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Original Article

Performance Analysis of 1Φ Vienna Rectifier Fed DC Drive Using Model Predictive Control

B. Manimaran[1], R. Ranihemamalini[2]

[1,2]*Department of Electrical and Electronic Engineering, St. Peter's Institute of Higher Education and Research, Chennai, India.*

[1]*Corresponding Author : manimaran.as12@gmail.com*

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Abstract - *Battery Electric Vehicles (BEVs) are becoming more popular today and are a promising technology that could eventually replace gasoline-powered vehicles. When the BEVs and the charging stations were connected, the power grade deteriorated and fell short of IEEE criteria. There are various converters/rectifiers in the electronics world, such as Swiss rectifiers, matrix converters, unidirectional boost converters, Vienna rectifiers, etc. The Vienna rectifier is the most favourable topology due to fewer switches, ease of fabrication, high power density, and unity power factor with the suitable control strategy. To control the DC components, the conventional Vienna rectifiers are designed with Proportional-Integral (PI) controllers, which give a prolonged response to the reference input, and also the PI controller with an AC component having a zero-crossing point very close to the line current. So, the device's Power Factor degrades (PF), increasing THD. To overcome the problem, this paper presents the Model Predictive Controlled (MPC) Closed Loop 1Φ Vienna Rectifier fed DC Drive System (CLSPVRDDS). The proposed system is tested with the MATLAB/Simulink software and compared with the conventional PI controller-based system. Performance metrics for CLSPVRDDS employing MPC, such as settle and rise time, peak time, and steady-state error, may be compared to those of current PI controllers. The simulation result shows that fast dynamic speed and torque responses can be obtained using the CLSPVRDDS system with the MPC controller. This proposed method produces a quicker dynamic reaction than the existing PI controller.*

Keywords - *Vienna rectifier, Model Predictive Control, 1Φ, PI controller, Converter.*

1. Introduction

Pre-regulators are being used more frequently due to rising awareness of power quality issues and rules set forth by utilizers of power. The circuits of these preregulators, which also serve as load resistors and are effectively nonlinear converters, are regulated to generate a load with a unity power factor [1]. The system cost of pre-regulators has been increased, complicates the circuit, and results in more power being lost. It is moderated by choosing a straightforward, affordable, highly efficient pre-regulator circuit topology with low current harmonics.

The Vienna rectifier is the best choice of pre-regulator for 3-phase, high-power, and end users due to its straightforward design, sparse use of active switches, and great efficiency. Many different converters/rectifiers exist in electronics, including Swiss rectifiers, matrix converters, unidirectional boost converters, Vienna rectifiers, etc. The Vienna rectifier topology is the most advantageous of these. This is because the Vienna rectifier has fewer switches overall, is easier to fabricate, has a higher power density, and can potentially attain the power factor to unity with the suitable control strategy [2]. The Vienna rectifier in high switching frequency applications [3] suggested an irregular space-vector modulation based on the carrier in variable clamping in 2019 [4]. Suggested a method for controlling the current with high bandwidth for a 3Φ Vienna rectifier to increase the system's stability and decrease the harmonics. The natural a-b-c frame was used to derive the model for the 3Φ Vienna rectifier by calculating the averaged varying inductance into account. Tao Wang and colleagues devised the 2-channel interweaved Vienna rectifier topology was developed.

In the sectors surrounding the current peak, the current ripple has been reduced by shifting the phase angle between the two channels [5]. For a three-level Vienna rectifier, [6] suggested a modified Proportional Resonant (PR) based control technique that lowers harmonic distortion and unbalanced supply voltage surroundings. By the control method, the harmonics in the input side currents can be chosen mainly and removed. The output voltages of the Vienna rectifier can be balanced with the help of a PI controller. This technique can control the vector and the hysteresis current. In [7] explained that the Vienna rectifiers are low cost, the power factors extended from -30- to 30 degrees with the use of STATCOM, and it works under low voltage. The author [8, 9] proposed that the Sliding mode control with an orthogonal system is used for AC power factor corrections and regulates DC output voltage. The harmonics are reduced from 20.71% to 1.27%. In conventional rectifiers, current harmonics are the most critical problem that causes low power factor and voltage distortion. By using filters, the overall cost and losses increase, reducing efficiency.

June-Seok Lee et al. explained that the results of this study show that the overall harmonic distortion has decreased from 12.820% to 3.588%. Current distortion is removed, and the Reference voltage is modified. Implementing it in a Microcontroller Unit (MCU) is straightforward [10]. The Vienna rectifier's benefits include its reduced power factor of 0.866 and a phase discrepancy of 30 degrees between the current and the input voltage. The CB-PWM technique does not provide a power factor of 0 to 1. To address the unbiased voltage balance issue, [7] suggested a standard design methodology for three-phase Vienna rectifiers. The design framework simplified building several neutral point voltage balancing techniques while providing stability [11]. By selecting various zero-sequence voltages, three typical neutral point voltage approaches were presented for demonstration.

The three methods were thoroughly compared regarding current quality at the input, fluctuation in the capacitor voltages, and system effectiveness. [12] modelled a Vienna rectifier for charging the electric vehicle with a PFC controller for EV charging stations. The author explained that the power factor is improved using this converter, decreasing the distortion in harmonics regarding efficiency, THD, and power aspects. A Vienna rectifier or converter is an ideal choice. It also has low complexity, greater efficiency, greater power density, low input THD, and a better power factor modelled as a single-phase Vienna rectifier. This paper deals with decoupling the system into three discrete pieces, leading to a third-order, more straightforward approach.

According to this paper, the individual phases are regulated with the use of two PI controllers, one of the PI is for output voltage regulation, and another PI is for shaping the current at the input by directly measuring the voltage at the output, input voltage, and the wind in the control method. The author [13] developed a control of model-based predictive control using the 1Φ Vienna rectifiers. This paper proposed the MPC algorithm, which includes finding conduction modes. The presented algorithm estimates the duty cycle using prior and current inductor current data. [14] suggested a framework for a predictive duty cycle regulation technique that effectively maximizes three-phase duty cycles for Vienna rectifiers. The first step in getting the three-phase duty cycles is anticipating how they will affect changes in instantaneous current fluctuations and reducing a cost function. By taking into account the physical traits of the Vienna rectifier, a unique three-phase duty cycle adaptation approach is developed to ensure the grid's current output. The paper [17] suggests a modulation technique constructed around a consistent control set predictive model. The switching inefficiency may be significantly decreased with a pair of phase clamping and an additional phase regulated without increasing the computational effort, and the neutral point voltage can be managed without weighting factors. By employing the recommended method, it is possible to decrease zero-crossing disturbance across the whole modulation index range. In a 3-level Vienna rectifier, [18] introduced the essential finite control-set predictive model control based on a quick vector selection approach. This approach has a low input current THD, an ideal-controlled DC-link voltage, fewer redundant vectors, and less computational work. It also has a good power factor. Compared to the typical PI control approach, this allows the developed technique to have a fast dynamic reaction. The standard method and the new method are compared in this waveform. The THD and PF are measured on each of the load conditions to show how much the MPC algorithm is correct. Power considers many load scenarios.

Conclusions using model-based predictive control, this research presents a method for advancing the road current distortion for single-phase Vienna rectifiers. As a result, unlike the traditional PI control approach, the proposed method can own a fast dynamic reaction. The PSIM simulation [16] has been done here, and hence, the verification has been done as per the performance of the suggested approach. The literature survey concluded that the critical problem of PI controller is linear, while the systems used in the power quality areas are nonlinear. It produces many problems in the control area. Predictive controllers are nonlinear controllers and can efficiently deal with nonlinear systems. PI controllers are used in the traditional Vienna rectifiers. Since their dynamic reaction is too slow to control alternating current, these devices are best suited for controlling DC components. Therefore, if the PI controller is active for controlling the AC, the harmonic distortion of the bus current grows, and an adequate output cannot be computed.

As a result, the line current distortion issue becomes more prominent as the system power declines and the line current frequency rises. A gap between the input and output currents that occur close to the voltages' zero-crossing point, as well as the sluggish reaction and significant faults of the PI controller, are additional causes of current distortion. Around this neutral point, the input voltage and line current's phase difference likewise get more extreme.

Thus, the new controller needs to have a faster response, and the ability to maintain the unity power factor is required to lessen the response error and solve issues related to the DCM. The demand for advanced control strategies that improve performance, robustness, and efficiency and address the research gap of conventional PI control methods despite adapting to contemporary power electronics requirements causes the research gap in Vienna rectifiers produced with Proportional-Integral (PI) controllers. A significant research deficit in this area also relates to investigating cutting-edge methods to reduce harmonic distortion and guarantee dependable functioning in numerous applications. Compared to conventional PI controller techniques, the suggested method's implementation of predictive control founded on earlier data allows for speedier dynamic reactions, clearly exhibiting an innovation in control strategy.

Furthermore, compared with previous study findings, it provides a noticeable increase by successfully reducing harmonic distortion, improving performance, and guaranteeing dependable operation. To overcome the abovementioned issue, this paper presents the MPC control approach based on 1Φ Vienna rectifier-fed DC drive. In this strategy, the older data are typically used to anticipate the current. This estimated current is used to determine the ideal duty cycle. The suggested controller features a straightforward algorithm and quick dynamics. Because of this, the controller can obtain a faster dynamical reaction than the conventional PI approach. The contribution of the proposed technique follows:

- The MPC control approach is proposed to enhance the quality of line current in a 1Φ Vienna rectifier.
- Estimating the next state can minimise the main and source current discrepancy.
- The proposed technique reduces the ideal duty cycle, reduces the distortion in the harmonics of the current, and maintains the PF to unity.
- The simulated closed-loop Vienna rectifier with PI and MPC controller is compared to the PI and MPC controller concerning time domain metrics like Rise and Settle Time (tr) and (ts), Peak Time (tp), and Error during Steady-State condition (ess).

The paper's outline is as follows: section 2 provides the control techniques such as PI and model predictive control. Section 3 represents the proposed system description; section 4 illustrates the simulation results of the proposed method. Finally, section 5 provides the conclusion.

2. Control Techniques

2.1. PI Controller

The most widely used controller is the well-known PI controller. Because of its ease of use and capacity to automatically adjust a few parameters, the PI controller quickly became one of the most widely used industrial controllers. Industries that need slow processes make use of a PI controller. With this controller, reduced overshoot and slow settling time can be accomplished. Numerous theoretical and practical investigations on PI controller setting rules have been conducted. In 1942, Zeigler and Nichols presented a technique for assessing the PI controller parameter. Other methods were introduced by Hagglund and Astrom in 1955 and Cheng Ching in 1999 [19].

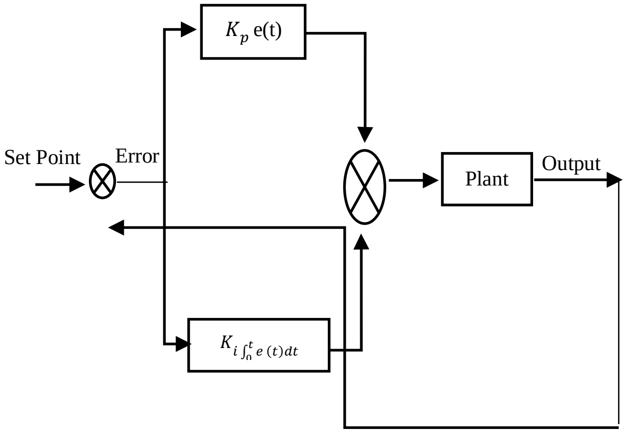

Fig. 1 Principle of PI controller

2.2. Model Predictive Control

A precise system model is necessary for the MPC approach. The system's future behaviour is calculated using the system's current values and the optimizing cost function that the horizon principle can obtain.

The input vector can be determined at every step within a predetermined optimization window. Figure 2 depicts the MPC's fundamental principle [21]. The estimated control sequence V is provided below for time instant t. At time instant k, the first element of V is selected as an input.

$$\Delta V = [\Delta v(t) \Delta v(t+1)\ \Delta v\ (t+2) \ldots \Delta v(t+Nc-1)] \quad (1)$$

$$(t) = \Delta(t) + v(t-1) \quad (2)$$

$$(t+1) \ = \ (t) + Bv(t-r) \quad (3)$$

$$(t) = (t) \quad (4)$$

Expected state and output equations of the discontinuous system are given by,

$$\hat{x}((t+j|k)) \ = \hat{A}\hat{x}((t+j-1|k)) \ + \hat{B}\hat{u}((t+j-\hat{r}|t)) \quad (5)$$

$$\hat{y}((t+j|t)) \ = C\hat{x}((t+j|t)) \quad (6)$$

Optimizing the function of cost is given in (7). The weight matrixes qW and rW must be correctly selected to develop a system model. The cost function can be obtained by using the optimization window.

$$J = (rS - y)\ TqW(rS - y)\ + \Delta VTrW\Delta V \tag{7}$$

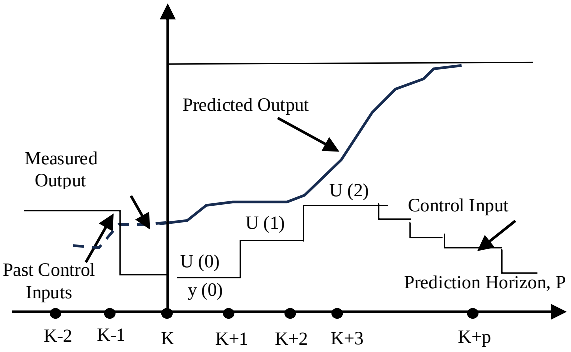

Fig. 2 Process of model predictive control's fundamental principle

3. Proposed System Description

Figure 3 displays a procedure of an entire 1Φ Vienna rectifier system, complete with control electronics. The error may be determined between the observed DC electrical and standard voltage. The measured error can be given to the input of the PI controller that makes up the voltage controller that is part of the outer control loop.

The D_p and D_n diodes are incorporated into the circuit. The traditional and proposed method-applied system's voltage controllers are PI controllers. The reference current is the voltage controller's output.

The grid voltage's waveform, shown in this illustration by sint, is created by isolating the measured grid voltage with its magnitude. By dividing i* by sint, the last line current reference, il*, is produced. The difference in the detected line current i_L, and i_L* is the input to the internal loop control [20]. The current controller is switched to a PI controller, and its output is the duty cycle of PWM. The line current should have a broader bandwidth (cc) than the line voltage control. Additionally, this bandwidth of 1st of 20 or 1st of 10 switching frequencies to avoid noise and disruption.

The switching frequency thus sets a limit on the system's cc. Figure 4 shows a procedure of a closed-loop-PI/MPC-controlled-SP-VR-DCM. The speed is measured and compared to the reference speed of the motor. The speed-PI/MPC is affected by the error. The PI/MPC output is compared to the discontinuous current mode current. PWM receives the output of the PI/MPC. VR's pulse width is updated to control DCM's speed.

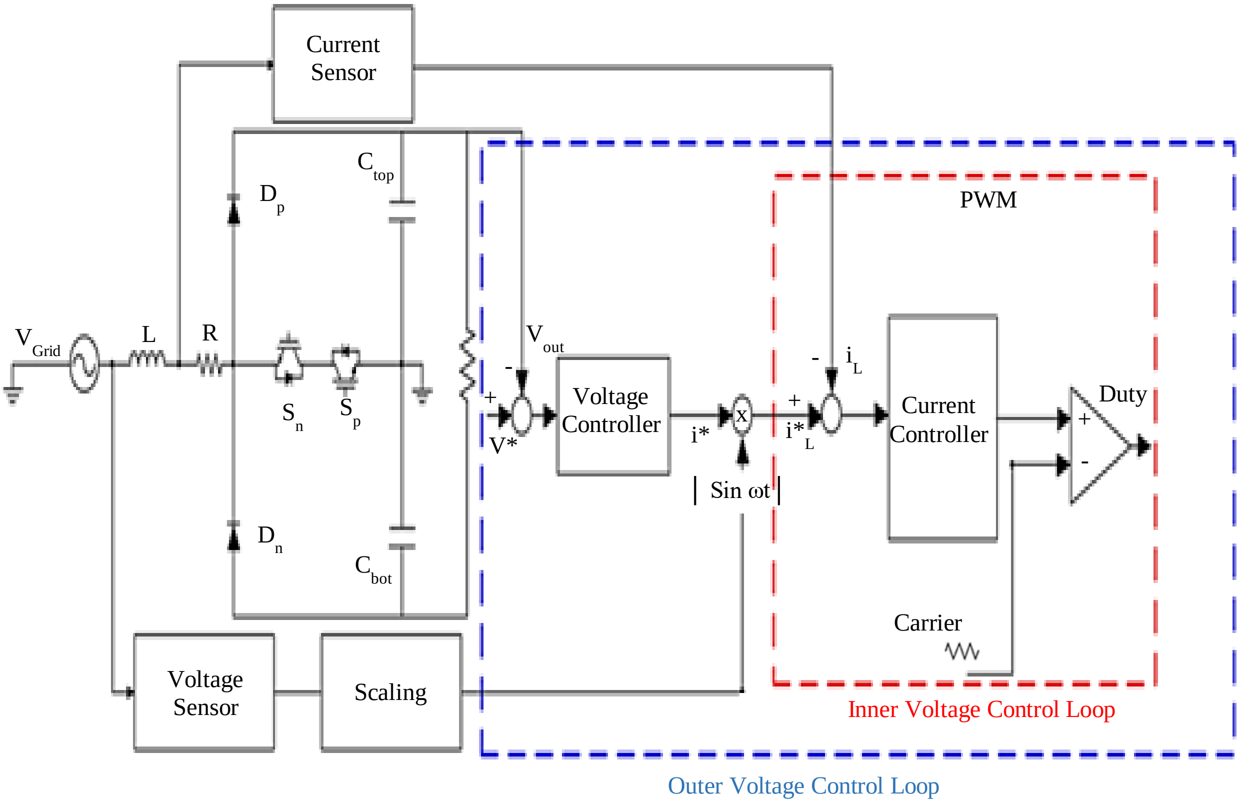

Fig. 3 Working procedure of a closed loop single phase Vienna rectifier with MP controller

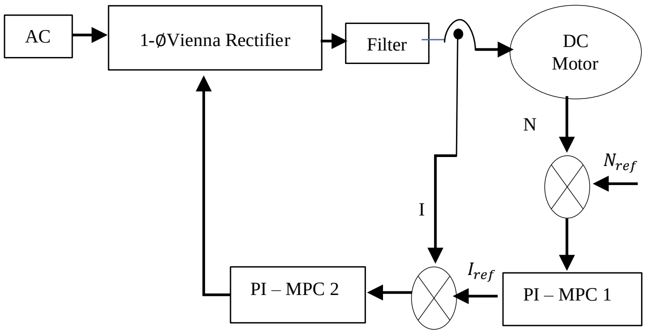

Fig. 4 Block diagram of a closed loop PI/MPC controlled SP-VR-DCM system

4. Simulation-Outcomes

The analysis of the proposed Model Predictive Controlled (MPC) Closed Loop Single-Phase Vienna Rectifier fed DC Drive System (CLSPVRDDS) is examined in this section. Here, the suggested system is tested using the MATLAB/Simulink program. To demonstrate the suggested system's efficacy compared to the established closed-loop PI controller-based system.

4.1. Closed Loop - PI-Controlled SP-VR-DCM System

Table 1. Parameters of PI controlled SP-VR-DCM system

Parameter	Actual Value
Input Voltage	56V
Voltage across Motor Load	100V
Motor Speed	1300 RPM
Current through Motor Load	20A
Motor Torque	5 N-m

Figure 5 describes a simulation diagram of a closed-loop Vienna rectifier with a PI controller. Table 1 provides the actual value obtained by PI controlled SP-VR-DCM system. Figure 6(a) shows the input voltage, which is 56V.

Figure 6(b) shows the voltage across the motor load, which is 100V. Figure 6(c) shows the motor speed, which is 1300 RPM. Figure 6(d) shows the current flowing through the motor load, which is 20A. Figure 6(e) shows the motor torque, which is 5N-m.

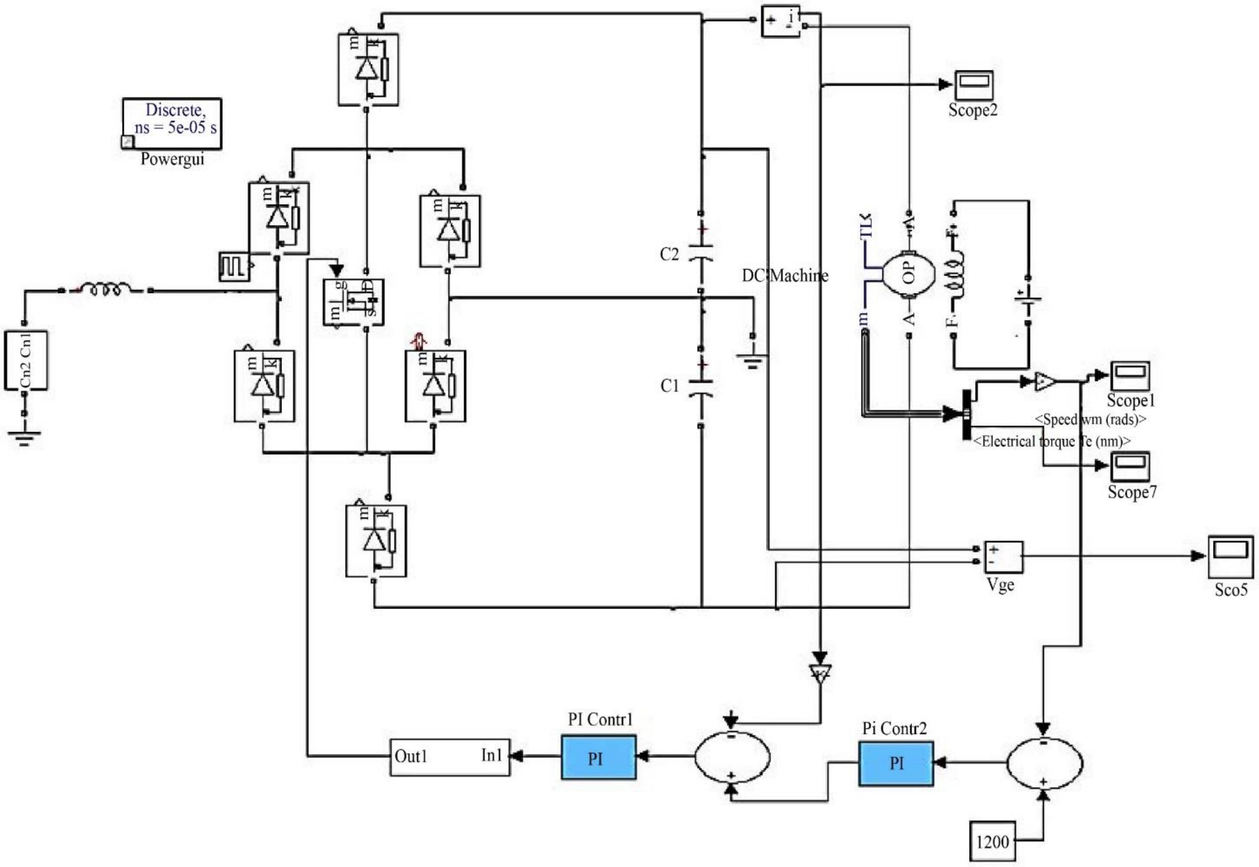

Fig. 5 Vienna rectifier with closed loop PI controller circuit diagram

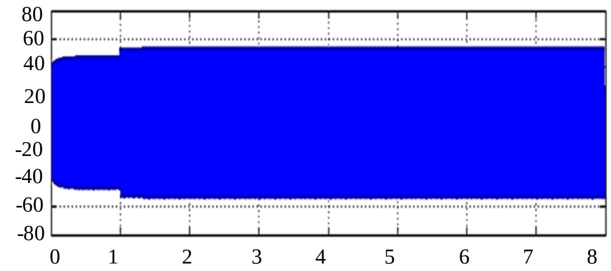

Fig. 6(a) Input voltage of PI-controlled SP-VR-DCM system

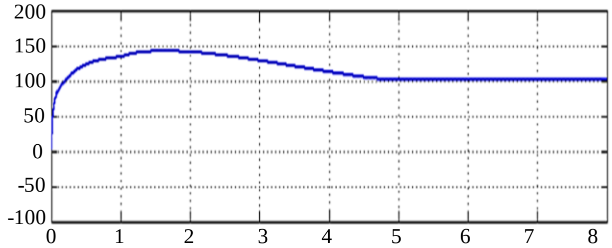

Fig. 6(b) Voltage across a motor load of PI-controlled SP-VR-DCM system

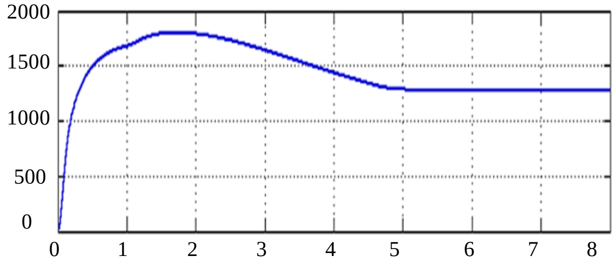

Fig. 6(c) Motor speed of PI-controlled SP-VR-DCM system

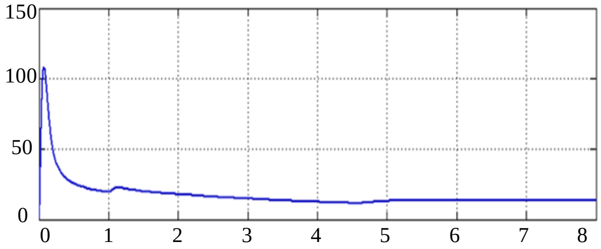

Fig. 6(d) Current through motor load of PI-controlled SP-VR-DCM system

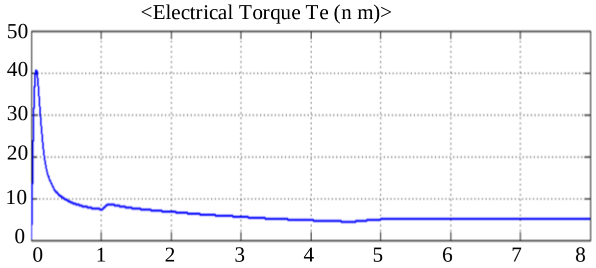

Fig. 6(e) Motor torque of PI-controlled SP-VR-D

4.2. Closed Loop - MPC-Controlled SP-VR-DCM System

Modelling of the closed loop Vienna rectifier with Model Predictive Controller is shown in Figure 7. Table 2 provides the actual value obtained by the controlled SP-VR-DCM system. Figure 8(a) shows the block diagram of the closed-loop Vienna rectifier with an MP controller. Input voltage is delineated in andits value is 56V. The load voltage is represented in Figure 8(b) and its numerical value is 100V.

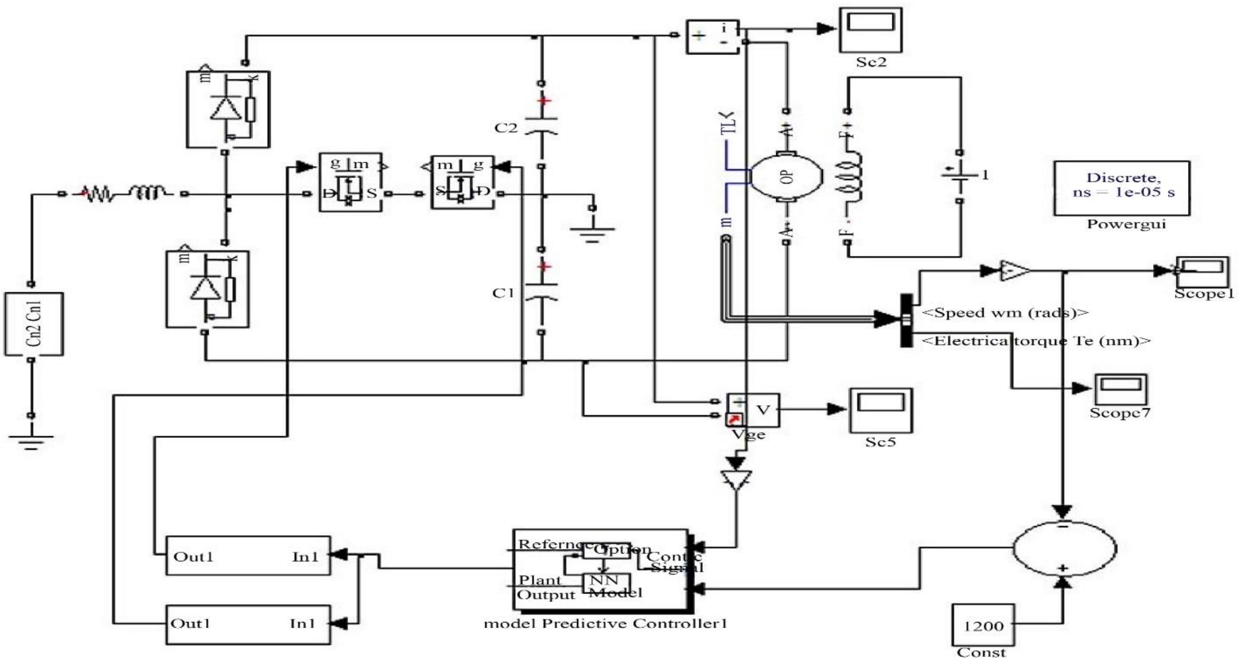

Fig. 7 Design of Vienna rectifier with Model Predictive Controller

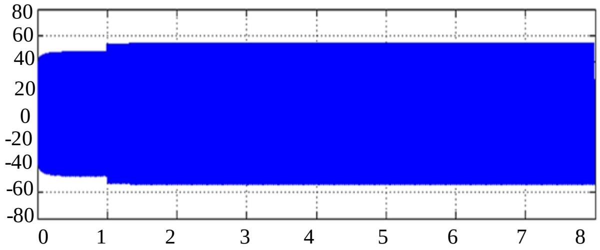

Fig. 8(a) Input voltage of MPC-controlled SP-VR-DCM system

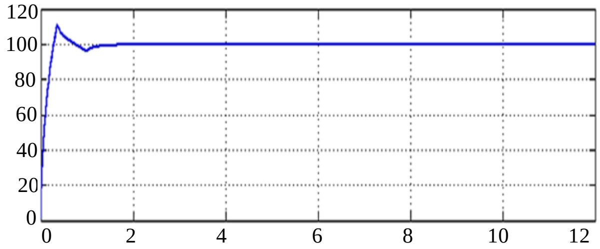

Fig. 8(b) Voltage across a motor load of an MPC-controlled SP-VR-DCM system

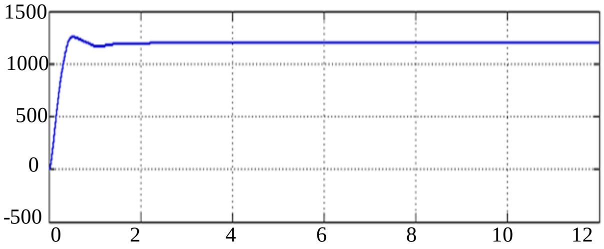

Fig. 8(c) Motor speed of MPC-controlled SP-VR-DCM system

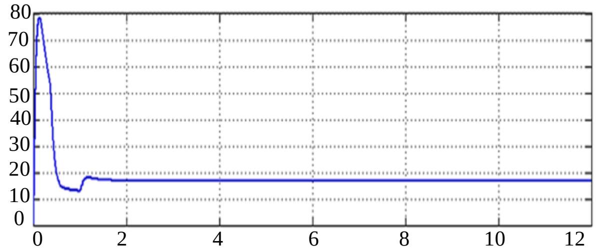

Fig. 8(d) Current through a motor load of MPC-controlled SP-VR-DCM system

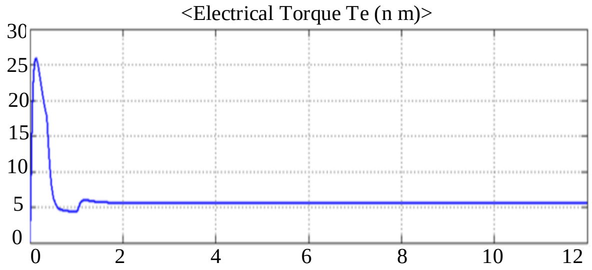

Fig. 8(e) Motor torque of MPC-controlled SP-VR-DCM system

The motor's speed is specified in the Figure 8(c) and the numerical value is 1300 RPM. The load current is illustrated in the Figure 8(d) and the numerical value is denoted by 18A. Motor torque is delineated in Figure 8(e) and its value is 6N-m. Figure 9 shows a bar chart.

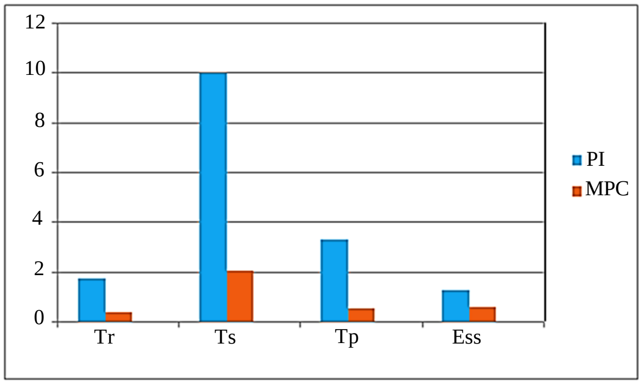

Fig. 9 Bar chart of time domain parameter using PI and MPC

Table 2. Parameters of MPC-controlled SP-VR-DCM system

Parameter	Actual Value
Input Voltage	56V
Load Voltage	100V
Motor Speed	1300 RPM
Load Current	18A
Motor Torque	6 N-m

Table 3. Time domain metrics comparison using PI and MP Controller

Controller	Tr	Ts	Tp	Ess
PI	1.45	4.78	1.46	1.8
SMC	0.25	2.00	0.35	0.9
HC	0.23	1.35	0.35	0.6
MPC	0.43	2.10	0.58	0.56

Table 3 compares the time domain metrics utilizing PI and MP controllers. Using the MP controller, the tr is decreased from 1.45 sec to 0.43 sec, the peak time is reduced to 0.58 sec, and the settling time is diminished to 2.10 sec. From 1.8V to 0.56V, the ess value is decreased. The results show that the closed loop Vienna rectifier with MP controller outperforms the Vienna rectifier with PI controller in terms of performance.

The selection of Model Predictive Control (MPC) as the control approach for Vienna rectifiers is principally responsible for the study's improved findings. A substantially faster dynamic reaction is made possible by MPC's intrinsic nonlinearity and use of prior data, which improves performance measures.

Additionally, the MPC controller surpasses standard Proportional-Integral (PI) controllers in terms of reducing harmonic distortion and preserving a unity power factor. The efficacy of the MPC technique is shown by the study's validation using MATLAB/Simulink models and a comprehensive comparison of performance measures with a traditional PI controller.

This study has wider ramifications for power electronics and the electrifying of transportation, notably in Battery Electric Vehicles (BEVs) [15] and the associated charging infrastructure, in addition to filling the gaps in Vienna rectifier control.

5. Conclusion

This paper analyzes the performance of the Model Predictive Controlled (MPC) Closed Loop 1Φ Vienna Rectifier fed DC Drive System (CLSPVRDDS). The proposed system is tested with the MATLAB/Simulink software and compared with the conventional PI controller-based system. The difference in inaccuracy between the primary current and the standard current can be minimized by estimating the next state; the proposed MPC controller algorithm reduces the ideal duty cycle for controlling the input current in the smallest amount of time. It offers a quick dynamic reaction that enables a small degree of inaccuracy; the source current should follow the optimal wind. The proposed technique reduces the distortion in the harmonics of the current and maintains the PF to unity. The closed loop Vienna rectifier with PI and MP controller is developed, and the time domain metrics are compared. The results are compared with tr, tp, ts, and ess parameters. Using the MP controller, the tr is decreased from 1.45 sec to 0.43 sec, the peak time is reduced to 0.58 sec; settling time is diminished to 2.10 sec. From 1.8V to 0.56 V, the ess value is decreased. The results show that the closed loop Vienna rectifier with MP controller outperforms the Vienna rectifier with PI controller in terms of performance.

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