

3-Phase Power Factor Correction, Using Vienna Rectifier Approach and Modular Construction for Improved Overall Performance, Efficiency and Reliability¹

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1.0 Abstract:

While applications for 1-Phase PFC are now familiar and prevalent, the same is not the case with 3-Phase PFC. Many equipments using kilowatts of power from 3-Phase mains should be candidates of 3-Phase power factor correction, because several advantages ensue, both to the user of the equipment and to the utility. The Vienna Rectifier approach to achieve 3-Phase power factor correction offers many advantages and convenient, user-friendly features as compared to the two-level, six-switch boost PWM Rectifier. Amongst them are: continuous sinusoidal input currents with unity power factor and extremely low distortion; no need for a neutral wire; reduction in voltage stress and switching losses of power semiconductors by almost 40%; immunity towards variation or unbalance in mains 3-Phase voltages or absence of one of the phases; wide mains voltage range: 320VAC to 575 VAC; very low conducted common-mode EMI/RFI; very high efficiency of the order of 97.5%, say, for power levels of 10 KW and input line voltage of 400 VAC and short circuit immunity to failure of control circuit. The paper describes the Vienna Rectifier's power stage and control techniques, with particular emphasis on modular construction. What is proposed in this paper is a new approach of employing Fuzzy Logic for building controller for Vienna Rectifier DCB Modules for 3-Phase AC to DC power conversion.

2.0 Overview

In the past decade, there is growing awareness about line pollution and deteriorating power factor due to all pervading inductive and non-linear loads. Utilities are as much concerned as the users. Passive power factor correction techniques are neither convenient nor economical; they need bulky components and are not adaptive to changing needs. Although many solutions were offered for 1-Phase power factor correction, 3-Phase active power factor correction was seldom considered. As all high power equipments derive electrical power from 3-Phase mains, incorporating an active 3-Phase PFC front end can contribute significantly in improving overall power factor and reducing line pollution.

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

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effects are lower I^2R losses, steadier terminal Voltages, released system capacity and reduced cable & switchgear sizes. Active PFC front ends also help meet the IEEE 519-92, IEC-555 and European EN 61000-3-2 standards for allowable harmonic contents of mains.

2.1 Advantages

Although there are some passive and active 3-Phase PFC solutions, Vienna Rectifier is unique by virtue of its embodiment of several advantages:

1. It is a 3-Phase, three level PWM rectifier, utilizing three MOSFETS, with controlled output Voltage; three wire input, not requiring any connection to Neutral.
2. It is a dual boost type PFC with continuous sinusoidal input current and unidirectional power flow
3. It needs only three active switches, i.e. MOSFETS
4. It is Operational even in presence of unbalanced mains or only two phases.
5. Total switching losses are reduced by a factor of six, assuming switching frequency below 50 KHz.
6. Any malfunction in control circuit does not manifest itself in short circuit of output or PFC front end.
7. Sinusoidal input currents with Power Factor = 0.997, THD<5% and overall efficiency > 97% are obtainable with current designs.

As can be seen, Vienna Rectifier is the 3-Phase PFC solution that needs to be fully exploited. Readymade Vienna Power Semiconductor modules, embodying MOSFETS+ FREDs to make a stand alone Direct Copper Bonded Power Circuit, make it quite convenient and user-friendly. Powerful, yet inexpensive, microcomputers and DSPs make it attractive to design compact controllers for the Vienna Rectifiers.

A new approach of employing Fuzzy Logic for building embedded controller for Vienna rectifier for 3-Phase AC to DC power conversion is proposed here.

3.0 Applications

A large number of industrial, telecom and computing equipments now use 3-Phase mains power. Salient amongst them are:

1. A.C. and D.C Drives
2. Telecommunication Power Supplies
3. Uninterruptible Power Supplies
4. Air Conditioning Units
5. Large Computer Installations
6. Power supplies for all industrial uses such as welding, surface treating, motion control, large appliances and process control
7. R.F. Transmitters and Radar Transmitters and repeater stations

8. Regulated and tracking +350V and -350VDC, for high power bidirectional servo amplifiers for driving heavy-duty critical loads such as Antenna Tracking and Positioning systems.

All the above and many more such systems are good candidates for using Vienna Rectifiers for achieving performance improvements as per the advantages listed in 2.1.

4.0 Vienna Rectifier

4.1 Modus Operandi

Vienna Rectifier as shown in Figure 1, was originally developed at the Technical University Vienna. It comprises a semiconductor switch, say, a MOSFET in each phase leg of a 3-Phase diode bridge. By adjusting the width of the pulse that turns ON the MOSFET, corresponding line current is forced to be sinusoidal and in phase with the Voltage. When the MOSFET is turned ON the corresponding phase is connected, via the line inductor, to the center point between the two output capacitors. The phase current rises, through the MOSFET, during that pulse period, charging the capacitor. When the MOSFET is turned off, current tapers through the diode half bridge (upper or lower depending on direction of the current flow).

4.2 Objective of Vienna Rectifier

It is a highly efficient method of high current, 3-Phase AC to DC conversion and is particularly attractive for achieving unity power factor operation. In figure-1 ACR, ACY and ACB are 440V, 50Hz, 3-Phase sinusoidal line Voltages. -Vdc and +Vdc are the DC outputs connected to load. There are three semiconductor switches, corresponding to each phase T1, T2 and T3. These are switched continuously at around 25 KHz. The duty

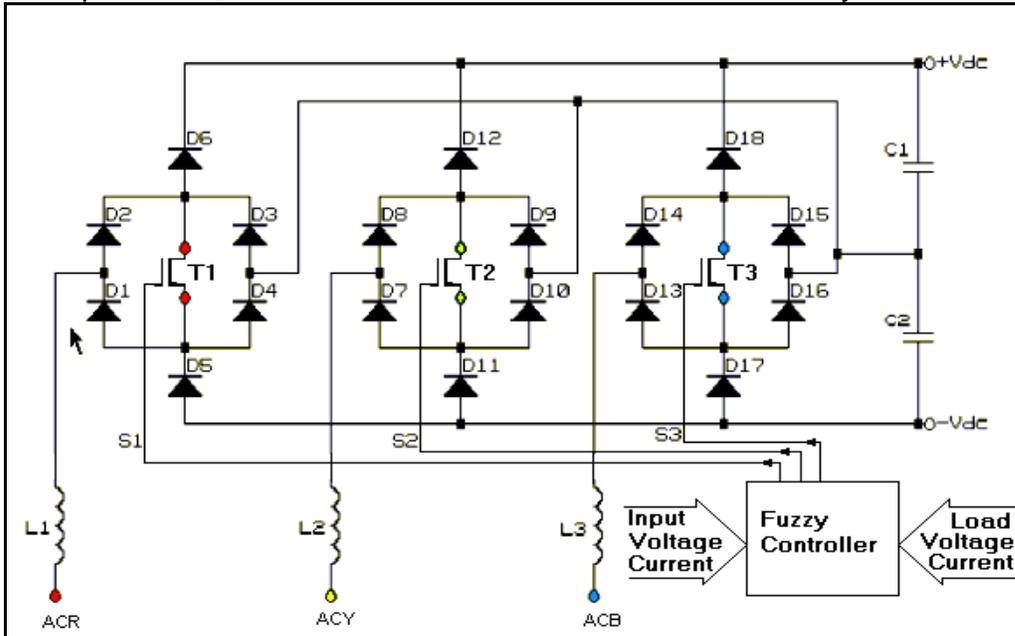


Figure 1. 3-Phase Vienna Rectifier Configuration

Cycle of the pwm switching is so programmed that the current drawn from each phase is sinusoidal and in phase with the corresponding line Voltage, thus ensuring near unity power factor and minimum total harmonic distortion.

4.3 Description

In Vienna Rectifier configuration, as shown in figure-1, the output capacitor is split in two parts as two equal value capacitors, C1 and C2, connected in series. Across the output capacitors the $-V_{dc}$ and $+V_{dc}$ are developed as 3-Phase peak detected outputs. A switch for each phase is connected, such that when "ON", it connects the line phase to the center node of C1 and C2 through a series inductance. For a short switching period, (assuming 10 microseconds), the capacitors charge linearly. This offsets $-V_{dc}$ and $+V_{dc}$. The offset depends on the corresponding phase voltage and the switch "ON" time duration. The common node of C1 and C2 will have Voltage with triangular wave shape, having three times the mains frequency and its amplitude will be one quarter of the phase voltage.

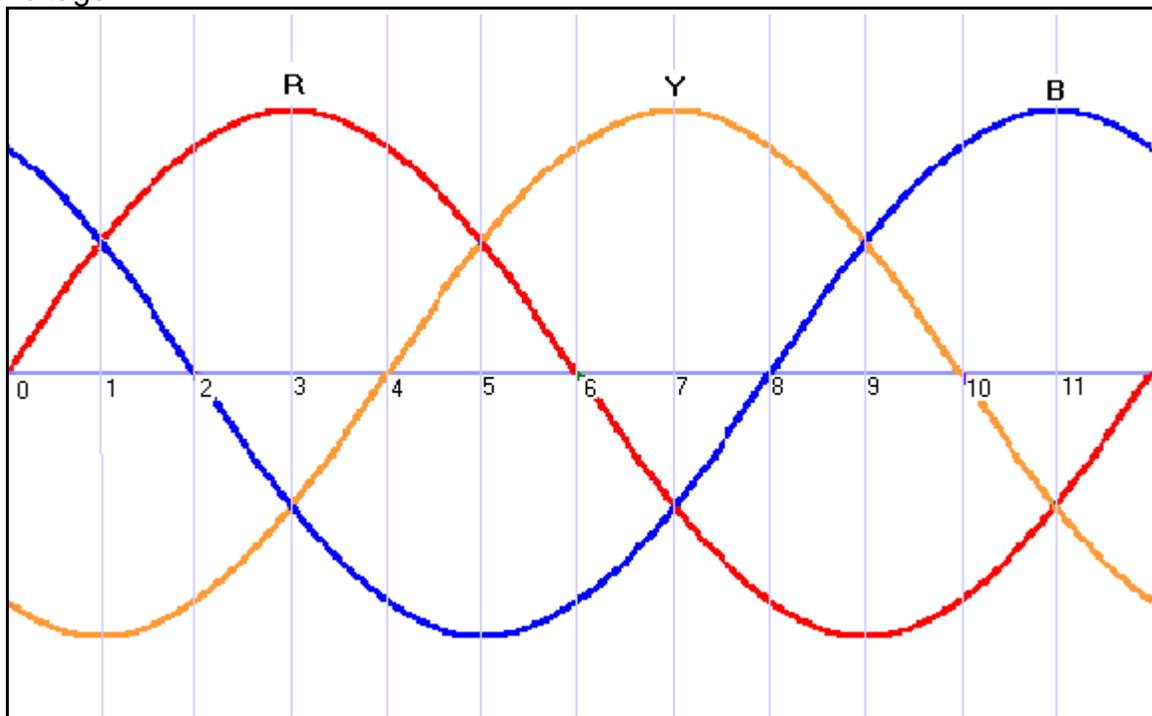


Figure 2. 3-Phase line voltages red, yellow and blue with 12 time segments From 0 through 11

4.4 Vienna Rectifier Modules

Looking at Figure 1, it becomes apparent that if one were to assemble the entire 3-Phase Vienna Rectifier PFC circuit using discrete components, many different power semiconductors have to be connected together. This is not only inconvenient and costly, but also involves a degree of variation in performance from unit to unit. The lead inductances and parasitic capacitance may tend to oscillate, making its operation at high enough switching frequency a task by itself.

Fortunately, readymade Vienna Rectifier power modules are available in DCB (Direct Copper Bonding) ceramic base plate. These have a number of useful attributes:

1. These modules have isolation voltage of 3600 Volts AC, ensuring personal and equipment safety and are U/L recognized. There is no need for external isolation.
2. Extremely low package inductance, facilitating high speed switching
3. Easy to mount on a printed circuit board for either wave soldering or manual soldering
4. Kelvin source for reliable driver connections for the MOSFETS
5. The MOSFET, built using HDMOS process has low $R_{DS(on)}$ and R_{Gint} and low R_{thJS} and low input and output capacitances and low gate charge and rise fall times for low conduction and switching losses
6. FREDS (Fast Recovery Epitaxial Diodes) have low V_F and extremely low t_{rr}
7. Consistent and predictable performance from unit to unit

4.5 Advantages of DCB

The Direct Copper Bonded substrates have a number of very attractive features as given below:

1. They have very good mechanical strength, hold stable shape with good adhesion and are corrosion resistant
2. They have very good thermal conductivity, enhancing heat dissipation to heat sink. This allows very close packaging of chips, further reducing lead inductances and translating more power per unit volume.
3. Very good thermal cycling capability, giving reliable performance over many years
4. The thermal expansion coefficient is close to that of silicon so no interface layers are required
5. They feature good heat spreading thus leaving no hot spots during actual operation
6. They can be structured just like printed circuit boards or “IMS Substrates”
7. These are environmentally clean
8. DCB ceramic is the basis for the “chip-on-board” technology, which represents the present and future packaging trends.

5.0 Vienna Rectifier Controller

5.1 Driving Scheme for MOSFETS

Looking at the main Vienna Rectifier circuit in Figure 1, tells us that the MOSFET's gate and Source terminals will have to be driven using isolated gate drive scheme. Therefore, the outputs from Fuzzy Controller will require MOSFET Drivers as well as some form of isolation. Two options are available:

1. Use Gate Drive Transformers: Readymade Gate Drive Transformers with turns ratios 1:1 or 1:1.5 for operation for $f_{sw}=10$ KHz to 100 KHz are available.

2. Use opto-couplers: This option necessitates having isolated power supplies for the output side of the opto-couplers.
3. For a Vienna Rectifier Module with MOSFET rated at $V_{DSS} = 500\text{ V}$ and $I_D=35\text{ A}$, it is possible to have 10 to 16 KW of AC to DC power conversion and a 4.0 Amp peak MOSFET Driver is recommended, considering highest switching frequency of 50 KHz.
4. Likewise for a Vienna Rectifier Module with MOSFET rated at $V_{DSS} = 500\text{ V}$ and/or 600 V , $I_D=130\text{ A}$, it is possible to have up to 40 KW of AC to DC power conversion and a 14.0 Amp peak MOSFET Driver is recommended, considering highest switching frequency of 50 KHz.

It is important to note that although it is possible to have a higher switching frequency, in the interest of having high conversion efficiency and to keep the DCB Vienna Rectifier Module's case temperature within reasonable limits, an arbitrarily chosen $f_{sw} = 50\text{ KHz}$ is assumed.

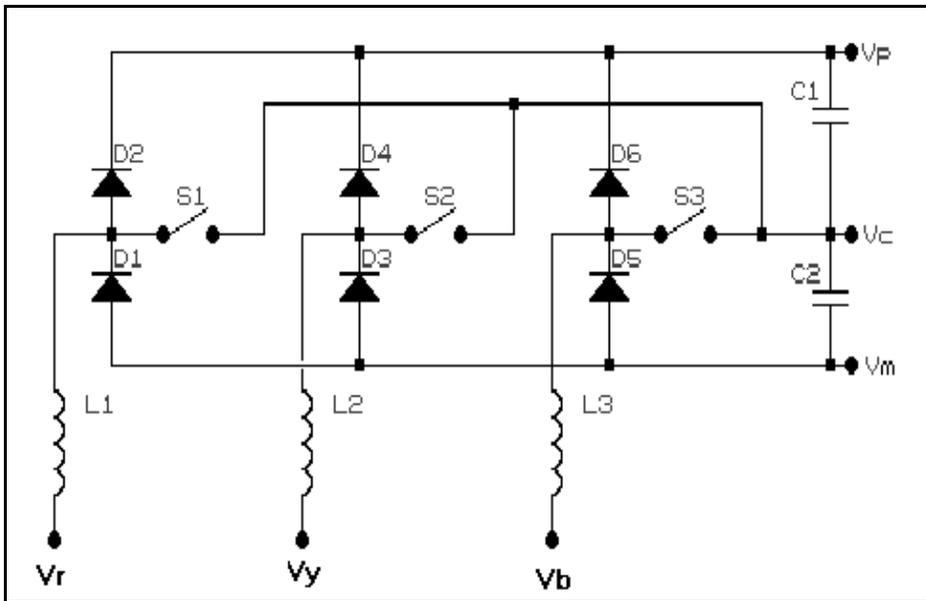


Figure 3. A simplified diagram of 3-Phase Vienna Rectifier

5.2 Control Characteristics of Vienna Rectifier Switches

Control signal S1, S2 and S3 are shown in figure-1 is generated using a Fuzzy controller. A simplified Vienna Rectifier switching diagram is shown in figure-3. Vp, Vc and Vm are output dc voltages. A Vienna simulator as shown in figure-4 is designed to verify the control characteristics. The line voltage as seen with respect to the common dc voltage Vc is shown in simulation of figure-4 in red, yellow and blue. Simulated switching signals S1, S2 and S3 are shown in lower window.

Duty ratio of switching pulse width is a complex function of line and load voltages and currents. To simplify the control the switching function is segmented in 12 zones corresponding to 0 to 360 degrees phase angle of power frequency as shown in Figure-2.

A rule based control strategy is implemented using fuzzy logic. This avoids trigonometric or floating-point computations and is suitable for low cost embedded controllers working with high reliability. The normalized pulse widths for linear phase change are stored in a different tables corresponding to the 25 input output voltage ranges that are normalized with respect to desired set point.

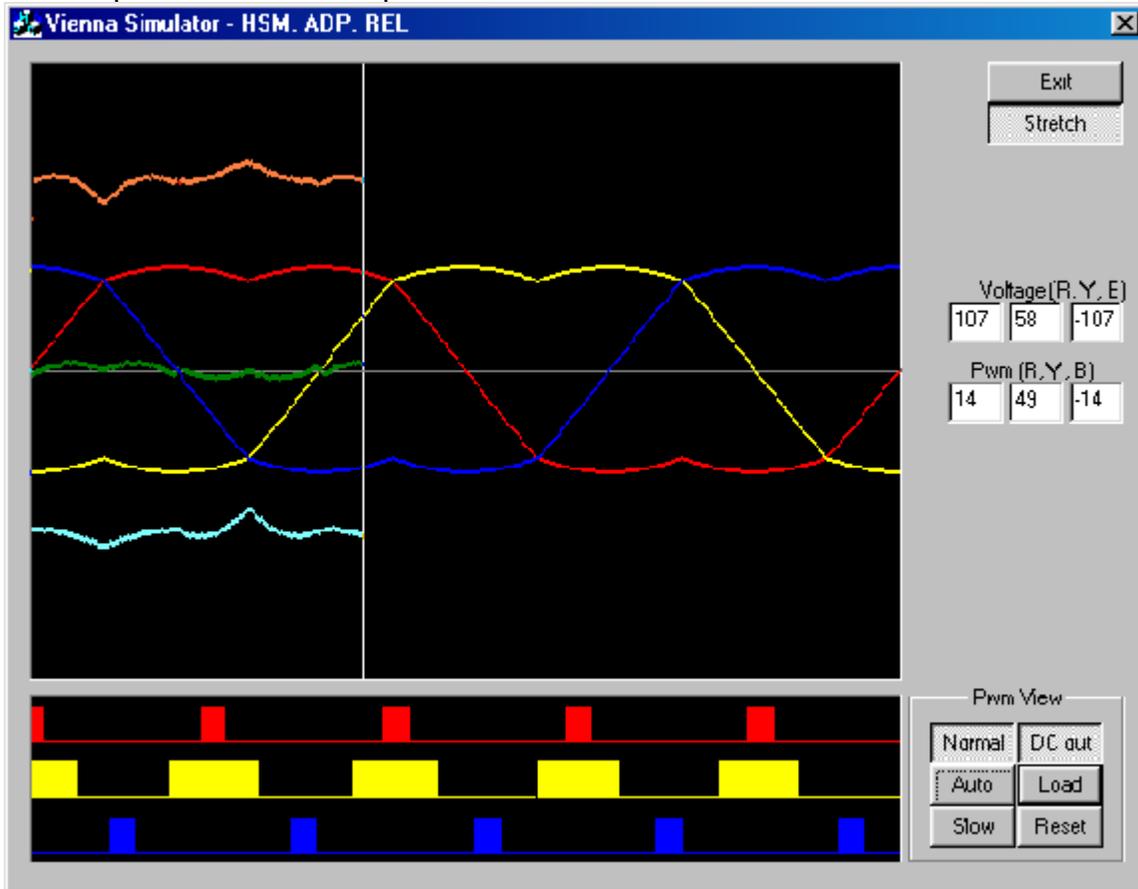


Figure 4. Simulation of 3-Phase Vienna Rectifier control operation. In upper window three-phase line voltages red, yellow and blue are plotted with respect to the output dc voltage V_c of figure-3. Top (orange) and bottom (sky-blue) trace indicates output DC voltage in loaded state. The lower window shows the magnified PWM control signals generated at cursor position of upper window.

Table-1 Fuzzy Control matrix of PWM tables, X indicates the active control state.

		Load Voltage				
		V.Hi	Hi	Set Pt.	Low	V.Low
L i n e t	V o l t	V.Hi				
		Hi			X	
		Nominal				
		Low				
		V.Low				

Table-1 shows the fuzzy control matrix of 25 states. Each states represents a PWM look-up table for signals S1, S2 and S3. Fuzzy rules are used to identify the state from

measured value of input and output voltages and select the appropriate pulse width table to generate PWM signals. Safety measures are implemented using higher priority fuzzy rules. Using similar approach it is possible to implement desired output voltage and current profile for cold start, shut down or fault conditions.

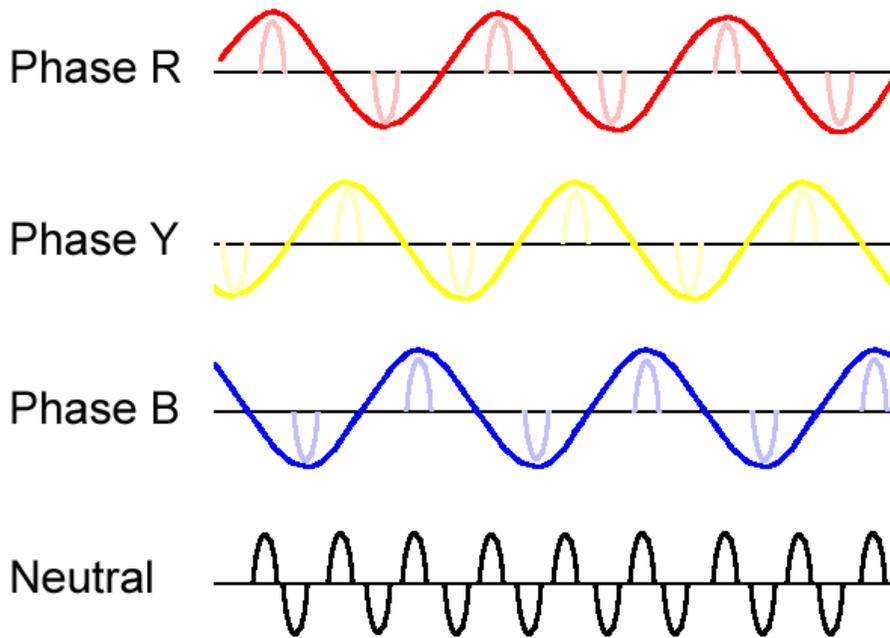


Figure 5. Currents drawn from each phase, while feeding non-linear loads. Neutral conductor carries summation of currents from all the three phases

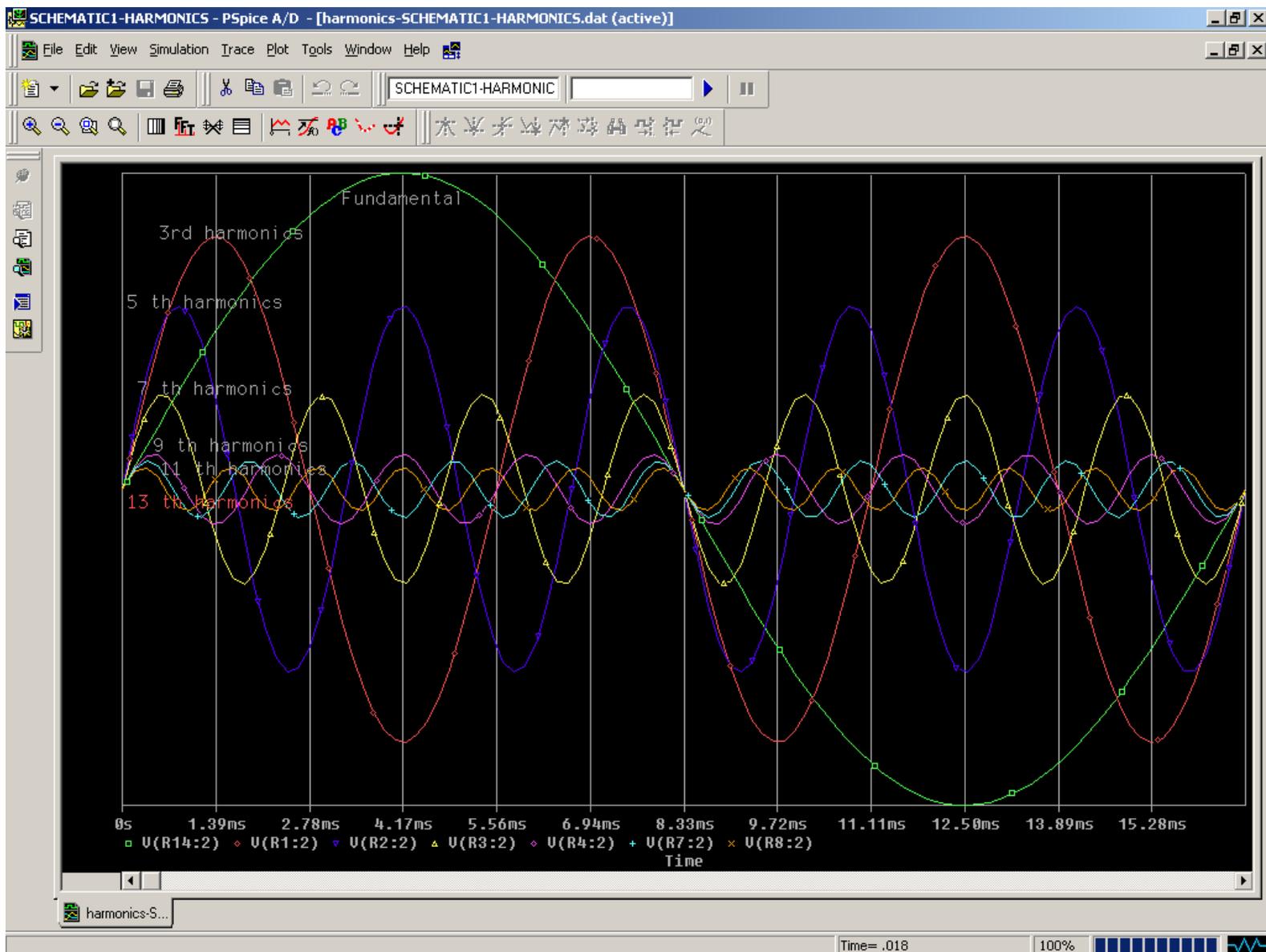


Figure 6. Mains fundamental with odd harmonics from 3rd through 13th with their relative amplitudes due to presence of non-linear loads

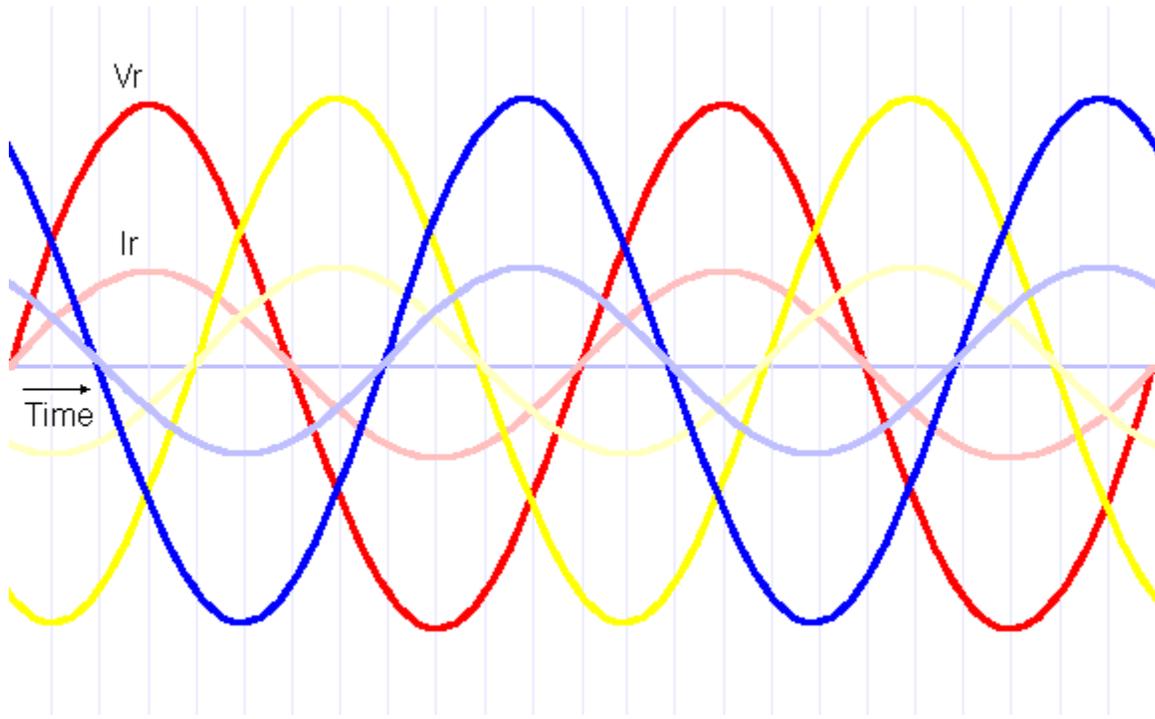


Figure 7. Phase Voltages and Phase Currents, showing near unity Power Factor and very low THD, When Vienna Rectifier is used for AC to DC power Conversion

6.0 Fuzzy Logic Controller for Vienna Rectifier

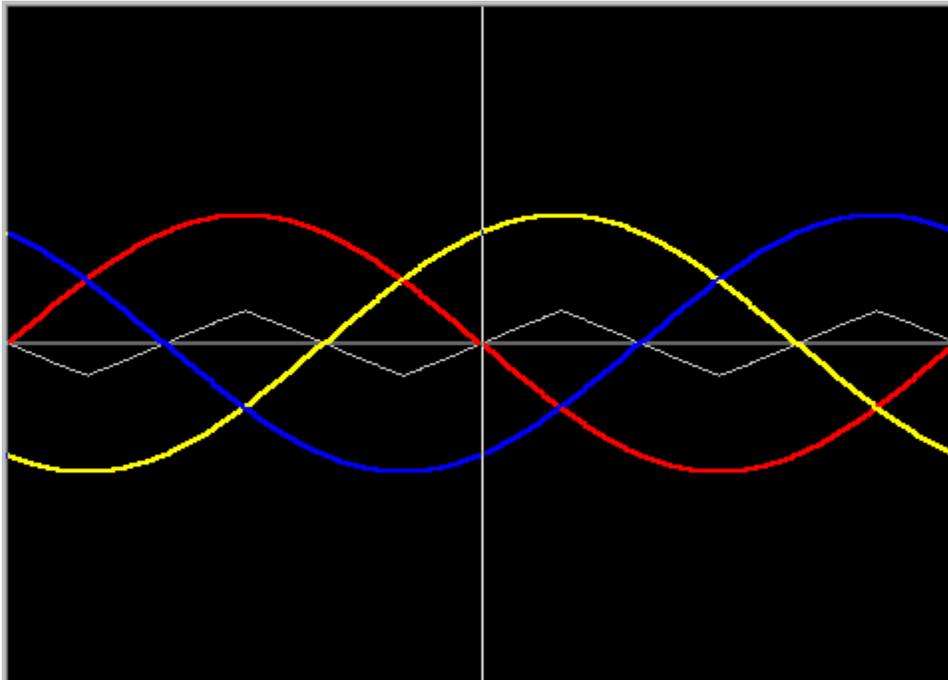


Figure 8. Simulator output shows 3-Phase line voltages in red, yellow, and blue colors. The gray triangular wave is the output dc voltage V_c of figure-3, appearing at the junction of output capacitors, and is measured with respect to neutral of line voltage.

6.0 Working of pwm3p- A computer simulation of the Fuzzy Controller for the Vienna Rectifier:

“Pwm3p” is a simulation tool for explaining working of Vienna Rectifier under the control of Fuzzy Logic Controller. Here is how the tool works:

Please refer to Figure 4 for understanding the explanation below

1. By depressing “Current” button, one can see the currents
2. The PWM View has six windows.
 - (A) **Normal/Zoom:** As the names suggest, this option allows on to see the PWM wave forms in normal or Zoomed condition
 - (B) **Auto/Drag:** This option allows one to see the changes in pwm pulse patterns either automatically from to left to right or one can drag the cursor from left to right to see these changes manually
 - (C) **Slow/Fast:** This selection helps see the PWM pulse patterns either slowly moving from left to right or fast.

- (D) **Load:** This window allows one to see the change in DC Bus Voltage when load is connected.
- (E) **Reset:** As the name applies this allows one to reset the simulation
- (F) **Step:** this option allows one to study every thing in a step by step manner
- (G) **Voltage (R,Y,B):** These windows show each voltage magnitude
- (H) **Pwm (R,Y,B):** These windows show the level of pwm modulation

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