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Performance Evaluation Of SPWM Based Three-Phase PWM Rectifier

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Abstract: The rectifier basically converts AC input to the DC output. In general, different types of rectifier topologies are available like diode bridge rectifier, thyristor-controlled rectifier, PWM based rectifier etc. This paper discusses front end PWM rectifier, its working principle and generation of gate pulses using two different modulation techniques namely sine pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM). This paper also features the description of 3-level front end PWM based rectifier and generation of 3-level space vector PWM. Simulation models of two level SPWM, two level SVPWM and three level SVPWM based front end rectifier are developed and simulated in MATLAB / SIMULINK platform and a comparative analysis is presented. sinusoidal Pulse width modulation (SPWM) technique and direct power control (DPC) Pulse width modulation technique for three-phase AC to DC converters using. MATLAB/SIMULINK software. Pulse width modulation (PWM) techniques are frequently used due to improved performance such as unity power factor operation with reduced total harmonic distortion (THD) at ac mains. In this paper simulation models for both PWM techniques are simulated with closed loop at rated load condition and then comparative analysis has been done in terms of input current THD and power factor. DPC is the efficient technique because of the better performance

***Index Terms* – AC/DC converter, total harmonic distortion, SPWM, PI control.**

I. Introduction

The AC/DC power converters are extensively used in various applications like household electric appliances, power conversion, dc motor drives, adjustable-speed ac drives, power supplies like SMPS and UPS and so on. The main problems faced by the power electronic design engineers are about the reduction of harmonic content in low or medium power applications. Normally the input voltage to an AC-to-DC converter is sinusoidal but the input current is non-sinusoidal i.e. harmonic currents are present in the ac lines. PWM (Pulse Width Modulation) rectifiers are AC-to-DC converters that use pulse width modulation techniques to control the output voltage and current. They offer advantages over traditional diode-based rectifiers, including the ability to maintain a sinusoidal input current and unity power factor, and they can be operated in a bi-directional power flow mode.

Uncontrolled PWM rectifiers are a type of AC-DC converter that uses diodes (uncontrolled devices) for rectification and PWM (controlled devices) for control. This introduction explains that uncontrolled rectifiers, like diode rectifiers, convert AC to DC using diodes, while PWM rectifiers offer more advanced control and flexibility.

Controlled (PWM) rectifier is a type of AC-to-DC converter that uses forced commutation with power electronic switches to control the output voltage and improve power factor. Instead of simply blocking or allowing current flow like diodes, these switches can be turned on and off rapidly, modulating the width of the pulses to achieve a desired DC output. This control enables bi-directional power flow, sinusoidal input current, and reduced harmonic distortion, making them suitable for applications like traction and active filters.

II. LITERATURE SURVEY

Three-phase PWM rectifiers have been extensively studied and developed to address the limitations of uncontrolled rectifiers, particularly in terms of power quality and efficiency. These rectifiers offer several advantages, including unity power factor operation, low input current distortion, and bidirectional power flow capability (Chung & Sul, 1999; Lee & Lim, 2002).
Various control schemes have been proposed for three-phase PWM rectifiers. A novel control scheme eliminating both AC input voltage and current sensors has been developed, reducing system cost and improving reliability (Lee & Lim, 2002). Another approach focuses on minimizing conduction and switching losses through an optimized PWM strategy, potentially reducing switching losses by up to 46% compared to continuous space-vector PWM rectifiers (Chung & Sul, 1999). A hysteresis current control concept has also been introduced, providing more regular switching of power transistors and intrinsic stability of the output center point voltage (Dalessandro et al., 2005).

Interestingly, hybrid rectifier systems combining uncontrolled diode-bridge rectifiers with PWM rectifiers have been proposed to achieve high efficiency while maintaining the benefits of PWM rectifiers in reducing line current harmonic content (Soeiro & Kolar, 2013). These hybrid systems can potentially achieve higher efficiency and require less silicon area than single PWM rectifiers.

In comparison to uncontrolled rectifiers, PWM rectifiers offer significant advantages in terms of power quality and control. Uncontrolled rectifiers with capacitive filters are highly sensitive to line voltage unbalance, drawing significantly unbalanced line currents even under slightly unbalanced voltage conditions (Jeong & Choi, 2002). PWM rectifiers, on the other hand, can be designed to operate effectively under unbalanced and distorted supply conditions, minimizing input current distortion and maintaining a smoother DC-link voltage (Tang et al., 2010). Additionally, PWM rectifiers allow for a wide output voltage control range, which is not possible with uncontrolled rectifiers (Nussbaumer & Kolar, 2007).

III. PROPOSED SYSTEM

A conventional SRM drive using a diode bridge rectifier produces high current harmonics and a poor power factor. The proposed system **uses a** PWM converter as the front-end converter to improve the power factor at the AC mains supply with low current harmonics

The proposed system is a three-phase PWM rectifier designed for efficient AC to DC conversion with:

- Unity power factor
- Low harmonic distortion (THD)
- Regulated output DC voltage
- Bidirectional power flow (if needed)

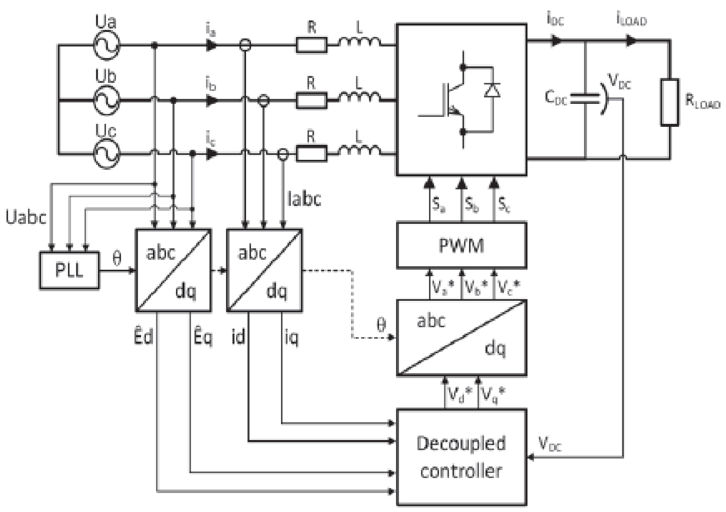

Fig. 1 Proposed three-phase PWM rectifier with R load

The proposed system as shown in Fig. 1 is a Pulse Width Modulation (PWM)-based three-phase rectifier, designed to enhance the performance and efficiency of AC to DC power conversion. Traditional rectifiers using diodes or thyristors suffer from drawbacks such as poor power factor, high harmonic distortion, and limited control over the output voltage. The PWM rectifier addresses these issues by incorporating modern switching devices and advanced control algorithms. Sine Pulse Width Modulation technique is one of the simplest pulse width modulation methods used for the triggering of the switches of converters. The SPWM is a famous modulation technique for pulse generations, where a carrier signal is compared with a sinusoidal signal. The main advantages of carrier based SPWM are easy generation, less complexity and good dynamic response of the converters. The ratio of carrier signal frequency to that of modulating signal frequency gives the number of pulses per cycle.The block diagram of closed loop operation of SPWM is shown in Fig.2. This topology uses IGBTs in the rectifier. The Simulink model of 3-phase SPWM based front end rectifier and its subsystem model of the closed loop operation.

IV. System Overview

The PWM rectifier utilizes power electronic switches such as IGBTs (Insulated Gate Bipolar Transistors) or MOSFETs arranged in a bridge configuration. These switches are controlled using a high-frequency PWM technique to synthesize a waveform that draws nearly sinusoidal currents from the AC supply and maintains a stable DC output.

Key Components:

- Three-Phase AC Input: The system operates from a standard three-phase AC supply (e.g., 400V, 50/60Hz).
- PWM Bridge Converter: A three-phase bridge with IGBTs or MOSFETs that rectifies the AC input using PWM signals.
- DC Link: Includes a DC capacitor to filter and stabilize the output voltage.
- Control Circuit: A digital controller (DSP, FPGA, or microcontroller) generates PWM signals based on real-time feedback.
- Sensors: Voltage and current sensors provide data for closed-loop control.

Control Strategy

The control of the PWM rectifier typically involves:

- Current Control Loop: Ensures the input current is sinusoidal and in phase with the voltage
- Voltage Control Loop: Maintains the output DC voltage at the desired level.
- Modulation Technique: Sinusoidal PWM or Space Vector PWM (SVPWM) is used to generate gate signals.

Advantages of the Proposed System

- Improved Power Quality: Low total harmonic distortion (THD) in the input current.
- Unity Power Factor Operation: Better energy efficiency and compliance with grid standards.
- Regulated DC Output: The output voltage can be precisely controlled.
- Bidirectional Power Flow: With proper configuration, energy can flow back to the grid (useful in regenerative braking).
- Reduced Stress on Grid: Due to smooth current draw and less reactive power.

Applications

- **Motor drives**
  Renewable energy systems (e.g., wind and solar)
  Electric vehicle charging stations

- **Industrial automation**
  UPS and battery storage systems

V. Converter Topology

1. Three-phase uncontrolled bridge rectifier

The ac to dc converters using diodes are termed as rectifiers. As the instant at which a diode can be turned on cannot be controlled, these rectifiers are uncontrolled rectifiers. The output voltage of an uncontrolled rectifier is always fixed and positive. The load current is also always positive. The flow of power will always be from the source to load. i.e. these converters are unidirectional in nature.

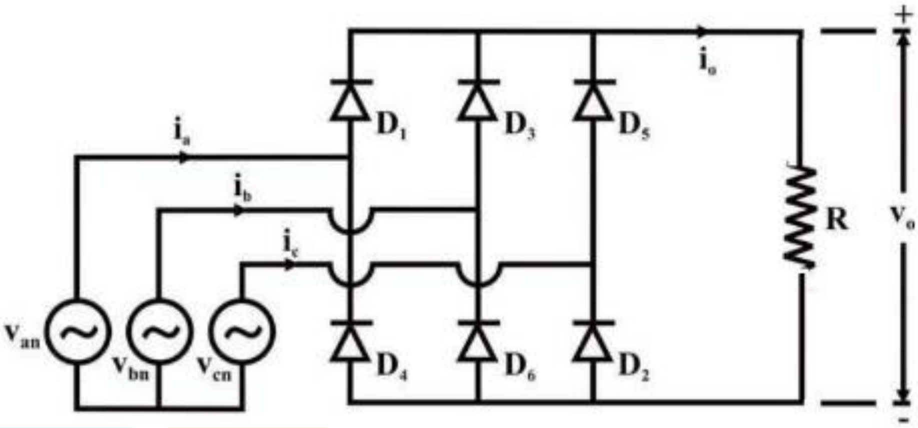

Fig.2 Three –phase uncontrolled bridge rectifier

The main circuit topology of a three-phase diode rectifier comprises three diodes connected to each of the three phases of a transformer's secondary winding. The diodes are commonly configured in an uncontrolled bridge arrangement and connected to the three phases of an AC voltage source. The diodes rectify the input AC voltage, resulting in a DC voltage at the output.

2. Three-phase controlled bridge rectifier

PWM techniques have been widely implemented to control the outputof power converters as they allow shaping voltage and/or current waves based on specific applications The three-phase PWM rectifier circuit, as shown in has three-legs with IGBT transistors. It is known as a bi-directional boost rectifier (increasing the voltage) and works using fixed DC voltage polarity. Input inductors are an integral part of the rectifier and are selected based on their design We achieve harmonic compensation through the input inductors, and we ensure smooth voltage waveforms by using capacitors.

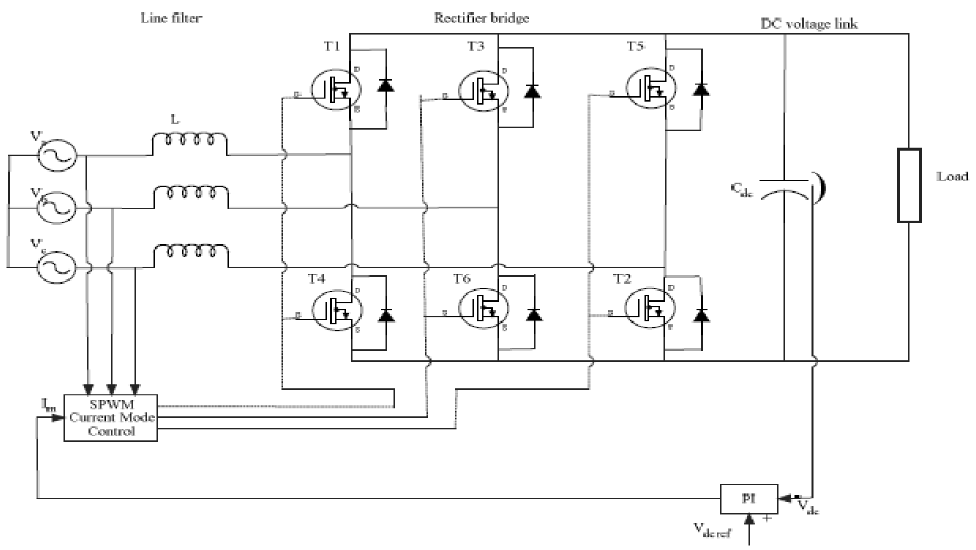

Fig.3 Three –phase controlled PWM rectifier

Three-phase PWM rectifier systems are quite similar to the objectives for the three-phase case. They are focused on achieving unit power factor, constant output dc voltage and a suitable low harmonics sinusoidal waveform for the input current. The difference is to be found in the fact that the control aim for the current loop should be achieved for every phase, taking into account the shifts associated with a three-phase current flow.

Table.I Switching Modes of Front End Pwm Rectifier

ON Switches	OFF Switches	State
T1, T3, T5, are ON	T6, T4, T2, are OFF	1
T5, T3, T4, are ON	T2, T6, T1, are OFF	2
T2, T3, T4, are ON	T5, T6, T1, are OFF	3
T2, T6, T4, are ON	T5, T3, T1, are OFF	4
T2, T6, T1, are ON	T5, T3, T4, are OFF	5
T1, T5, T6, are ON	T2, T3, T4, are OFF	6
T2, T3, T1, are ON	T5, T6, T4, are OFF	7
T5, T4, T6, are ON	T2, T3, T1, are OFF	8

rectifier is established as follows

$$\begin{cases} u_a = v_a - L\frac{di_a}{dt} - Ri_a \\ u_b = v_b - L\frac{di_b}{dt} - Ri_b \\ u_c = v_c - L\frac{di_c}{dt} - Ri_c \end{cases} \quad (1)$$

The mathematical model of the available voltage source PWM rectifier in the a-b-c coordinate system is derived as

$$\begin{cases} v_a = L\frac{di_a}{dt} + Ri_a + U_{dc}(\frac{2}{3}S_a - \frac{1}{3}S_b - \frac{1}{3}S_c) \\ v_b = L\frac{di_b}{dt} + Ri_b + U_{dc}(\frac{2}{3}S_b - \frac{1}{3}S_a - \frac{1}{3}S_c) \\ v_c = L\frac{di_c}{dt} + Ri_c + +U_{dc}\left(\frac{2}{3}S_c - \frac{1}{3}S_a - \frac{1}{3}S_b\right) \\ C_{dc}\frac{dU_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - \frac{U_{dc}}{R_L} \end{cases} \quad (2)$$

Through the Clark and Park transformation matrix [27], (2) is transformed into the d-q coordinate system. Its mathematical model is

$$\begin{cases} L\frac{di_{d0}}{dt} = v_d + \omega_0 L_0 i_{q0} - Ri_{d0} - u_{d0} \\ L\frac{di_{q0}}{dt} = v_q + \omega_0 L_0 i_{q0} - Ri_{d0} - u_{q0} \\ C_{dc}\frac{dU_{dc}}{dt} = i_{d0}S_d + i_{q0}S_q - \frac{U_{dc}}{R_L} \end{cases} \quad (3)$$

Define $S_i = 1$ when the upper bridge arm is on, $S_i = 0$ when the lower one is on, i=a, b, and c Define $u_{d0} = U_{dc}S_d$ and $u_{q0} = U_{dc}S_q$.

VI. CONTROL STRATEGY FOR PWM RECTIFIER

Control strategy is one of the most critical aspects in the design and operation of a PWM rectifier. It defines how the switching devices are modulated to achieve desired objectives such as constant DC output voltage, unity power factor at the AC side, low harmonic distortion, fast dynamic response, and system stability. Various control methods have been developed and optimized over the years to meet these objectives effectively.

A control strategy for a PWM rectifier aims to regulate the output voltage and current, often in a three-phase system, by modulating the switching pulses of the power switches. Common strategies include double closed-loop control, direct power control, and advanced control techniques like sliding mode control, fuzzy control, and predictive control. These strategies are designed to improve stability, accuracy, and performance, especially in challenging scenarios like unbalanced supply conditions or high-power applications.

One of the most widely used techniques for PWM rectifiers is Synchronous Reference Frame (SRF) Control. In this method, the three-phase AC currents are transformed into a rotating d-q frame using Clarke and Park transformations.

In the d-q frame:

- The direct-axis (d-axis) component is controlled to regulate active power (hence controlling the DC bus voltage).
- The quadrature-axis (q-axis) component is controlled to zero to eliminate reactive power.

Key steps in SRF Control:

1. Measure the input voltages and currents.
2. Synchronize with the grid using a Phase-Locked Loop (PLL).
3. Transform three-phase quantities to the d-q frame.
4. Apply PI controllers for regulating the d-axis and q-axis components.
5. Inverse transform the control signals back to three-phase and generate PWM signals.

The Fig 4. presents the control architecture of a three phase PWM rectifier.

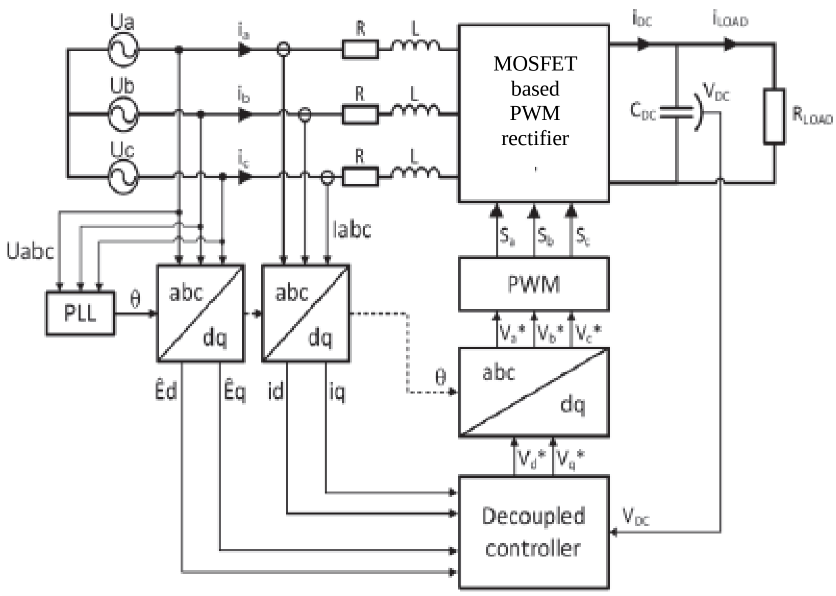

Fig.4 Control strategy for PWM rectifier

VII. RESULTS AND DISCUSSION

The simulation model comprises of two part one is power circuit and second, control circuit. The power supply consists of three phase supply, PWM rectifier and the load. Whereas the control circuit has sampling, coordinate conversion, PI controller SPWM module. The converter has been simulated in MATLAB/ SIMULINK environment with the following parameters: Input inductance is 1 mH, and per phase input resistance is 0.1 Ω. The DC-link capacitor C_{dc} = 1000 uF. For each converter. Switching frequency is 10kHz. AC input voltage is 400 V RMS. Resistive load having the value of10 Ω. The DC voltage reference for each converter is set to 600V initially.

Figure 5 represents the DC-link voltage, phase voltage, source side line current of phase A of three-phase uncontrolled rectifier. It is observed that desired voltage level cannot be achieved using this type of rectifier. As shown in the Fig.5 600V cannot be achieved and after 0.2 second it is unable to supply 800 V. The FFT analysis of line current is depicted in Fig. 6 where it has been seen that %THD is quite high i.e. 33.51%. The power factor for the uncontrolled rectifier is recorded as 0.965

Again, we simulate the same scenario using three-phase PWM or controlled rectifier.Figure 6 represents the DC-link voltage, phase voltage, source side line current of phase A for three-phase

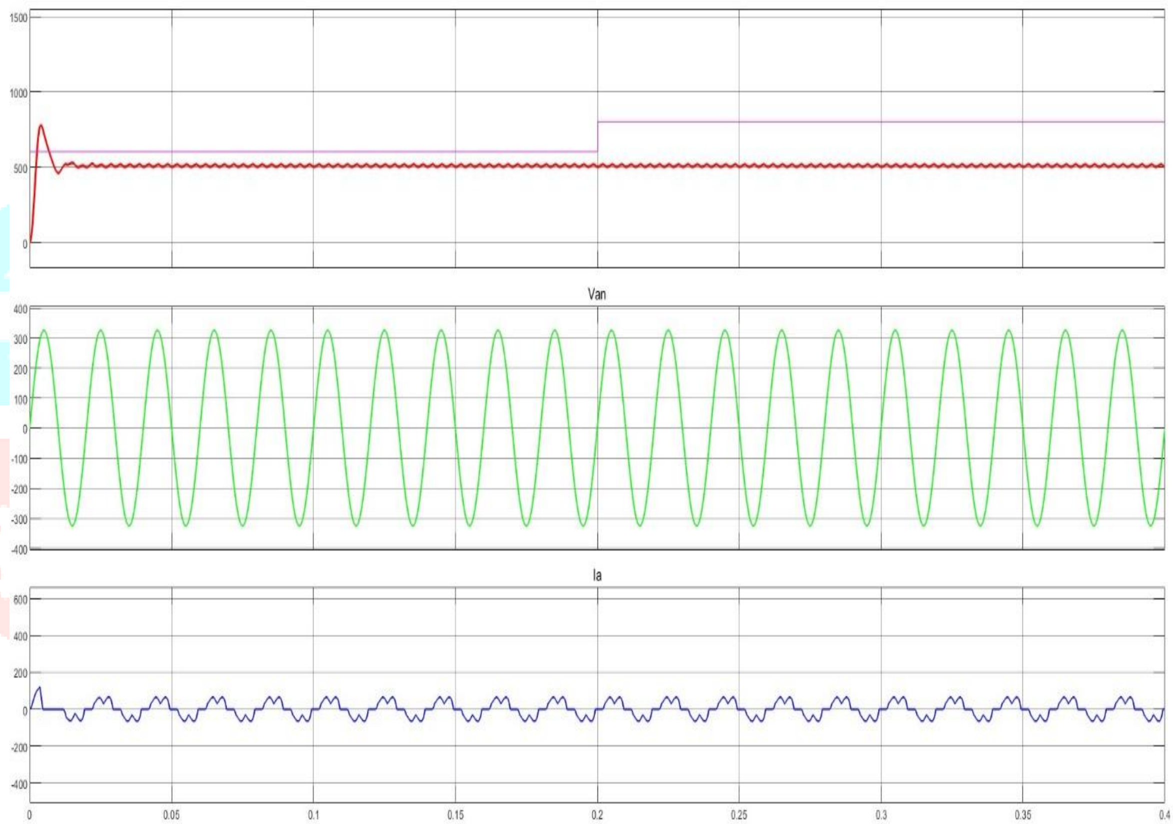

Fig. 5 From top to bottom DC-link voltage, phase voltage, source side line current Three – phase uncontrolled rectifier

controlled rectifier. It is observed that desired voltage level can be achieved using this type of rectifier. As shown in the Fig.8 600 V is now been achieved and after 0.2 second it is accurately tracking the reference DC-link voltage of 800 V. The FFT analysis of line current is depicted in Fig. 9. where it has been seen that %THD is now been improved to 4.62%. The power factor for the PWM rectifier is also improved and recorded as 0.99 as seen in Fig. 10.

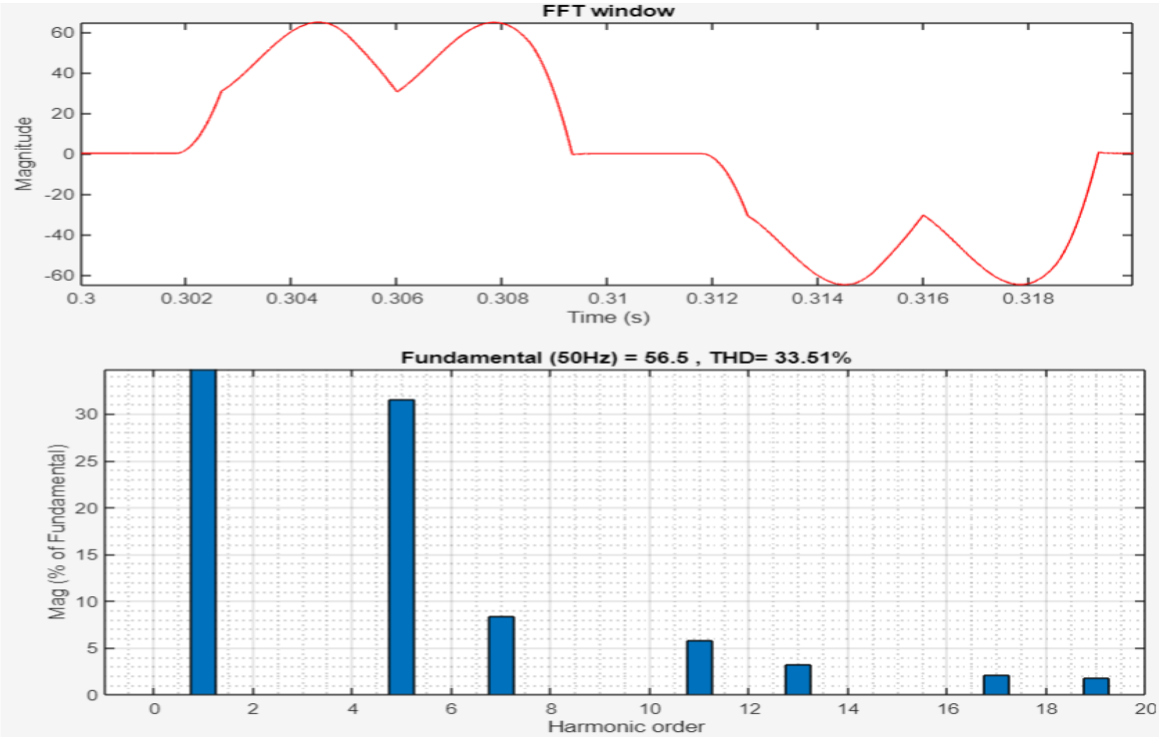

Fig. 6 Three – phase uncontrolled rectifier FFT window/THD

Fig. 7 Three – phase uncontrolled rectifier power factor

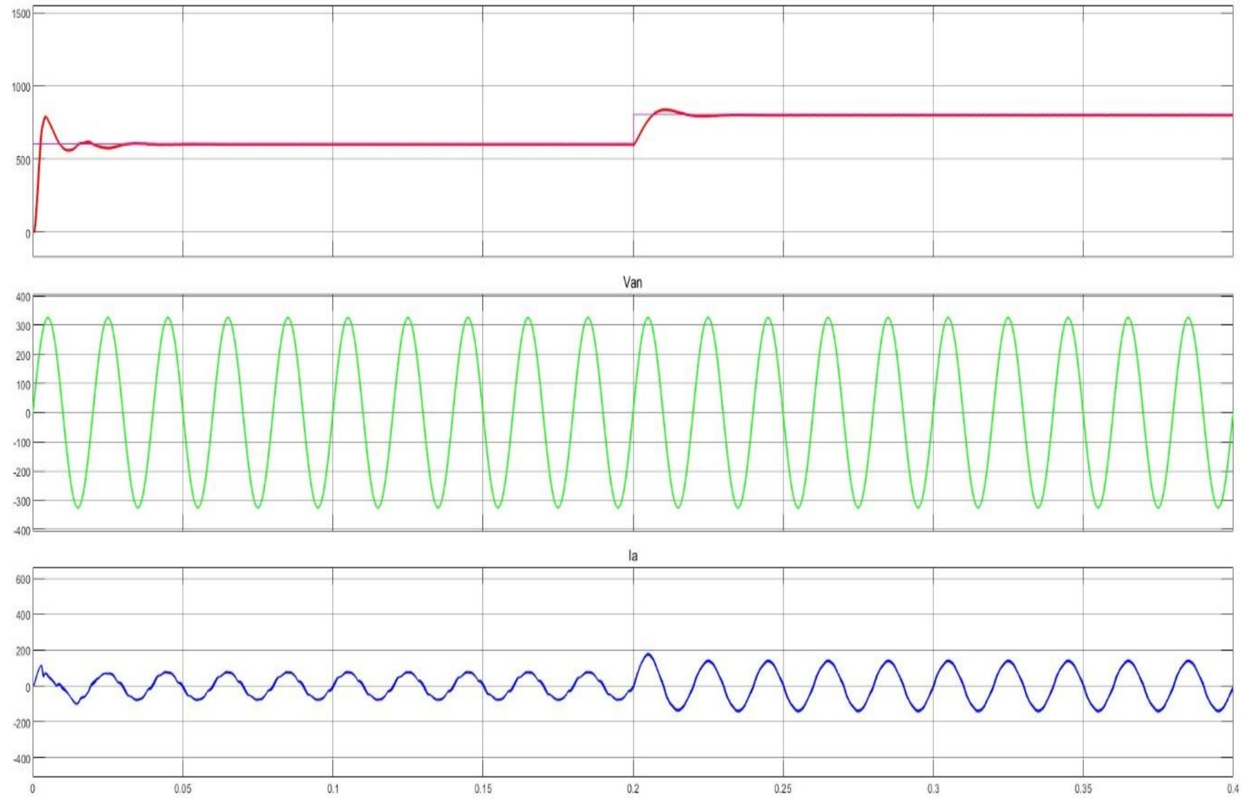

Fig. 8 Three – phase controlled PWM rectifier

The following points are observed after incorporating the PWM rectifier

- Reference voltage is achieved
- %THD of supply current is improved
- Supply power factor is also improved

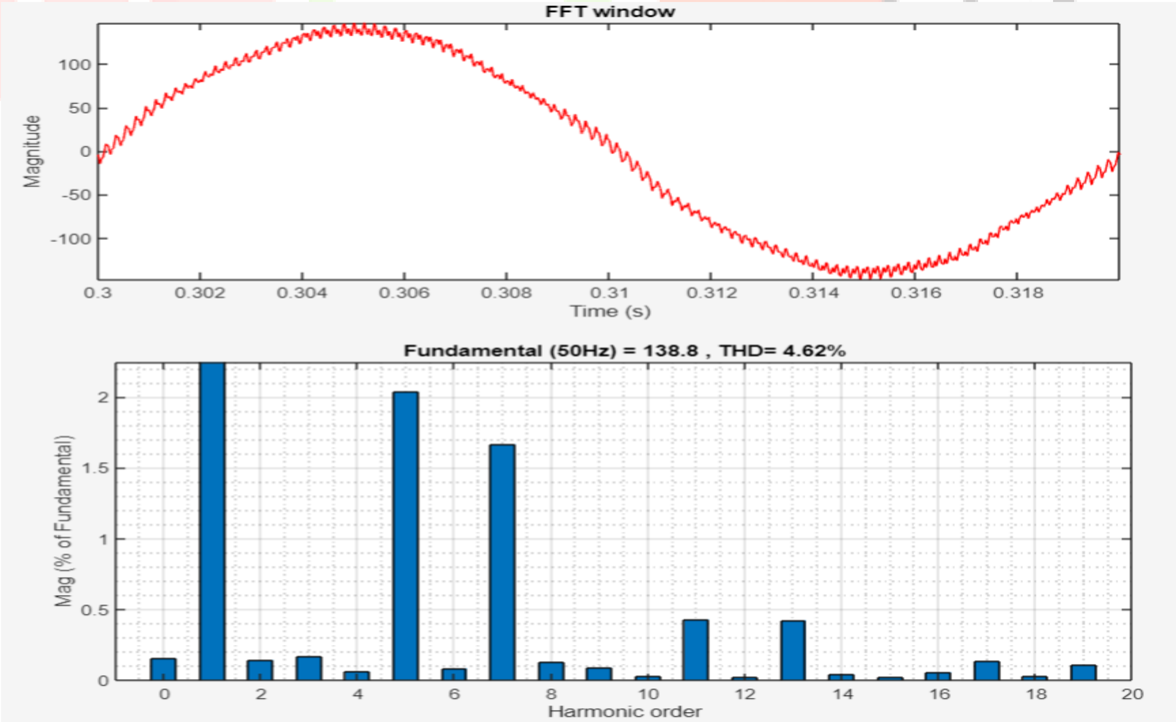

Fig. 9 Three – phase-controlled rectifier FFT window/THD

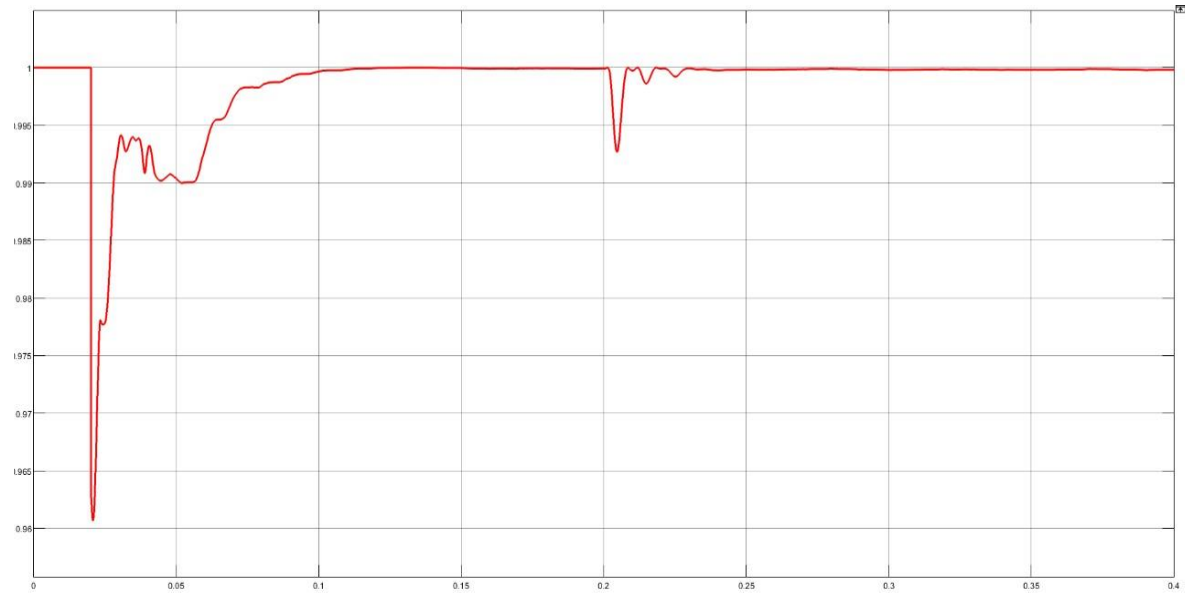

Fig. 10 Three – phase-controlled rectifier power factor

VIII. Conclusion

Three-phase PWM rectifiers demonstrate excellent power factor correction capabilities, typically achieving near-unity power factor operation. These rectifiers significantly reduce harmonic distortion in the input current, leading to improved power quality and compliance with grid standards. They provide precise control over the DC output voltage, maintaining stability under RL load conditions. The simulation study in MATLAB/ SIMULINK has established the effectiveness of PWM rectifiers successfully and exhibit its superiority over the traditional low-cost uncontrolled rectifier.

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