (Three 806 Ohms load coils in parallel). The switching frequency is 50 kHz. The experimental waveforms are shown in Figure-6. Three-phase Input Current waveforms (Ch1 - Ch3) of iNR, iNS, iNT and Input phase Voltage waveform (Ch4) of uNT at 230 V phase Voltage when an Output Resistive Load of 3 kW applied.

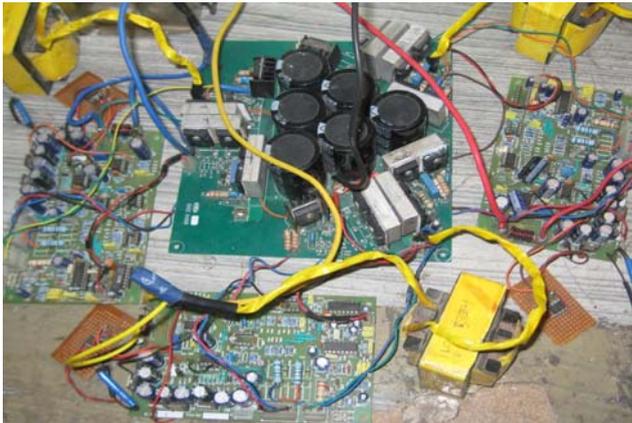


Figure-5(a). Real-Lab prototype set up of the Vienna rectifier power section.



Figure-5(b). Real-Lab prototype set up of the Vienna rectifier logic section.

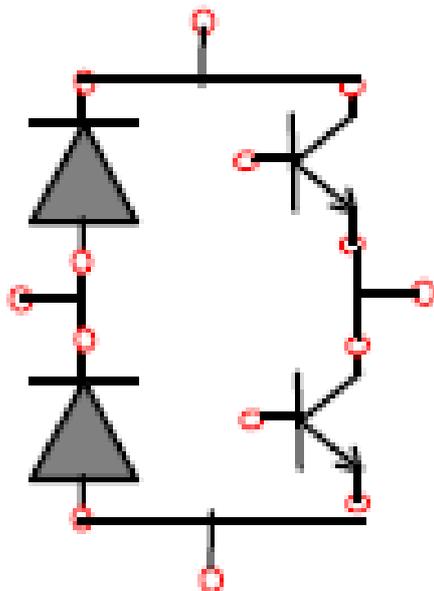
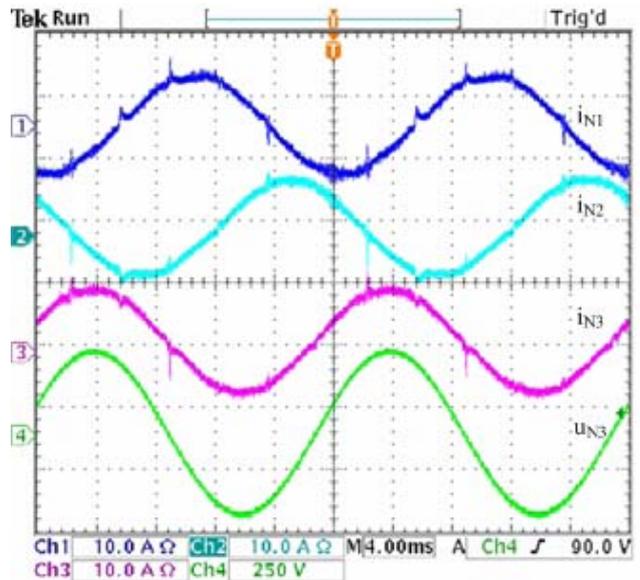


Figure-5(c). Bi-directional switch used in the prototype.



Ch1: 6A, Ch2: 6A, Ch3: 6A, Ch4: 250V; Scale: 4.0 ms; Trigger: Ch4 +90V

Figure-6. Three-phase Input Current waveforms (Ch1-Ch3)  $i_{NR}$ ,  $i_{NS}$ ,  $i_{NT}$  and input phase voltage waveform (Ch4) of  $u_{NT}$  at 232 V when Resistive Load of 3 kW applied on output.

Readings have been taken in order to verify the input current harmonic content at different power levels (keeping the output voltage constant). Tabulated readings of current harmonics and efficiency, by changing the loads on the output with R, RL and RL variable type and presented in the following Figures 7(a), 7(c), 7(e) and 8, respectively. The measured power factor is 0.994 and the output voltage 900V. Output Voltages and current are shown in the following Figures 7(b), 7(d) and 7(f), respectively. The current spectrum shown in Figure-7(a) is with Resistive (R) Load. The input current is,  $i_{NR} = 4.68A$  (corresponding to 3kW) at 237V input voltage, only harmonics 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, 13<sup>th</sup>, and 17<sup>th</sup>, are considered. Third and its multiples are negligible to consider. The efficiency at rated power is 91%.

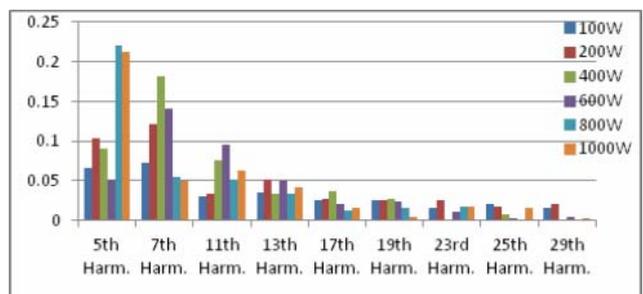
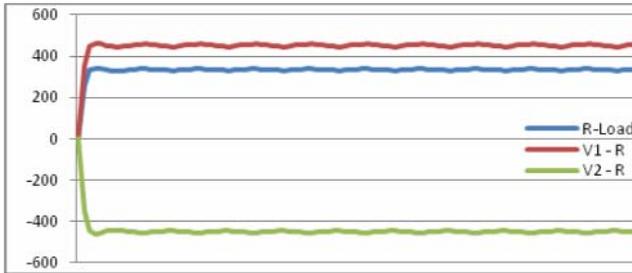
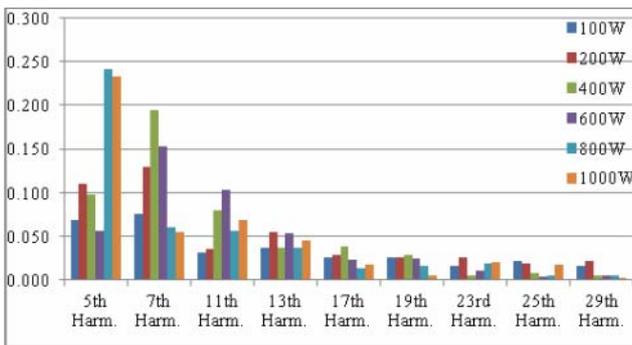


Figure-7(a). Input current harmonics at different resistive load levels.

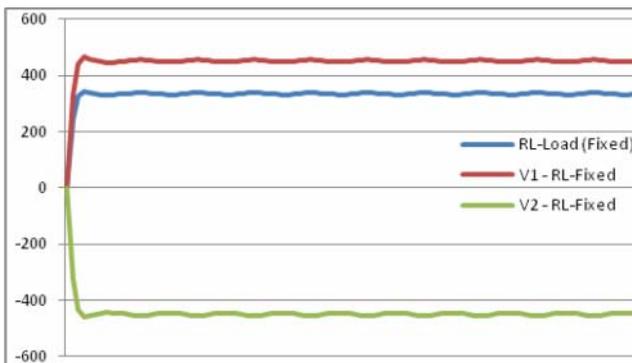


**Figure-7(b).** Output voltage and current when resistive load of 3 kW applied on output.

The current spectrum shown in Figure-7(c) is with Resistive and Inductive (RL) Load with a fixed power factor. The input current is,  $i_{NR} = 4.82A$  (corresponding to 3kW) at 236V input voltage, only harmonics 5th, 7th, 11th, 13th, and 17th, are considered. Third and its multiples are negligible to consider. The efficiency at rated power is 89%.

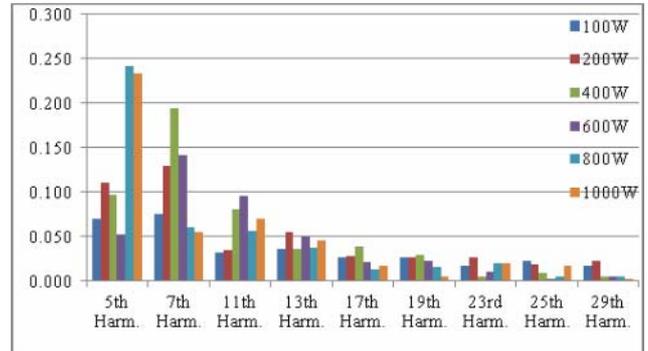


**Figure-7(c).** Input current harmonics with resistive and Inductive (RL) Load with a fixed rated power factor.

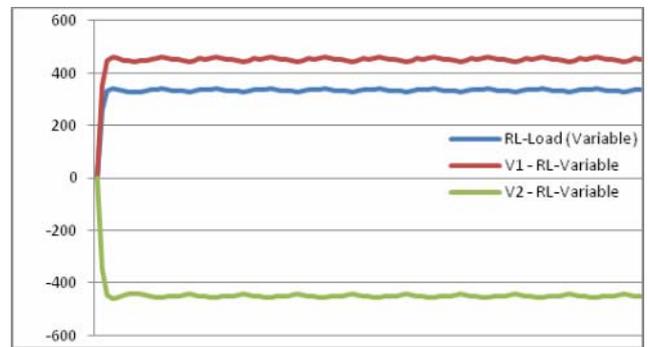


**Figure-7(d).** Output voltage and current when fixed resistive and inductive (RL) Load of 3 kW applied on output.

The current spectrum shown in Figure-7(c) is with Resistive and Inductive (RL) Load with variable power factor from unity to rated level. The input current is,  $i_{NR} = 4.80A$  (corresponding to 3kW) at 236V input voltage, only harmonics 5th, 7th, 11th, 13th, and 17th, are considered. Third and its multiples are negligible to consider. The efficiency at rated power is 89%.

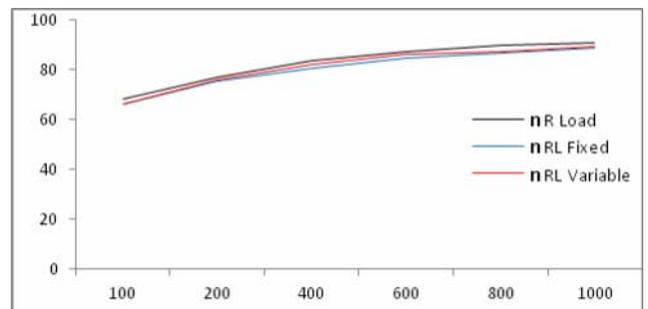


**Figure-7(e).** Input current harmonics with resistive and inductive (RL) load with variable rated power factor from unity to rated.



**Figure-7(f).** Output voltage and current when variable resistive and Inductive (RL) Load of 3 kW applied on output.

The efficiency shown in Figure-8 is with Resistive, Resistive and Inductive (RL) Load with fixed power factor and with variable power factor from unity to rated. Tabulated measurements by changing the loads on the output of the setup. The efficiency varied based on the type of load and also percentage of the load from 66% to 91%.



**Figure-8.** Efficiency with various load levels.

The various working details of the Vienna Rectifier are shown in Figures 9(a) to 9(f) at various important transitional points of all three-phases. So, there are six main transitional points to review in a cycle. The direction of the current and the power flow are the areas of



importance in understanding the workings of the Vienna Rectifier.

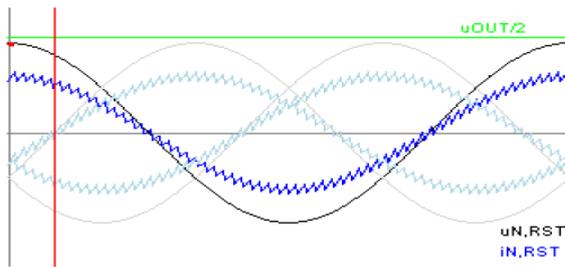
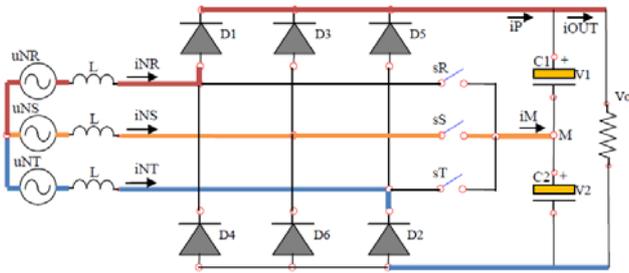


Figure-9(a). Phase S moving to its positive side from negative.

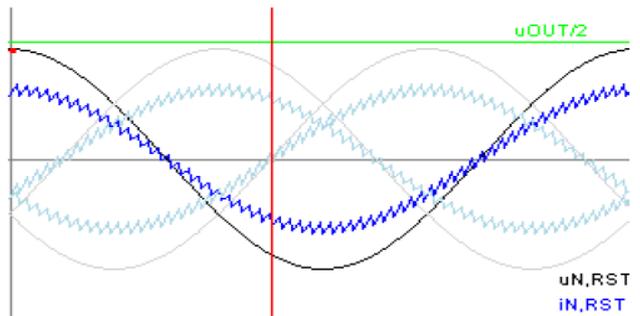
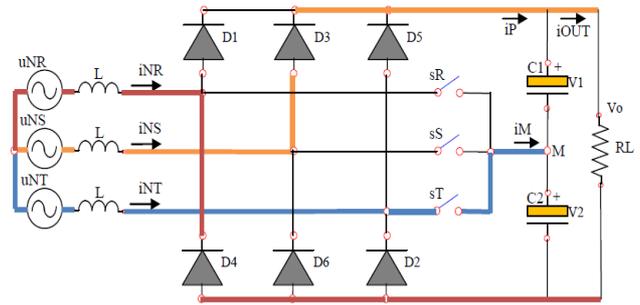


Figure-9(c). When Phase T moving to its positive side from negative.

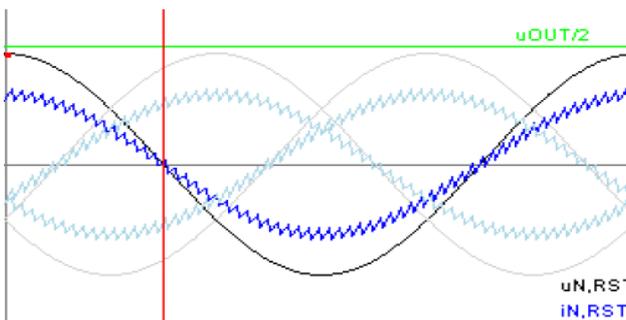
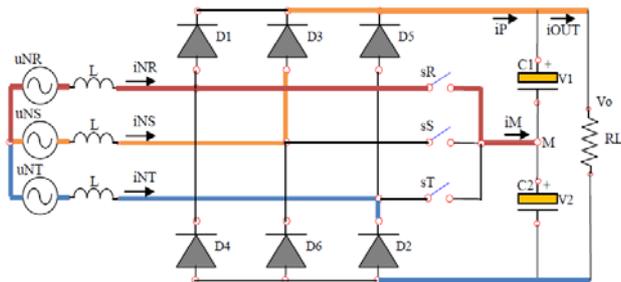


Figure-9(b). When Phase R moving to its negative side from positive.

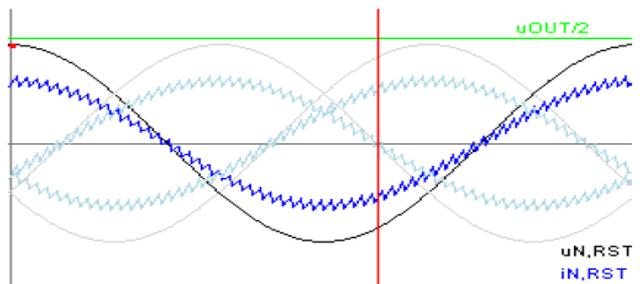
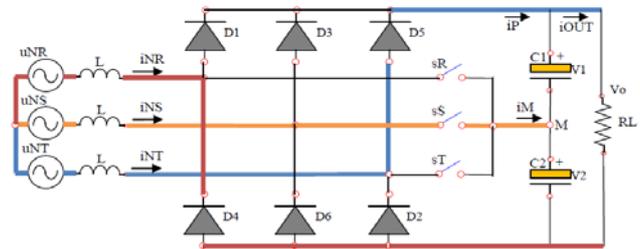


Figure-9(d). Phase S moving to its negative side from positive.

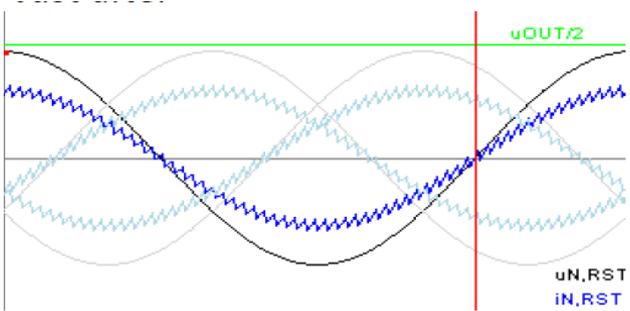
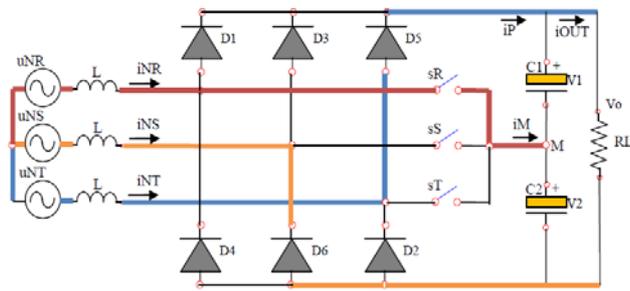


Figure-9(e). When phase R moving to its positive side from negative.

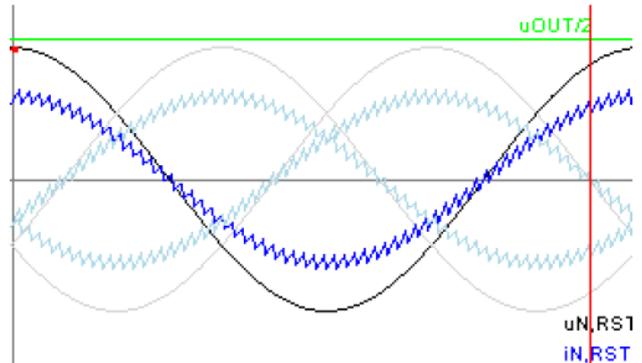
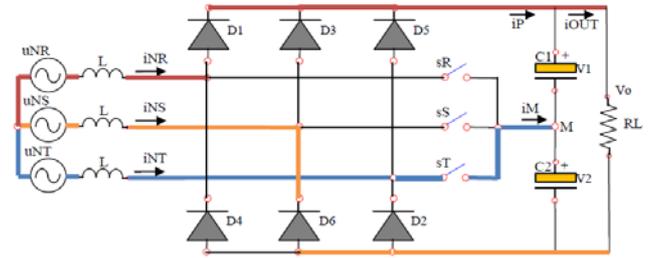


Figure-9(f). When Phase T moving to its negative side from positive.

Details of various switch conditions; voltage and current waveforms are shown in Figures 10(a) and 10(b), just before and just after phase T moving to its negative side from positive side, respectively.

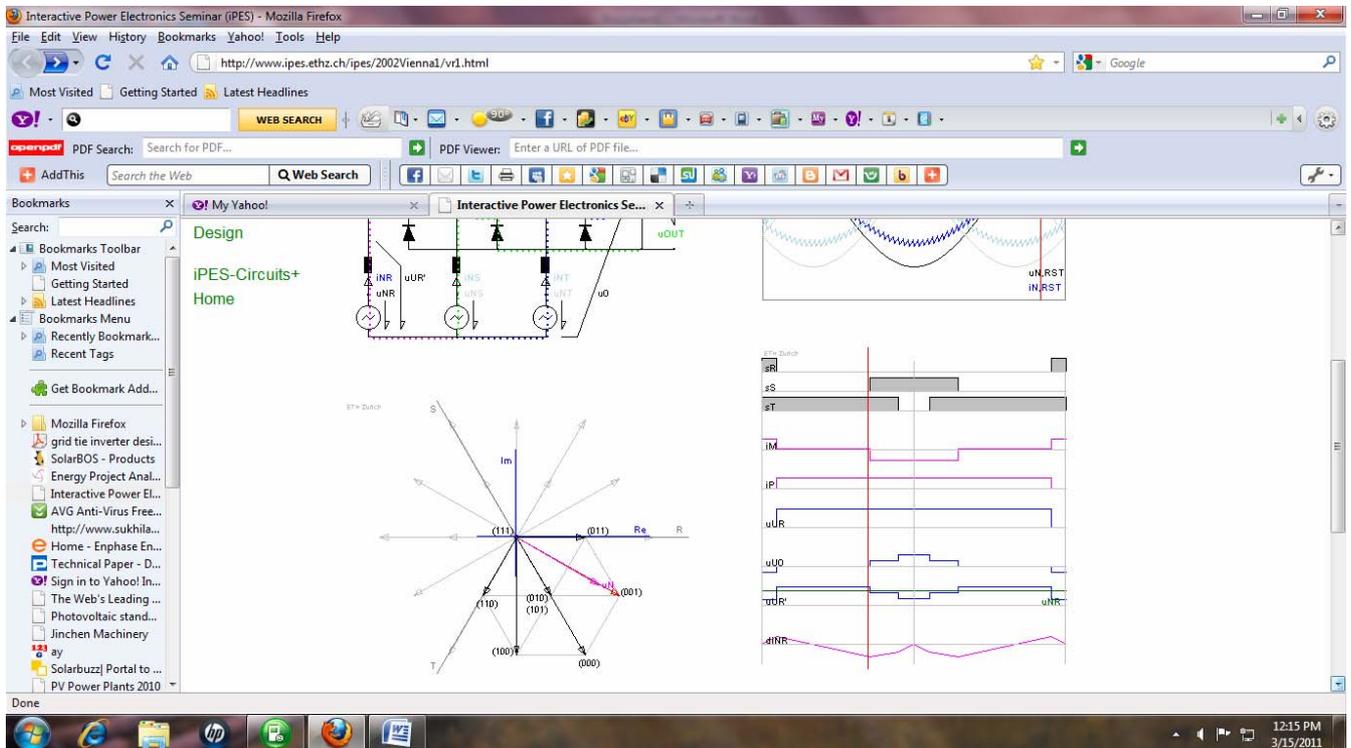


Figure-10(a). Just before phase T moving to its negative side from positive.

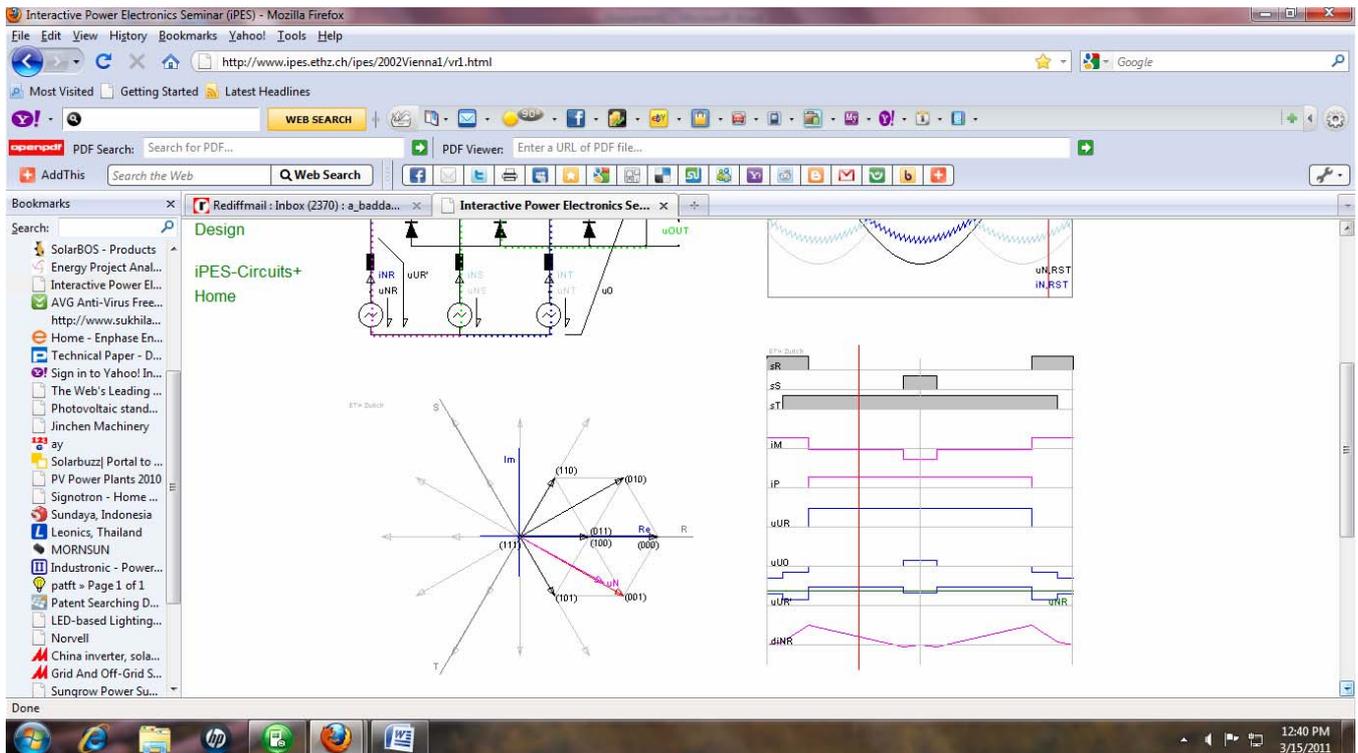


Figure-10(b). Just after phase T moved to its negative side from positive.

## 6. CONCLUSIONS

The proposed three-phase three-switch three-level (VIENNA) rectifier circuit with unity power factor is investigated and is able to control current distortion that is generally produced by diode bridge rectifiers with capacitive filter. A new three-phase synchronous logic control is introduced and simulations show that it can produce very low output voltage ripple and very low input current harmonics with unity power factor. The resulting current harmonics are below the limits of IEC 61000-3-4 for any power level. It is possible to compensate for input over-voltage also by adjusting the sinusoidal PWM control signals for bidirectional switches.

Under conditions of mains voltage imbalance there is a deterioration of power factor and the occurrence of output voltage ripple. As the IEC1000-3-2 harmonic emissions standard is defined for ideal mains conditions, the temporary loss of unity power factor is inconsequential. This is an area of investigation for other researchers to follow up to get a better understanding. A new technique is introduced that utilizes a three-phase, phase lock loop as part of a control strategy to compensate for mains imbalances. Simulation shows that under these conditions very low voltage ripple is achieved.

An experimental circuit of a 3 kW VIENNA rectifier was built to verify the concept. Near unity power factor was measured in all three-phases. The proposed controller is implemented by sensing input voltages, currents, output currents and output voltage. The controller is very simple and reliable. The inductance value is reduced as compared to the purely passive filter circuit. The experimental results confirm the circuit behavior.

## REFERENCES

- Interactive Power Electronics Seminar, Simulation of the circuits from <http://www.ipes.ethz.ch/ipes/2002Vienna1/vr1.html>
- Kolar J.W, Drofenik Zach F.C., Current handling capability of the neutral point of a three-phase/switch/level boost-type PWM (VIENNA) rectifier. PESC 96 Record. 2: 1329-1336.
- Kolar J.W, Ertl H., Zach F.C. 1996. Design and experimental investigation of a three-phase high power density high efficiency unity-power-factor PWM (VIENNA) rectifier employing a novel integrated power semiconductor module. APEC'96, San Jose, CA. IEEE. 2: 514-523.
- Kolar J.W., Zach F.C. 1997. A novel three-phase utility interface minimizing line current harmonics of high power telecommunications rectifier's modules. IEEE Trans on Industrial Electronics. Vol. 44, IEEE. pp. 456-467.
1998. Commission Electro technique International, IEC 61000-3-4. Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A per phase. 3 rue de Varembe, Genève, Switzerland.
- Qiao C. and Smedley K.M. A General Three-phase PFC Controller. Part I for rectifiers with a Parallel-connected Dual Boost Topology. IEEE IAS'99.



Qiao C. and Smedley K.M., A General Three-phase PFC Controller. Part II for rectifiers with a Series-connected Dual Boost Topology. IEEE IAS'99.

E. L. M. Mehl, I. Barbi. 2000. An Improved High-Power Factor and Low-Cost Three-phase Rectifier. IEEE Trans. On Industry Applications. Vol. 33, NO.2, March/April, 1997, pp. 485-492. Industry Applications, 36(4): 1189-1196.

J.W. Kolar, F. Stögerer, Y. Nishida. 2001. Evaluation of a Delta-Connection of Three Single-phase Unity Power Factor Rectifier Systems (Delta-Rectifier) in Comparison to a Direct Three-phase Rectifier Realization. Part I - Modulation Schemes and Input Current Ripple. Proceedings of the 7<sup>th</sup> European Power Quality Conference (PCIM) Nuremberg. pp. 101-108. June 19, 21.

J. A. G. Marafao, J. A. Pominio, G. Spiazzi. 2001. A High-Quality Three-phase Rectifier complying with IEC 61000-3-4 Standards. 6<sup>th</sup> Congresso Brasileiro de Elettronica de Potencia (COBEP), Florianopolis, November. pp. 162-167.

H. Ohashi. 2003. Power electronics innovation with next generation advanced power devices. The 25<sup>th</sup> International Telecommunications Energy Conference INTELEC '03. pp. 9-13. October, 19-23.

T. Nussbaumer, M.L. Heldwein and J.W. Kolar. 2004. Differential Mode EMC Input Filter Design for a Three-phase Buck-Type Unity Power Factor PWM Rectifier. Proceedings of the 4th International Power Electronics and Motion Control Conference Xian. 3: 1521-1526. August 14-16.