Comparative Study of Pulse Width Modulated and Phase Controlled Rectifiers

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***Abstract*— Fixed DC voltage is one of the very basic requirements of the electronics' circuits in modern systems. Thus, single phase diode or thyristor rectifiers are commonly used in many industrial applications where we require a high-power DC supply or an intermediate DC link of AC/AC converters. The benefits include simple structure, high safety and most importantly, low cost.**

However, it is reasonable to assume that a price is to be paid for these benefits. The major drawback is the power system harmonics that these bridge rectifiers introduce within a system. The economic advantage that these systems enjoy can be nullified overnight if stricter harmonic standards are implemented. With this in mind, there is an increased interest in active filters and schemes like PWM that can counter these. The less prominent (but important from the consumers' point of view) issues include low power factor, voltage distortion, heating of transformer cores etc. A single standard scheme that can work for all applications is an ideal yet impractical solution. Thus, different schemes that have been introduced need to be compared so that it is easier to choose whichever fits best with the task at hand.

Keywords—Rectifier; PWM; Phase Control; Comparison; THD

I. INTRODUCTION (*Heading 1*)

Rectifiers are converters that convert AC to a constant DC supply. Applications of AC–DC converters are widespread in industries and house utilities. Rectifiers have the advantages of being simple, robust and having low cost. However, they generate harmonics and reactive power in AC side, which result in voltage distortion, poor power factor at power supply side and slowly varying rippled DC output at DC side [1]. Decreasing the Total Harmonic Distortion (THD) of the input current, unity power factor and fixed DC output voltage with minimum ripple are the important parameters. A comparison is drawn between two commonly used control schemes for rectifiers and their common applications have been listed.

II. RECTIFIER TOPOLOGIES

A. *Current Source Rectifier(CSR)*

Fig 1 shows the schematic of a current source rectifier. The bridge is fed directly by a current source in the case of a current source rectifier [8]. To constitute the bridge, SCR (Silicon Controlled Rectifier), GCT (Gate Commutated Thyristors) or SGCT (Symmetrical Gate Commutated Thyristors) may be used. Series inductor is used as the DC link in order to (1) Store Energy for the load and (2) minimize the ripple content from the dc output [4].The inductor also serves useful for limiting fault current. When used inside a drive system, current source configuration has to be operated in a closed loop, as the output tends to become unstable. Because of the use of DC choke, the dynamic response of the system is poor and the system becomes bulky, consequently increasing heat dissipation inside the system. Also, current ripple is inversely proportional to the size of the DC choke, so, a trade-off between size (read cost) and performance arises. This topology requires input filter/isolation as the harmonics injected are high. Current source rectifiers are therefore rarely used for high performance applications.

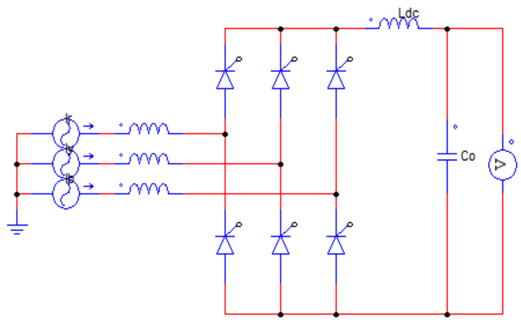

Fig. 1 Current Source Rectifier

B. *Voltage Source Rectifier(VSR)*

Fig 2 shows the schematic of a voltage controlled rectifier. The bridge is fed by a voltage source. As the DC link, parallel capacitors are used which perform the function of storing energy and removing ripple content. Voltage source designs do not use DC inductors to form a DC link. The instantaneous current is provided by capacitors. The absence of inductor is a benefit as it reduces the overall size. The most commonly used switches in this topology are IGBTs. The triggering voltage for an IGBT being lower than the corresponding triggering current for a GCT/SGCT, the failure rate for a VSR is far lower. Harmonics injected are less and lower order harmonic content is better removed than CSR. Efficiency does not vary significantly with variable load. Because of these reasons, VSR is widely used in high performance applications [4].

III. CONTROL SCHEMES

A small scale model was made to simulate both the topologies and compare the output. For a practical model to work, it was necessary to synchronize the triggering pulses with the input waveform in order to avoid any mismatch that could lead to a discrepancy in the output. Since the pulses were triggered by a microcontroller board, it was necessary to use a zero crossing detector and use its output to control the Arduino triggering.

A. Phase Controlled Rectifier

In phase controlled rectifiers, the width of the gate pulse is changed according to the output voltage desired. More the width of the gate pulse, less will be the average output voltage and vice versa [2]. Fig 3 demonstrates the above relationship. As this is a half controlled rectifier, during negative half cycle Thyristor will be turned off automatically on account of negative voltage appearing across it.

The equation of the average output voltage in terms of peak voltage and firing angle is as follows.

$$V_o = \frac{V_m}{\pi}(1 + \cos\alpha) \quad (1)$$

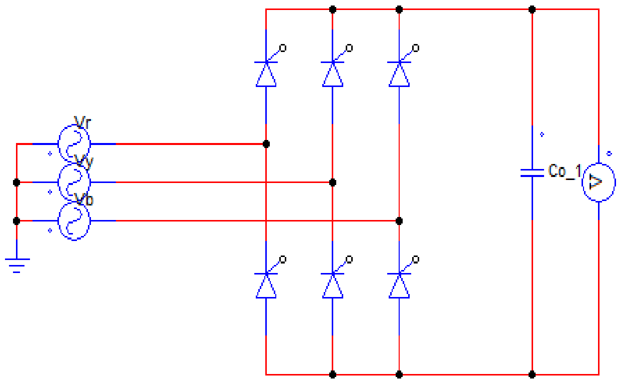

Fig. 2 Voltage Source Rectifier

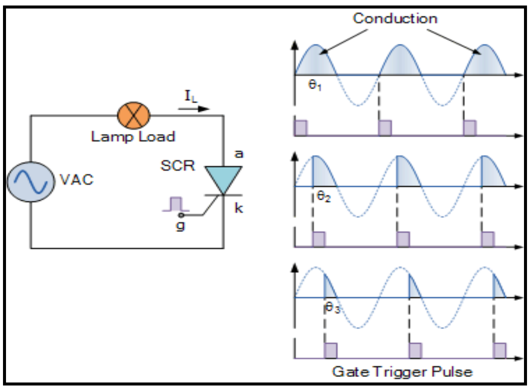

Fig. 3 Single phase Half-wave controlled rectifier

Where,
V_o= DC Output voltage level
V_m = peak value of input AC voltage
α = Firing angle

In the table below, for various firing angles the output voltage is shown in terms of peak voltage.

TABLE 2 OUTPUT VOLTAGE AT DIFFERENT FIRING ANGLES

Firing Angle	Calculated Vo	Actual Vo
0	63.70	68.00
30	59.42	59.80
60	47.43	46.56
90	31.84	34.00
120	15.92	16.05
150	4.26	4.23

The following simulation for the firing angle 0° is carried out in PSIM.

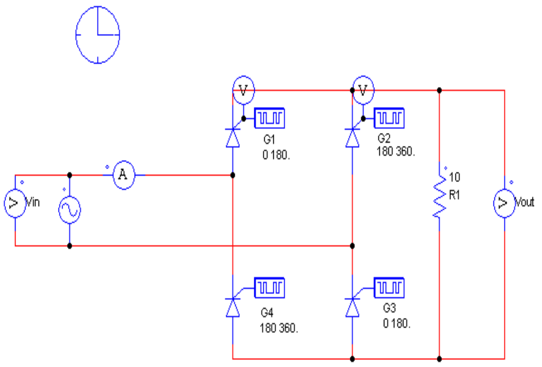

Fig. 4: Single phase fully controlled rectifier in PSIM

The waveforms for input AC voltage, source current, gate pulses, output voltage and average output voltage are obtained from the above simulation and shown in Fig 5

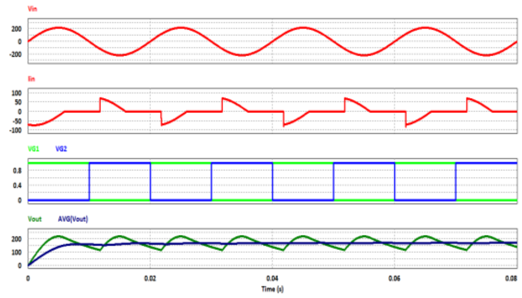

Fig. 5: Waveforms for firing angle 0°

Disadvantages of phase controlled rectifier:

- Lower order harmonics are dominant and hence, size and cost of filters will increase.
- On account of lower order harmonics total harmonic distortion (THD) increases.
- Higher ripple voltage and ripple current.
- As source current has dc component it can lead to saturation of the input transformer. [3].

However, the above method has simple circuit and low cost.

B. PWM Rectifier

The dominant lower order harmonics of source current can be reduced, if the source current has more than one pulse per half cycle. In the PWM controlled rectifier, the switch is turned ON and OFF several times in single half cycle and the width of pulse is varied to have desired output voltage [5].

In this method, to generate gate pulses, triangular wave is compared with constant dc. When the magnitude of triangular wave is greater than that of a constant dc, pulses are generated. The pulse width can be varied by changing the constant dc level. Depending upon the set level of constant dc the average output voltage will change. The same concept is illustrated in fig 6. Fig 7 shows the simulation for above concept is carried out in PSIM.

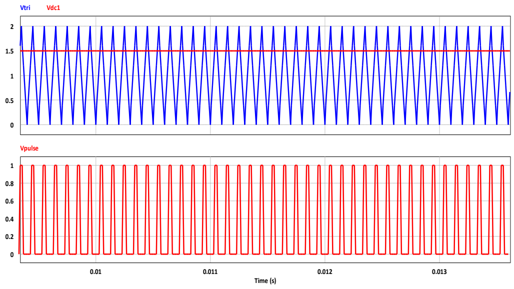

Fig 6: Generating Pulses using DC and Triangular Waves

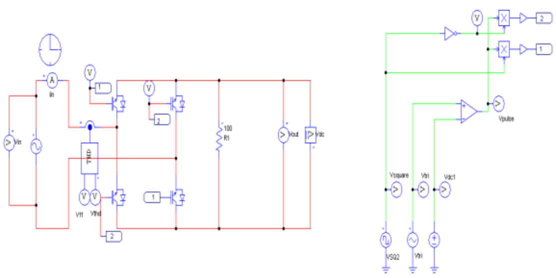

Fig 7: PWM controlled rectifier in PSIM

Once the pulses from comparison are generated, they are multiplied with square waves of fifty percent duty cycle, having 0º and 180º phase shift respectively. One of the multiplied signals is given to switches 1 and 3 and the other to switches 2 and 4.

Output voltage waveform with this method is shown below in fig 8, the red line indicating the average value.

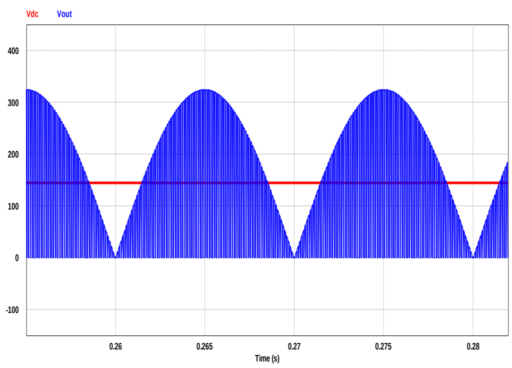

Fig 8: Output Voltage Waveform

Advantages:

- By selecting proper number of pulses per half cycle, lower order harmonics can be eliminated.
- Higher order harmonics in the source current can be eliminated by input filters, which will have reduced size and cost compared to those for lower order.

Disadvantages:

- If number of pulses per half cycle are too large, then switching losses of thyristor will increase.
- Thyristors with lower turn off time would cost more.

C. Comparison

1. Total Harmonic Distortion:

Table 2 shows the values of Firing Angle (Out of maximum 180 degrees) and the DC level (Maximum 2V) used to obtain an output of the same magnitude.

The main issue with the conventional rectifiers is the harmonic content, as the firing angle is increased, the harmonic profile worsens as the obtained waveform deviates more and more from the ideal sinusoidal.

TABLE 2 FIRING ANGLE AND DC LEVEL NEEDED FOR THE SAME OUTPUT VOLTAGE

INPUT AC VOLTAGE (RMS in V)	DC OUTPUT VOLTAGE	FIRING ANGLE (Degrees)	DC LEVEL (in V)
230V	10V	163	1.87
230V	30V	137	1.66
230V	60V	108	1.25
230V	100V	94	0.97
230V	150V	61	0.51
230V	200V	13	0.32

The harmonic content is decided by how much the input current profile deviates from the ideal sinusoidal waves. As can be easily see that for higher values of firing angle (and consequently lower values of the output voltage), the waveform is a highly distorted sine wave which results in a higher %THD. The table below shows the %THD for different values of firing angle. It has been calculated for a peak input voltage of 100V.

TABLE 3 %THD COMPARISON BETWEEN SCHEMES FOR SAME VOLTAGE LEVELS

INPUT AC VOLTAGE (RMS in V)	DC OUTPUT VOLTAGE	PWM CONTROL (%THD)	PHASE-CONTROLLED (%THD)
230V	10V	57.75	222.47
230V	30V	44.98	122.80
230V	60V	32.72	77.66
230V	100V	26.56	61.79
230V	150V	24.42	32.45
230V	200V	21.97	3.16

The table above compares the values of %THD for the same output voltage levels. For comparison, the harmonic orders of up to 100 have been considered (i.e. up to 5000Hz for fundamental frequency of 50Hz). As can be observed, for higher values of firing angle, there is a clear advantage to using a PWM rectifier.

2. Order of Dominant Harmonics:

FFT analysis was done for a DC voltage output of 10V. It was noted for the phase controlled rectifier that the lower order harmonics (3, 5, 7..) are predominant as their value relative to fundamental is considerably high.

On the other hand, for a PWM controlled rectifier, the lower order harmonics are less than 1% of the fundamental. In fact, the predominant harmonics are of a much higher order (over 40 which corresponds to over 2000Hz). These higher order harmonics are easier to eliminate using an output filter. Furthermore, the size of the filter is considerably reduced.

In case of PWM, the dominant harmonics are much higher and hence easier to filter. Thus, we can conclude that for a variable output voltage application (as is usually the case for use of either of the methods), a PWM controlled rectifier is preferable. In addition to reduction in the harmonic levels at low outputs, the harmonics are also easier to filter out. Also, the size of the output filter can be reduced [7].

IV. Hardware

A small scale model was made to simulate both the topologies and compare the output. For a practical model to work, it was necessary to synchronize the triggering pulses with the input waveform in order to avoid any mismatch that could lead to a discrepancy in the output. Since the pulses were triggered by a microcontroller board, it was necessary to use a zero crossing detector and use its output to control the Arduino triggering.

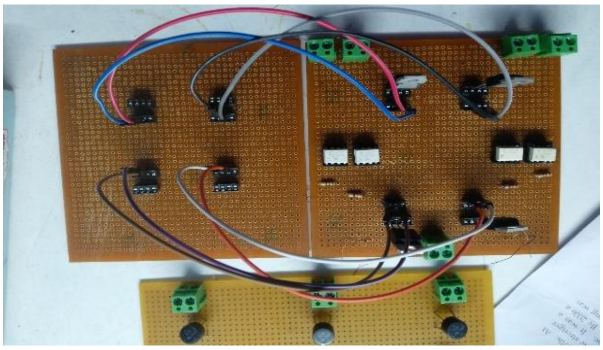

Fig 6: Hardware Model

A. Phase Controlled Rectifier

The phase controlled rectifier was implemented by connecting SCRs in an H-bridge configuration. The triggering was done directly using the Arduino interrupts that included a delay file where the delay after the rising pulse of ZCD output could be controlled by varying a variable. Thus, this variable could be used to actively change the output voltage level obtained.

B. PWM Rectifier

The PWM topology included MOSFETs (input being scaled down to 18V using a transformer to avoid reverse conduction) in an H-bridge configuration. The output of the first stage of comparison between the DC level and the triangular wave is uniform and thus can be synchronized by directly multiplying the ZCD output with this waveform. This could be done by either using an external multiplier IC or by using the digital input function in the Arduino.

The hardware model is shown in fig 6.

The final gate pulses were obtained using the Digital Output pins as shown in the simulation diagram through the MATLAB software. These were available on the corresponding pins of the Arduino and could be given to the switch after appropriate isolation and stepping up according to the required gate voltage.

V. Applications

Phase controlled rectifiers have advantages of being easier to implement, robust and are cheaper compared to PWM rectifiers. But the disadvantages of phase controlled rectifiers overshadow its use over PWM rectifiers for a lot of applications. Phase Controlled rectifiers when used, they have a major disadvantage of a bad THD profile. Another prime issue is a lower power factor. In case of PWM rectifiers the dominant harmonics present are much higher and thus are easier to filter out and the size and cost of the filters required will also be very less [6]. Also when compared to conventional unidirectional diode bridges, the PWM configuration can be made bidirectional. This allows it to be used in micro distributed systems that are more economical for power generation and have a much higher security (by reducing the consequences of the environment) [8].

PWM rectifiers can also be used in the charger circuit of the electric vehicles. Because of the presence of harmonics and unstable output voltage, PWM scheme is used. When used with PWM schemes, it showed positive results such as faster response with the system, and moreover the complexity of the system was reduced. In traction applications, PWM rectifiers are used as input rectifier. A traction vehicle when used with a PWM rectifier does not consume reactive power, will not load the supply network with harmonics, allows control over input output parameters (Voltage and Current), thereby reducing the size of energy storage elements.

REFERENCES

[1] H. Kanaan and K. Al-Haddad R. Chaffai and L. Duguay F. Fnaiech, “A Comparative Study of Hysteresis and PWM Control Techniques Applied to an Injection-Current-Based Three-phase Rectifier

[2] P. S. Bhimbra, Power Electronics, Khanna Publishers, 2006, 3rd ed.

[3] M. H. Rashid, Power Electronics, Pearsons Publications, 2012.

[4] Aaron VanderMeulen and John Maurin, “Current source inverter vs. Voltage source inverter topology” in White Paper WP020001EN Supersedes August 2010.

[5] Bin Wu, High-power converters and ac drives, A John Wiley & Sons, Inc., Publication

[6] Navid R. Zargari, Geza Joos, and Phoivos D. Ziogas , “A Performance Comparison of PWM Rectifiers and Synchronous Link Converters.”

[7] Omar Stihi and Boon Tech OOI,”A Single Phase Controlled Current PWM Rectifier.” IEEE Transactions on Power Electronics, VOL. 3, NO. 4, October 1988.

[8] Richter S.A, Bader B. and De Doncker R.W., “Control of a high power PWM current source rectifier”, IEEE, Sapporo, 2010, pp. 1287-1292 [Published in: Power Electronics Conference (IPEC), 2010 International