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Comparative Evaluation of Various Control Techniques For Three Phase Three Switch Three Level Boost Converter

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Abstract

This paper presents a comparative analysis of various control technique for the three phase three switch three level boost converter. Based on the results of the analysis a new control method has been proposed. The simulation analysis is investigated and evaluated with respect to factors like unbalanced power supply voltage and variable load conditions in terms of the line current harmonics distortion, stability of DC bus regulation, switching of transistor, power factor, power loss, control intricacy, etc. A discussion of simulation results of hysteresis current control, average current control and one cycle control methods using Matlab are presented. After a detailed analysis of the observations of the various techniques it is observed that it operate in the continuous inductor current mode, variable switching frequency as it is load dependent. In order to overcome this issues proposed the mixed conduction mode which will eliminate these factors effectively, the theoretical analysis of the proposed method is deduced and simulation models are verified with wide load variations and unbalanced input supply voltage.

Keywords: average current control; current harmonic distortion; hysteresis current control; mixed current control; one cycle control; power factor

Introduction

In general various topologies are used for the AC to DC conversion application using Diode and Thyristor rectifiers. most challenges in these requirements are input line current pollution causing high current THD, design of inductors and power factor. The advanced power electronics technology has been working towards to improve the performance and overcome the above challenges. The power quality has been improved using different topology converter by improving the power factor and reducing the harmonics interference in the grid. Among all topology converters the three-phase three-switch three-level rectifier (VIENNA rectifier) has more advantage which is developed by Johann W.Kolar in1994 [1]. The Vienna rectifier topology consists of three bidirectional switch connected with three phase diode bridge rectifier. The Dc link voltage is split into two equal values by connecting the same value capacitor in series and blocking voltage of switch becomes half compared to two level converter. In the DC bus system have three different voltages like E1/2, 0, E2/2. The switching state and the sign of the input current defined the rectifier input voltage. When the switch is turn on the input inductor starts charging and input current increases and when the switch is turn off the input inductor current discharge through the diode bridge rectifier. The Vienna rectifier bidirectional switch is switching On/Off state depends on the phase current of in each phase.

This converter have continuous sinusoidal input current, robust construction and switch blocking voltage stress becomes half, manufacturing cost is less, three level output voltage, boosting ability and power flows in unidirectional.

Various current control techniques have been applied for the three- phase three-switch three-level converter as shown in Fig.1 to achieve the good power quality and improve the power factor. The most popular current control techniques like hysteresis, average and one cycle control performance was analyzed using Matlab simulation model. In the study of analysis observed that operating in continuous inductor current mode, random switching frequency due to its load dependent and more complex under unbalanced mains conditions. Based on the analysis the new control method mixed conduction mode has been proposed to overcome the above problem.

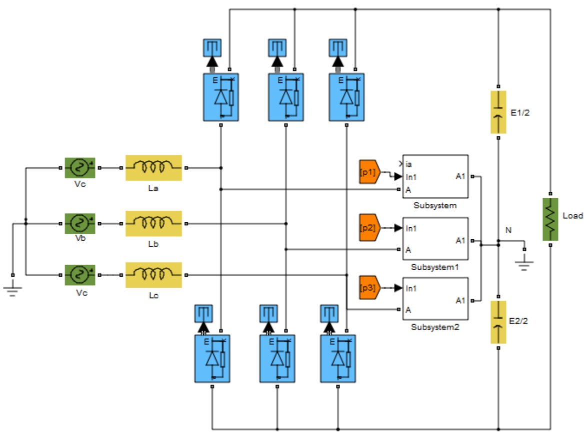

Figure 1: Three-Phase Three-Switch Three-Level (Vienna) Rectifier

This hysteresis current control (HCC) technique is more popular for controlling the three-level PWM rectifier system and easy to implement. In this current control technique have the inner current loop and outer voltage loop and it provides the PWM for switching the power transistor. The outer voltage feedback loop ensure the DC voltage regulation by adjusting the magnitude of the reference current for the inner loop, the inner current feedback loop conform the dq current tracking and cross decoupling cancellation based on the dq inputs. The switching command signals are generated by comparing the reference signal and the measured line current. These techniques have more advantage but it's discouraged because of load dependent variable switching frequency, hence the design of the EMI filter more complex.

The One Cycle Control (OCC) method is firmness for power disturbance, it is strong to reject source and load disturbance. The OCC is very simple, desirable than conventional feedback control method. This method is non linear control technique for the switching circuit, which is operating at constant switching frequency modulation; the magnetic size will be small. It consists of one or two integrator with reset, flip-flops, comparators, logic, linear devices. It doesn't require any multipliers and the voltage sensor. It can operates by sensing either the inductor current or switching current. The important idea of one-cycle control is forcing the switched variable exactly equal to reference signal. Assuming that the Vienna rectifier is operated in continuous-conduction- mode (CCM), a general equation that relates the input phase voltage and duty ratio of switches is derived from an average model of the Vienna rectifier.

The mixed conduction mode (MCM) is operating the converter in the continuous conduction input current and discontinuous conduction input current based on conductance of converter. The conductance is changes due to the load variations. It consists of two loops; one is voltage loop and current loop. The control signal is sent to switch through PWM circuit to control the input inductor current track the input voltage. The control signal is generated by adding the input current error signal and the minimum duty cycle value of CCM and DCM mode. The CCM and DCM mode is sensed based on the input voltage, output voltage, load current and voltage error signal. The conventional control techniques have more advantages in the boost converter wherein operates in continuous conduction mode (CCM) for high load, wherein it falls in the discontinuous conduction mode (DCM) for light load, which leads more complex control system to operate constant switching frequency, poor power factor and high total harmonic distortion. The operating mode selected by simple control algorithm and the output voltage is regulated by the PI controller. The boost inductor is optimized which can operated in the both operating modes, the input current sensor is not required for the output voltage regulation.

Hysteresis Current Control

A. Principal of Operation

The HCC technique has implemented for three- phase three-switch three-level converter, command signal generated each phase independently [2,3]. This method is directly generates the gate signal for the corresponding phase. The block diagram of HCC is shown in Fig. 2. This system is cascaded the inner and outer loop. In outer voltage feedback loop consist of DC voltage regulation, the DC bus voltage inherently split in V_{d1} and V_{d2} due to the three- level nature of the rectifier system. In order to regulate the DC voltage balancing, an extra PI controller loop is included to force $V_{d1} \approx V_{d2}$. The inner current feedback loop controlling the input phase current independently by generating the PWM signal to each phase, which is comparing the reference current with actual measured current and limiting the instantaneous error within a hysteresis band, which determines the switching frequency of the power transistors. The working principal of this converter system is, when the phase current is positive and switch state is on then the input current is flows through the switch and phase voltage is 0, the input inductor current is starts charging and input line current increases. When the input line current reaches the upper limit of the hysteresis band the power transistor command signal set to zero and the transistor is turns off. Under this condition diode D_{ap} turns on and C_1 charges and phase voltage is +E/2. As a result, the input line current decrease. When the line current reached the lower value of the hysteresis band the command signal is set to turn on the power transistor. When the phase current is negative, a similar process will happen with inverter logic operation. When the line current is cross the upper limit, the transistor will turn off and when it cross the lower limit it turns on the transistor. The hysteresis current band and switching pattern of one phase is shown Fig.3.

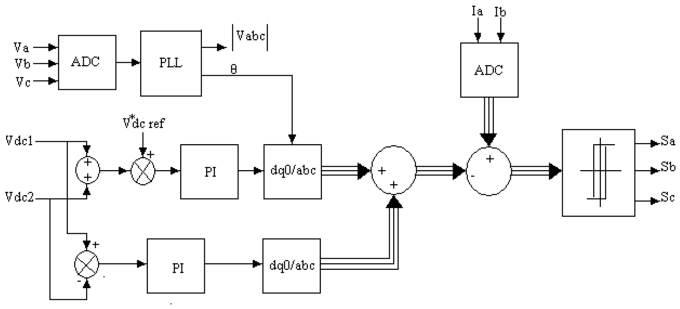

Figure 2: Block Diagram of The HCC Method For The Vienna Rectifier

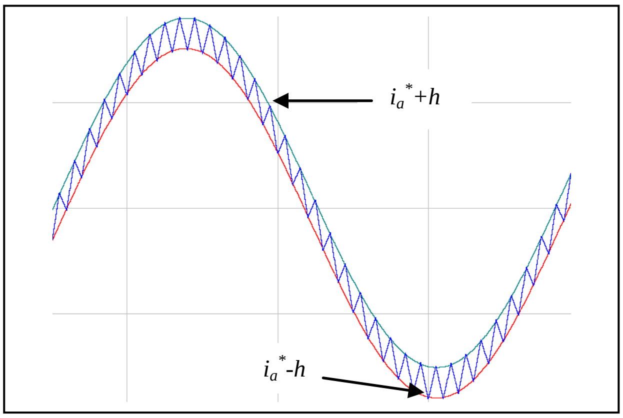

Figure 3: Hysteresis Current Band and Switching Wave Form

So for, using the analog devices achieving the HCC has the following disadvantages,

- Propagation delays were due to various stages because of the individual propagation delay of the devices.
- When the hysteresis band value has changed, it will vary the switching frequency. There will be some devices not performing well and additional heat will produce in the devices.
- In this application, short pulse generation has to be arrested by designing the additional circuitry which again increase the propagation will delay, cost and volume.

Average Current Control

A. Principal of Operation

The block diagram of the average current control for the Vienna rectifier has shown in Fig. 4. In the average current control have two control loops to generate the required switching pattern of the rectifier. The proportional-integral (PI) controller has introduced to increase the gain of the inner current loop in light loads operation [4]. The instantaneous reference current signal is compared with actual inductor current and current error is fed to the PI controller. The carrier signal frequency, amplitude and PI controller parameter has chosen according to the standard design presented in [5] [6]. The rectifier switching pulses are generated by comparing the carrier ramp signal and output of the PI controller. The common carrier ramp signal used for the three phases. The integral part improves the error between the reference and actual current [7]. The result in the average current control has merits and demerits as follows,

- High degree of accuracy for tracking the average current and noise immunity is excellent
- Slope compensation is not required, but there is a limit to loop gain at the switching frequency in order to achieve stability.
- The slop of the output of PI regulator should be less than the carrier signal slope to generate the switching pulses.

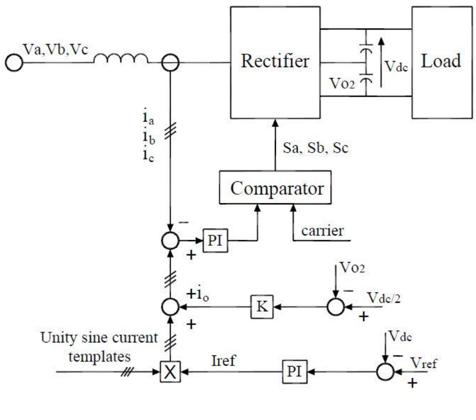

Figure 4: Control Block Diagram of The Average Current Control

B. Simulation Results

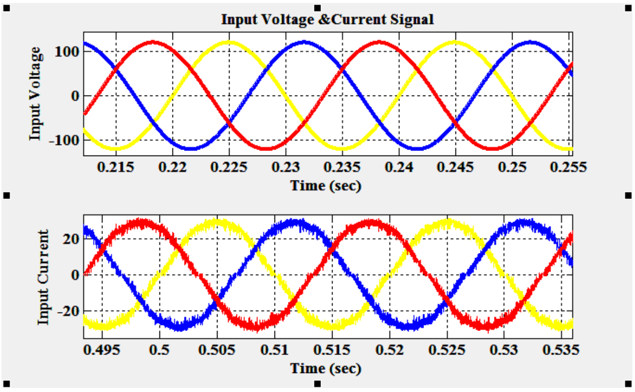

Figure 5: Three Phase Input Voltage and Current Signal of Vienna Rectifier

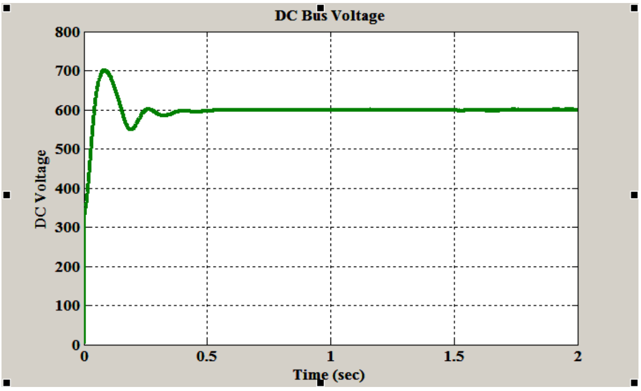

Figure 6: Stability of DC bus voltage under balanced mains supply

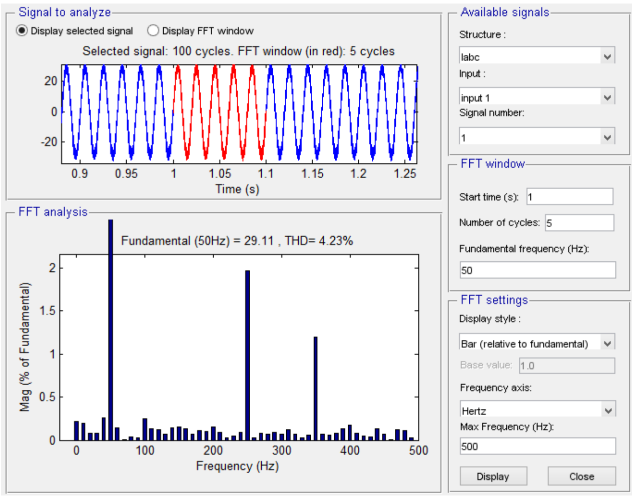

Figure 7: Input current THD bar chart balanced mains supply

The Matlab simulation results of hysteresis current control method for the Vienna rectifier are shown. The simulation is analysed 5kw model under various conditions. The simulation performances of average and hysteresis control methods are approximately same. The following parameters are considered to validate the control strategies, the input AC voltage is 120V/50Hz, input Inductor is 3x500uH, DC Link Capacitors are 2x4700µF, DC link reference voltage is 600V and rated output power is 5kW. The MATLAB simulation results of input voltage and current waveform under balanced supply conditions are shown in Fig. 5 and variable switching gate signal shown in Fig.8.

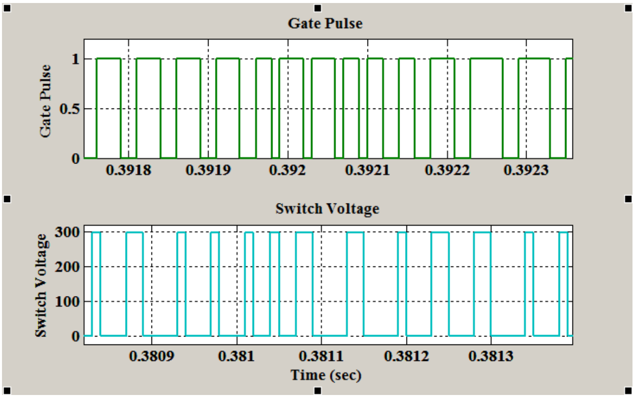

Figure 8: Variable switching frequency gate signal and switch voltage

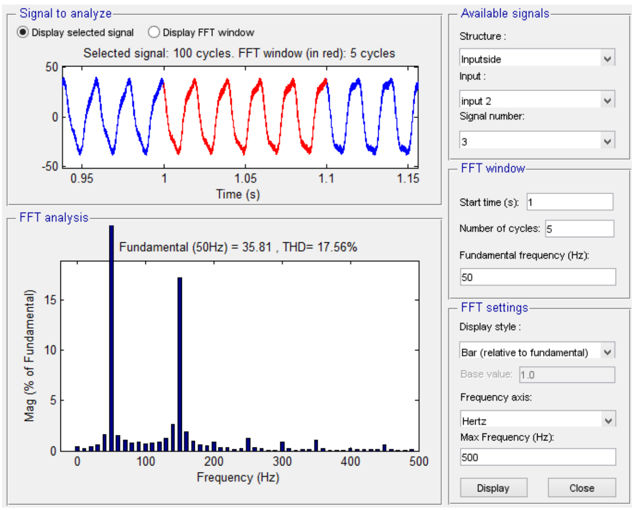

Figure 9: THD of Phase C In Unbalanced Input Supply

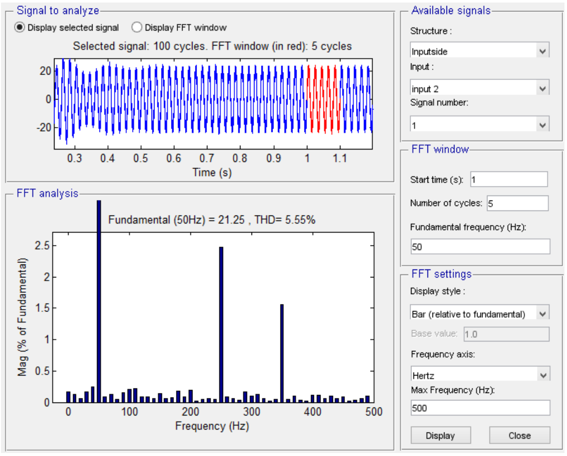

Figure 10: THD of Phase A In Different Load

In the unbalanced supply mains condition and different load condition, the THD levels are exceeds the limits. The input supply voltage phase A, C is 125V/50Hz and phase B is 60V/50Hz. The three phase A, B and C THD level are 15.12%, 26.15% and 17.56% respectively. The unbalanced input supply voltage THD level for phase C is as shown in Fig. 9.

One Cycle Control

A. Principal of Operation

OCC method is operating based on the modulation of the output waveform instead of PWM. The merits of this control system are removing the unwanted harmonics and traces the transient waveforms well [7]. The main important components of OCC control circuits are an integrator with reset and comparator are shown in Fig.12. There are three comparator compares the signal with each phase signal respectively. Considered the OCC operated in the CCM mode, the output control equation is derived from the average model of the Vienna rectifier. The average model of the rectifier is as shown in Fig. 11[8].

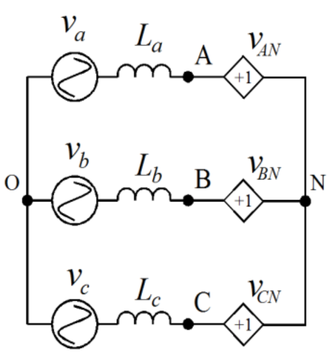

Figure 11: Switching Cycle Average Model of The Rectifier

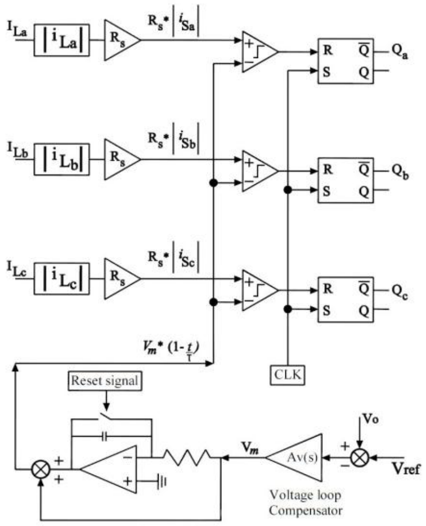

Figure 12: Block Diagram of The One Cycle Control Method

The vector voltage at node A, B, C with respect to the neutral point O is equal to the phase vector voltage minus the inductor voltage L_a, L_b, L_c, where L is the inductance of the input inductors. The average node voltage in each switching cycle V_{AN}, V_{BN}, V_{CN} are given [7].

The absolute value of current i_a, i_b, i_c are determined by using three full-wave rectifier circuits through sensing of either inductor currents or switching currents and voltage sensors are not required. The control equation with peak inductor current in equation (1)

$$\begin{cases} V_m * (1 - d_a) = R_S * \left| iL_{apk} \right| \\ V_m * (1 - d_b) = R_S * \left| iL_{bpk} \right| \\ V_m * (1 - d_c) = R_S * \left| iL_{cpk} \right| \end{cases} \tag{1}$$

The clock pulse generator is set the switching frequency of the converter and the integration time constant is also equal to the switching frequency. The clock plus set the SR flip-flop at starting of each switching cycle. The three phase inductor current i_{La}, i_{Lb}, i_{Lc} pass through the full wave rectifier circuit to convert absolute value of the Rs* i_{La}, Rs*i_{Lb}, Rs* i_{Lc} and fed to the input of the three comparator. The voltage loop compensator generates the V_m signal by comparing the output dc voltage and reference voltage. The V_m signal is integrated and subtracted from the V_m which is fed to another input of the comparator. The SR flip-flop resets by the output of the comparator for the respective phases and it turns off the semiconductor switches. Hence based on the clock pulse and comparator output decides the duty cycle of the corresponding switches for the each switching cycle.

B. Simulation Results

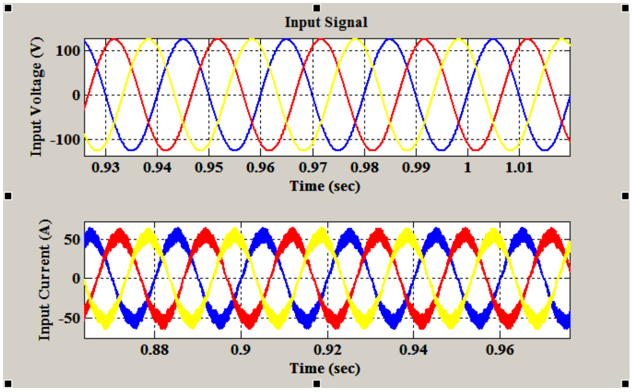

Figure 13: Three Phase Input Voltage and Current Waveform With OCC

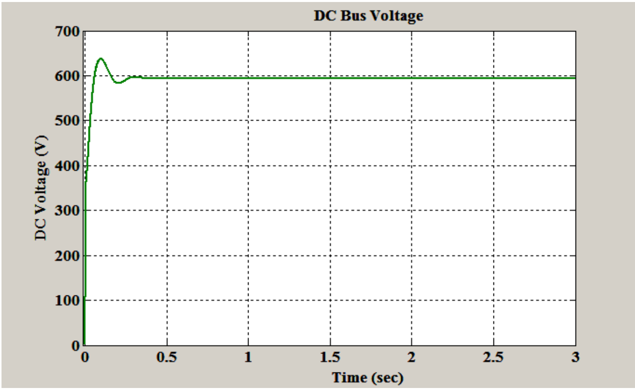

Figure 14: DC Bus Voltage of Vienna Rectifier With OCC

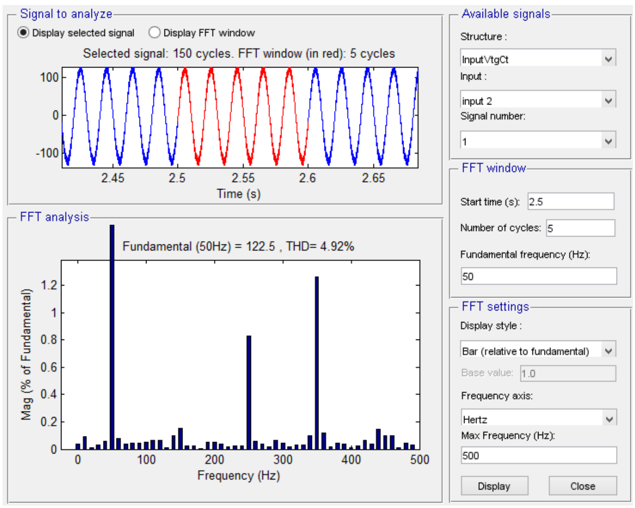

Figure 15: Input Current THD Bar Chart Balanced Mains Supply

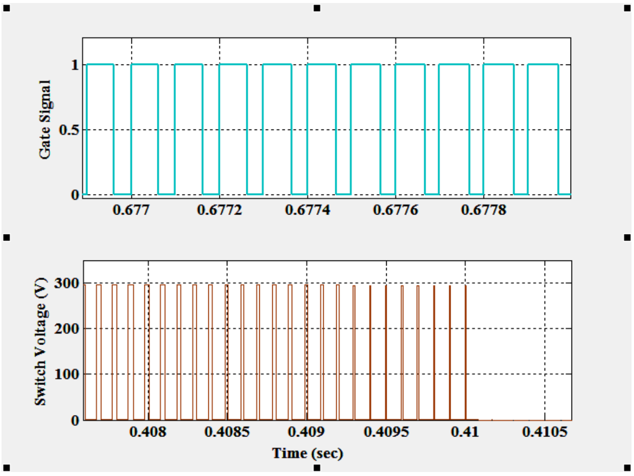

Figure 16: Constant Switching Frequency Gate Pulse And Switch Voltage

The Matlab simulation of one cycle current control method has been implemented [5]. The simulation has implemented in the following condition, the input voltage is 125V, the output voltage is 600V, the switching frequency is 10 kHz, the power is 5kW and under the balanced mains supply condition the measured THD is 4.92% as shown in Fig.15. In the OCC method gate pulse is switching at constant frequency as shown Fig. 16.

The simulation is carried over under unbalanced input supply condition phase A, C is 125V and phase B is 60V, THD level of Phase A, B and C is 13.36%, 15.06 and 13.66 respectively.

Mixed Conduction Control

A. Principal of Operation

The block diagram of proposed mixed conduction mode with duty ratio feedforward control system has been shown in Fig. 17. The conventional MCM operates in combination of CCM and DCM with two different constant switching frequencies to eliminate the dual mode operation (dual mode: where it is partially continuous and partially discontinuous in a half cycle of the utility supply) which is implemented for the single phase simple boost converter [9]. This mode selection is based on the load current, the CCM mode is selected at more than 50% of the load and the DCM mode is selected at less than 50% of load. The proposed MCM duty ratio feedforward method has approached based on the theoretical analysis with logical functional operation. In this method the switch is controlled by adjusting the duty ratio for controlling the inductor current to follow the input voltage. The conductance of the converter is calculated from the output voltage and output current. The conductance is multiplied with the input voltage and derived the current reference signal. The duty rang of CCM and DCM is estimated form the feedback and measured signal. The CCM duty is calculated by input voltage and output voltage, the DCM is calculated using the conductance, input voltage, and output voltage and feedback voltage error. The minimum duty value of CCM and DCM is added with the input current error signal to generate the gate signal. This control method is yield based on the theoretical analysis and it can be improve the performance of the input current and reduce the THD [10,11].

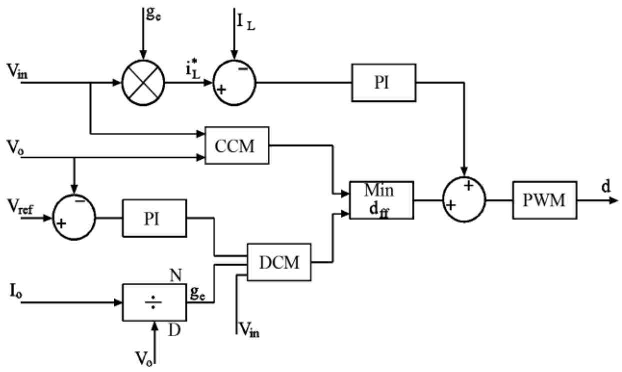

Figure 17: Block Diagram of The Mixed Conduction Mode

Conclusion

In this paper presented the simulation analysis of hysteresis, average and once cycle control method's performance on the three phase three switch three level rectifier. In detail analysis of all control methods, the input current THD level is within the limit as per IEC standard requirement and stable in the DC bus voltage under balanced input mains supply and particular load condition and the switch blocking voltage stress is half of the DC bus voltage. It is concluded that the all the methods are operating well at continuous input inductor current and particular operating mode either CCM or DCM based on the load condition. The hysteresis and average current control methods are operate in the variable switching frequency due the load dependency; hence the magnetic design becomes more complex. The one cycle control has working in constant switching frequency, when in the light load condition the input current harmonics become more due to the DCM mode operation. Therefore, to solve these issues proposed the duty ratio feedforward mixed conduction control method for the Vienna rectifier. This control method deduced based on the theoretical analysis, it will operate in the both CCM and DCM mode because it has two control loops for operating in CCM and DCM. The proposed method can be reduce the total harmonics distortion of the input current and improve the power factor. The further research will continuous on simulating and experimental verification. This research facilitates in making use of the merits of both the Vienna rectifier and the mixed conduction control method.

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