Enhanced controlling for Vienna Rectifier Using Sliding Mode and PSO

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***Abstract*: We propose strategy for Vienna rectifiers, grounded in sliding mode control (SMC) and formulated within the stationary α-β reference frames. This study explores the relationship between the DC-link neutral point voltage and the AC phase current and voltage relationship. The necessary control voltages for the rectifier are derived directly using a non-linear SMC approach. Theoretically, this allows for precise management of active and reactive power flows without ripple or cross coupling. Additionally, we achieve a fixed switching frequency by applying simplified space vector modulation (SVM), which effectively addresses the complexities involved in designing AC harmonic filters. Our improved strategy features dual closed-loop SMC [1] to enhance transient response during both start up and load variations, while ensuring steady-state stability. Furthermore, we incorporate a particle swarm optimization (PSO) algorithm to refine the sliding surface for active power, thereby increasing overall efficiency.**

***Keywords*: *SMC, Vienna, Active, Voltage, Current, PSO*.**

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INTRODUCTION

Optimizing Vienna rectifiers can greatly improve their performance and efficiency, especially when paired with advanced control methods like Sliding Mode Control (SMC) known for their compact design and high efficiency, (1) Vienna rectifiers are well-suited for demanding applications in power electronics. SMC offers robustness in the face of system uncertainties and nonlinearities, making it essential for effectively managing active and reactive power flows within these rectifiers. To further enhance the effectiveness of SMC, Particle Swarm Optimization (PSO) can be utilized to fine-tune the parameters of the sliding surface. PSO, inspired by the collective behaviour of swarm, systematically explores various solutions and adjusts them based on performance criteria such as efficiency, transient response, and stability. This optimization process starts with a swarm of candidate solutions, evaluates their performance, and iteratively updates their positions to converge on the optimal parameter set. By incorporating PSO, the performance of Vienna rectifiers can be significantly improved, leading to better control of active and reactive power, enhanced transient response during start up and load fluctuations, and increased overall efficiency. The integration of PSO with SMC not only sharpens the control strategy but also ensures that the rectifier operates with greater robustness and reliability.

The Vienna Rectifier [3] is an efficient and adaptable three-phase rectifier circuit celebrated for its strong performance and compact form factor. It excels in power electronics by effectively converting three-phase AC voltage into a regulated DC output with minimal harmonic distortion and superior power quality. A standout feature of this rectifier is its innovative topology, which combines a boost converter with a three-level inverter. This design results in high efficiency and reduced harmonic content, enabling a high power factor and low total harmonic distortion (THD), making it ideal for applications that prioritize power quality. Vienna Rectifiers are particularly prized in industrial drives, renewable energy systems and high-power applications where reliable and efficient power conversion is vital. In industrial environments, they supply stable DC voltage for motor drives and other equipment requiring precision. In renewable energy contexts, such as solar and wind power systems, they efficiently convert generated power, enhancing overall system performance and energy yield. Their compact and efficient design also makes them suitable for uninterruptible power supplies (UPS) and energy storage systems, where space and energy efficiency are paramount.

By overview the Vienna Rectifier's combination of high efficiency, low harmonic distortion, and compactness makes it a preferred solution for a wide range of high-performance power conversion tasks, meeting the increasing demand for efficient and dependable power management in various industrial and energy sectors.

Sliding Mode Control (SMC) is a resilient control technique that excels in handling systems characterized by uncertainties and nonlinearities, making it ideal for complex power electronic devices like Vienna Rectifiers. SMC functions by establishing a control law that drives the system state to "slide" along a predefined surface in the state space, referred to as the sliding surface. This method guarantees that the system retains favorable performance attributes, even in the presence of external disturbances and variations in parameters.

In the context of Vienna Rectifiers, which are utilized for high-efficiency power conversion in diverse industrial and renewable energy applications, Sliding Mode Control (SMC) offers considerable advantages. The operation of these rectifiers involves converting three-phase AC to DC while maintaining high power quality and efficiency. SMC effectively meets the control challenges of such systems by dynamically adjusting control inputs to keep the system state aligned with the sliding surface, where optimal performance characteristics are achieved. The main advantages of applying SMC to Vienna Rectifiers include increased resilience to parameter variations and external disturbances, improved transient response and accurate management of active and reactive power flows. By using SMC, Vienna Rectifiers can sustain stable operation under fluctuating load conditions and disturbances, ensuring consistent high performance and reliability. This makes SMC an essential approach for optimizing the control of Vienna Rectifiers, ultimately resulting in more efficient and dependable power conversion in demanding applications.

To achieve optimal performance from the Vienna-type rectifier, it is essential to enhance the controllers within the dual-loop system simultaneously. The outer loop utilizes a Sliding Mode Control (SMC) [7] controller to generate an accurate active power reference, while the reactive power reference is set to zero. In the inner loop, a [4] Direct Power Control (DPC) strategy based on SMC is introduced to directly manage active and reactive power. The required control voltage can be efficiently determined in the stationary reference frame and the space vector modulation (SVM) [6] technique is employed to maintain a constant switching frequency.

This paper is structured into seven sections. The introduction is followed by Section I which covers modeling of the Vienna Rectifier & about Enhancement. Section II SMC strategy and SVPWM strategy, Section III discusses the modeling of the Sliding Mode Controller, while Section IV provides details about the algorithm. Section IV presents the simulation results, Section V discusses the findings, and finally, Section VI concludes the paper.

I. MODELLING OF VIENNA RECTIFIER

In modern power electronics, the Vienna rectifier design allows for effective harmonic suppression and power factor correction across various industrial applications. Optimization techniques aim to enhance system performance, ensuring reliable operation and maximizing efficiency under different load conditions.

The input currents from the three-phase power grid are denoted as I_a, I_b and I_c. while the filter resistors are represented as R_a, R_b and R_c. The three-phase AC power supply from the grid is characterized by is e_a, e_b, and $e_c$and the corresponding filter inductors are labeled L_a, L_b and L_c. Additionally, the inductors for the up-and-down bridge arm filters are represented as C_1 and C_2.[39].

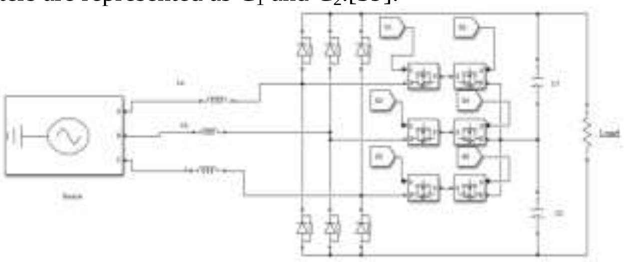

Fig.1 Vienna Rectifier

In a Vienna Rectifier system, the three-phase AC voltages are typically sinusoidal and represented as follows:

$$V_a(t) = V_{ao} sin(\omega t) \tag{1}$$

$$V_b(t) = V_{bo} sin\left(\omega t - \frac{2\pi}{3}\right) \tag{2}$$

$$V_c(t) = V_{co} sin\left(\omega t + \frac{2\pi}{3}\right) \tag{3}$$

The DC voltage $V_{dc}(t)$ can be expressed as:

$$V_{dc}(t) = V_{dc} + v_{dc}(t) \tag{4}$$

In this context, V_{dc} denotes the nominal DC voltage, while $V_{dc}(t)$ represents the ripple voltage. For a balanced system, and disregarding switching losses, the currents can be approximated by integrating the phase voltages over time.

$$I_a(t) = \frac{1}{L\int_0^t Va(\tau)d\tau} \tag{5}$$

This model needs to integrate various components, such as phase voltages, currents, DC voltage, and control inputs. Such a model is essential for engineers, as it enables a comprehensive analysis and improvement of the rectifier's performance. This is especially critical in applications requiring power factor correction and bidirectional power flow, where precise control and optimization are vital.

$$I_b(t) = 1/L \int_0^t V_b(\tau)\, d\tau \tag{6}$$

$$I_c(t) = 1/L\int \int_0^t V_c(\tau)\, d\tau \tag{7}$$

The equations for the other two phases follow a similar logic, and can be derived in the same manner.

$$v_{(a,b,c)n} = S_{(a,b,c)p} \cdot V_{cp} - S_{(a,b,c)n} \cdot V_{cn} \tag{8}$$

In the given context, $S_{(a,b,c)p}$ and $S_{(a,b,c)\,n}$ are defined using the following criteria:

- $S_{(a,b,c)o}$ is equal to 0 when $S_{(a,b,c)}$ is turned on.
- $S_{(a,b,c)p}$ equals 1 when $S_{(a,b,c)}$ is turned off and $I_{(a,b,c)}$ is greater than 0.
- $S_{(a,b,c)n}$ equals 1 when $S_{(a,b,c)}$ is turned off and $I_{(a,b,c)}$ is less than 0.

Assuming the three-phase system is symmetrical and balanced, the equivalent circuit of the Vienna rectifier in the [8] stationary α-β reference frame. The mathematical relationship between the phase currents and voltages can be described as follows:

$$E_{\alpha\beta} = R\, I_{\alpha\beta} + L\frac{dI_{\alpha\beta}}{dt} + V_{\alpha\beta} \tag{9}$$

$$C\frac{dV_{cp}}{dt} = S_{\alpha p}I_\alpha + S_{\beta p}I_\beta - \frac{V_{dc}}{R_L} \tag{10}$$

$$C\frac{dV_{cn}}{dt} = - S_{\alpha n}I_\alpha + S_{\beta n}I_\beta - \frac{V_{dc}}{R_L} \tag{11}$$

In this system, $V_{\alpha\beta}$ represents the voltage vectors generated by the setup. Based on the theory of instantaneous power, both active and reactive powers can be represented in three different contexts: the natural abc coordinate system, the stationary reference frame, and the rotating coordinate system. Here, P and Q denote the active and reactive powers at the input side, respectively, and can be expressed as follows:

$$P = e_\alpha I_\alpha + e_\beta I_\beta \tag{12}$$

$$Q = e_\beta I_\alpha - e_\alpha I_\beta \tag{13}$$

The changes in active and reactive powers are derived from the derivatives of P and Q. In the mathematical modeling of the Vienna Rectifier, the active power (P) and reactive power (Q) at the input side are determined using their representations in the stationary α−β reference frame. This method streamlines the analysis by converting the system's three-phase voltages and currents into two orthogonal components, [21] V_α, $V_\beta$which effectively represent the system's behavior in this reference frame. As a result, the expressions for (P) and (Q) in the α-β frame enable a clearer and more precise evaluation of the rectifier's performance.

Enhancement is a vital process across various fields aimed at enhancing the efficiency and effectiveness of systems or functions. In mathematics, it involves identifying the maximum or minimum values of functions, often under certain constraints, using tools such as calculus and optimization algorithms. In computer science, the focus is on refining algorithms to improve performance in terms of time and space complexity, utilizing strategies like code refactoring and dynamic programming. In engineering, optimization is applied to design systems that meet performance specifications while minimizing costs or resource usage, often employing simulation and specialized software. In economics, optimization seeks to allocate resources effectively to maximize utility or profit, using econometric models and game theory. Operations research uses optimization to solve complex decision-making challenges with techniques like linear programming and network flows. Across these disciplines, methods such as gradient descent, simulated annealing, and genetic algorithms are essential for achieving optimal outcomes and addressing intricate problems efficiently.

Sliding Mode Control (SMC) [10] is a powerful control strategy used to navigate the complexities of power electronics systems, including the Vienna Rectifier. This three-phase, three-level AC-DC converter is recognized for its high efficiency and low harmonic distortion, making it ideal for applications that require superior power quality. When applied to the Vienna Rectifier, SMC focuses on improving the control of the DC output voltage and enhancing the system's resilience to variations in input voltage and load conditions. It accomplishes this by establishing a sliding surface within the system's state space and adjusting the control input to guide the system's state trajectory toward this surface, ensuring desired performance. This technique allows the rectifier to sustain optimal functionality even under changing operating conditions. Although SMC offers notable advantages, such as improved transient response and reduced sensitivity to disturbances, it can also lead to challenges like chattering, which necessitates advanced solutions.

In the context of SMC for Vienna Rectifiers, [24] implementing a double closed-loop system enhances control accuracy and robustness. This method incorporates two interconnected feedback loops: an outer loop for voltage control and an inner loop for current control. The outer loop regulates the output DC voltage, ensuring it remains stable and within specified limits despite fluctuations in input voltage or load conditions. Meanwhile, the inner loop manages the current through the rectifier, maintaining it at optimal levels to effectively support the voltage control loop. This dual closed-loop structure improves the overall performance of the Vienna Rectifier by simultaneously addressing voltage and current dynamics. This layered control strategy not only bolsters the system's resilience against disturbances and parameter variations but also ensures precise tracking of the target voltage and current profiles. While this approach significantly enhances stability and performance, careful design is essential to balance the two loops and minimize potential issues such as chattering and response time delays. Overall, the double closed-loop SMC system in a Vienna Rectifier represents an advanced method for achieving high efficiency and reliability in power conversion applications.

II. SMC STRATEGY WITH SVPWM TECHNIQUE FOR VIENNA RECTIFIER:

In a Vienna Rectifier that utilizes a Sliding Mode Control (SMC) dual-loop system, the control strategy [12][13] is organized into two interconnected loops. The inner loop is dedicated to regulating the current or power, ensuring precise management of the rectifier's output. In contrast, the outer loop establishes reference values for these currents or powers, adjusting the rectifier's performance according to higher-level goals. This dual-loop structure enhances the control system's robustness and precision, allowing the Vienna Rectifier to operate optimally under varying conditions. By fine-tuning both loops, the SMC system effectively handles the dynamic response as well as the steady-state performance of the rectifier. While the inner loop focuses on controlling current or power, the outer loop is tasked with generating the reference values. To achieve a unity power factor, both the reactive power and reactive current loops are set to zero.

The Space Vector Pulse Width Modulation (SVPWM) technique [23], when paired with a Sliding Mode Control (SMC) controller for a Vienna Rectifier, greatly improves the system's performance. SVPWM is an advanced method that generates optimal switching patterns for the rectifier's semiconductor devices, maximizing the use of the available DC voltage while minimizing harmonic distortion. This approach ensures that the output voltage of the rectifier closely matches the desired reference, maintaining stability even amid variations in AC input or load conditions.

The DC link capacitor is essential in ensuring stable operation of the Vienna rectifier, particularly under SVPWM control**.** It helps in voltage stabilization, ripple suppression, energy storage**,** and maintaining DC bus voltage balance**,** which are critical for the sliding mode control (SMC) strategy and overall system efficiency. Optimizing its parameters using PSO further enhances the rectifier's performance. When integrated with an SMC controller, which effectively regulates the rectifier's output by keeping it on a specified sliding surface, SVPWM [20] enhances the control process further.

It allows for precise modulation of the switching actions, complementing the SMC's capability to manage disturbances and uncertainties. This synergy leads to better harmonic performance and overall efficiency, enabling the Vienna Rectifier to achieve high control precision and rapid dynamic response. In summary, the combination of SVPWM and SMC optimizes the rectifier's operation, ensuring effective and reliable power conversion.

III. SLIDING SURFACE AND CONTROL LAW IN SMC:

The switching surfaces [25] are designed as integral forms to accurately track the predefined trajectories of both active and reactive powers, ensuring minimal steady-state error and enhanced transient response. Furthermore, these surfaces can be constructed using advanced methods such as back-stepping and nonlinear damping. The sliding surface is defined as follows:

$$S_1 = e_p(t) + K_p\int_0^t e_p(\Gamma) - e_p(0) \quad (14)$$

$$S_2 = e_Q(t) + K_Q\int_0^t e_Q(\Gamma) - e_Q(0) \quad (15)$$

Where $e_p(t)$ represents the error in active power and $e_Q(t)$ denotes the error in reactive power. Thus, S1=0 and S2=0 when the system states reach the sliding manifold and stay on the surface. Here, K_P and K_Q are positive control gains selected to satisfy the system's requirements.

$$\dot{S} = F + DV_{\alpha\beta} \quad (16)$$

Where F & D should be

$$F = [F_p F_Q]^T \quad (17)$$

$$D = \frac{1}{L}\begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \quad (18)$$

$$V_{\alpha\beta} = [V_\alpha V_\beta]^T \quad (19)$$

$$F_p = -\frac{(e_\alpha)2+(e_\beta)2}{L} + \left(\frac{R}{L}\right) * P + \omega * P + \frac{dP_{ref}}{dt} + K_P(P_{ref} - P) \quad (20)$$

$$F_Q = \left(\frac{R}{L}\right) * Q + \omega * P + \frac{dQ_{ref}}{dt} + K_Q(Q_{ref} - Q) \quad (21)$$

In Sliding Mode Control (SMC), the Lyapunov method is commonly used to set conditions for the control law that guarantees the state trajectory converges to the equilibrium manifold. To achieve this, a quadratic Lyapunov function is frequently selected, which is defined as follows:

$$W = \frac{1}{2}S^T S \geq 0 \quad (22)$$

The reference for the rectifier's output voltage is generated in the stationary reference frame and then directly fed into the SVPWM module. This procedure enables the creation of the required switching voltage vectors and their corresponding time durations.

To control the DC voltage and obtain a faster response for the active power reference, Sliding Mode Control (SMC) is applied in the outer voltage loop. The sliding surface is defined as follows:

$$S_3 = \frac{C}{4} * K_3 * ((V_{dcref})^2 - (V_{dc})^2) + \frac{(Vdc)^2}{R_L} - P \quad (23)$$

$$S4 = K_4 * ((Q_{ref})^2 - (Q)^2) \quad (24)$$

According to the principles of SMC, [26] the sufficient conditions for the outer loop sliding surface are S3 = 0 and S4 = 0, which must be maintained to achieve the sliding surface.

IV. PSO ALGORITHM DESIGN:

To optimize the performance index S3 for a system, the [46] Particle Swarm Optimization (PSO) algorithm is used to determine the optimal value of K_3. The performance index S_3 is expressed by the following equation:

$$S_3 = \frac{C}{4} * K_3 * ((V_{dcref})^2 - (V_{dc})^2) + \frac{(V_{dc})^2}{R_L} - P \quad (25)$$

This formula consists of several important components. The first term, $\frac{C}{4} * K_3 * ((V_{dcref})^2 - (V_{dc})^2)$, represents the penalty for discrepancies between the squared reference DC voltage (V_{dcref}) and the actual DC voltage (V_{dc}) with K_3 acting as a scaling factor. The second term, $(V_{dc})^2/R_L$, accounts for power dissipation across the load resistance (R_L). The third term, -P modifies the index based on the actual active power P consumed by the system.

The PSO algorithm optimizes K_3 by initializing a group of candidate solutions, evaluating the performance index for each candidate, and iteratively refining the candidates based on their performance and the collective knowledge of the swarm. This iterative approach seeks to identify the value of K_3 that minimizes or maximizes S_3, depending on the optimization objective, thereby enhancing system performance by effectively balancing DC voltage accuracy, power dissipation, and active power efficiency.

The Particle Swarm Optimization (PSO) algorithm is utilized to find the optimal value of K_3 for the performance index S_3. The process starts by initializing a swarm of particles, each representing a distinct candidate value for K_3. These particles are randomly spread throughout the search space, with each assigned an initial position and velocity. Each particle then assesses the performance index S_3, which considers the deviation between the squared reference DC voltage and the actual DC voltage, as well as power dissipation and active power. Based on this assessment, the particles update their positions and velocities accordingly.

The [47] particles adjust their positions by taking into account both their individual best-known positions and the best-known position identified by the entire swarm. This updating process includes factors like inertia and the influences of both personal and global bests, steering the particles toward improved solutions. Through successive iterations, the swarm gradually converges on an optimal value for K3 that either minimizes or maximizes S3, depending on the goal. The algorithm proceeds until it satisfies the convergence criteria, such as reaching a maximum number of iterations or achieving an acceptable performance level. Ultimately, the optimized K3 value enhances the system's performance by effectively balancing DC voltage accuracy, power dissipation, and active power efficiency.

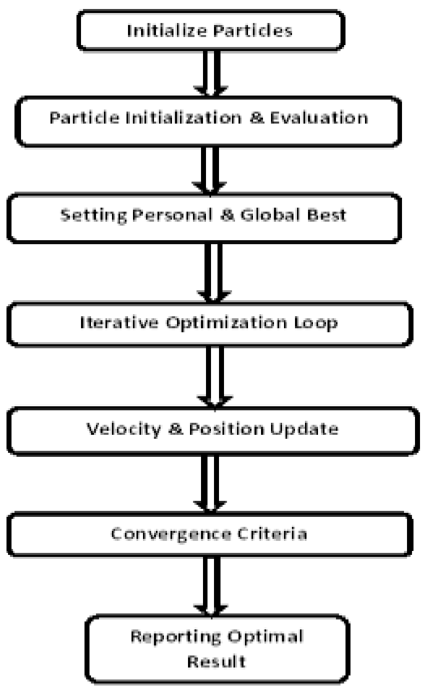

Fig.2 Flowchart

Particle Swarm Optimization offers an effective approach for tackling complex optimization challenges through a cooperative search mechanism. Its straightforward design and reliability make it a preferred option in numerous fields, particularly when global search capabilities are crucial.

V. SIMULATION:

This section presents a thorough simulation conducted on the MATLAB platform to validate the proposed control strategy. A detailed simulation is created using MATLAB/SIMULINK to assess the effectiveness of the proposed control approach.

Table 1. Parameters used in the simulation

Parameter	Value
Input Voltage	48.98 V
Source Frequency	50 Hz
DC Link Capacitor	470 μF
DC voltage Reference	119 V
Vc1 and Vc2	58 V
DC output voltage	116.7 V
Output power	14.77 Watt

In this simulation, the active switches of the Vienna rectifier are activated by the SVPWM system. The SVPWM system receives feedback on real and reactive power, as well as voltage balance between phase neutral voltages, in accordance with the mathematical modeling discussed in the previous section.

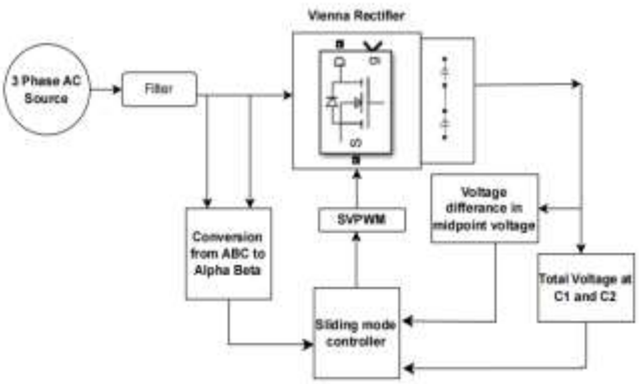

Fig.3 Block Diagram

VI. SIMULATION RESULT:

The simulation results presented in the diagram clearly indicate that the voltage and current on the input side are well-aligned in phase as per below figure 4.

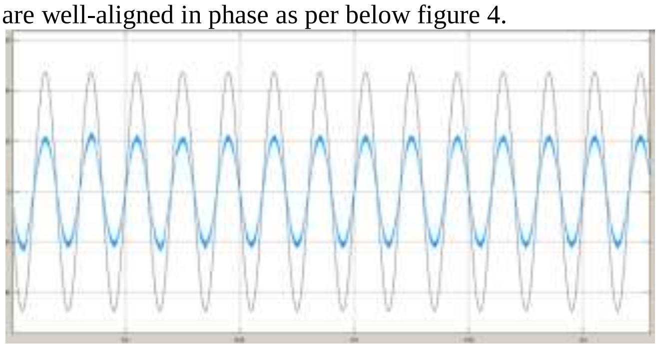

Fig.4 Voltage & Current in phase

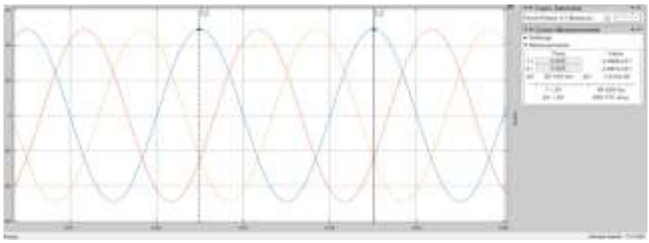

Fig.4 Input Voltage waveform

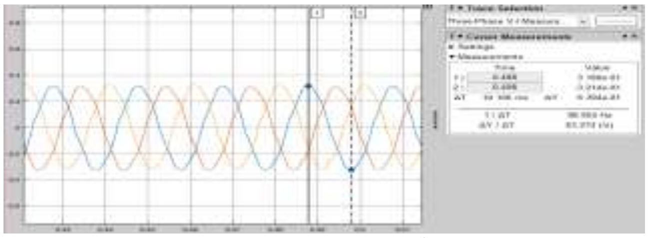

Fig.5 Input Current waveform

The Total Harmonic Distortion (THD) is measured at approximately 3.61%, which reflects a relatively low level of harmonic distortion. Furthermore, the THD for the AC side per phase current is notably low. This level of harmonic distortion is significantly lower than what is typically observed with other types of controllers, as illustrated in the results during the switching period.

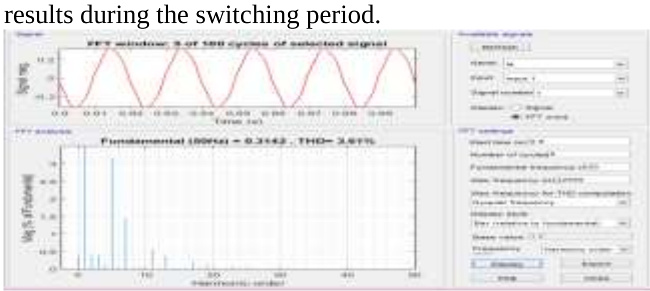

Fig.6 THD analysis

When there are fluctuations in load power, the system exhibits only a slight decrease in power, and it recovers rapidly to its previous state. This swift recovery is also evident in the voltage waveform, which demonstrates similar behavior.

Fig.7 Output Power of Vienna Rectifier using SMC

As the input power is 15.37 Watt and output power received is 14.77 Watt. Efficiency received at the end is 96.06% which is very well maintained after switching in load.

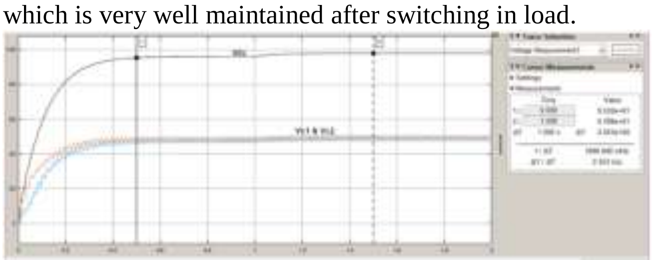

Fig.8 Output Voltage waveform

The time required for voltage regulation is minimal, taking about 40 ms. to stabilize. Additionally, the midpoint voltage remains consistent across both capacitors, ensuring uniform performance. After introducing resistance, the output power adjusts quickly, highlighting the system's efficient regulation capabilities.

Overall, the system achieves a high level of efficiency, with effective voltage regulation attained following load variations or switching events. The power factor also remains close to unity throughout the operation, indicating optimal performance.

VII. CONCLUSION:

The proposed Sliding Mode Control (SMC) scheme significantly enhances both the dynamic and steady-state performance of the Vienna-type rectifier. By utilizing a stationary alpha-beta reference frame for modeling, it effectively tackles challenges related to voltage regulation and system stability. SMC creates the reference voltage vectors for the Vienna rectifier, promising stable current control and rapid dynamic response. SVPWM then modulates these vectors to provide optimal switching signals, which improve voltage usage, reduce harmonics, and increase efficiency. The combination of SMC and SVPWM, further tuned by Particle Swarm Optimization (PSO), yields a high-performance control method with greater stability, lower losses, and higher power quality. This innovative approach outperforms traditional Proportional-Integral (PI) controllers, particularly in handling nonlinearities and parameter variations. The robustness of the SMC allows the rectifier to maintain efficiency and stability even in the face of disturbances, making it ideal for demanding power electronics applications. The outer loop of the SMC enhances the dynamic response of the DC voltage, facilitating quick adjustments to load and input fluctuations. Comparative analyses reveal that the SMC excels in voltage stability, current regulation, and power management. Moreover, it improves the quality of the current waveform and overall power efficiency, which are vital for energy quality and system reliability. In conclusion, the SMC approach stands out as a highly effective alternative to conventional control methods, delivering superior performance across key parameters.

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