Comparison of Three Phase SPWM and VF-DPC Techniques Based on Power Factor and THD

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Abstract: This paper presents the comparison of sinusoidal pulse width modulation (SPWM) technique and virtual flux based direct power control (VF-DPC) PWM technique for three-phase AC to DC converters for input power factor and input current total harmonic distortion (THD) using MATLAB/SIMULINK software. PWM converters are frequently used due to their improved performance such as unity power factor operation with reduced THD at ac mains and also provide constant-regulated dc output voltage even under fluctuations of ac voltage and dc load. In this paper simulation models for both PWM techniques are simulated with closed loop at rated load condition. The performance of SPWM and VF-DPC technique are analyzed for optimum harmonics operation in input current with power factor value.

Keywords: MATLAB, sinusoidal PWM, THD, unity power factor, VF-DPC.

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. The harmonic content of the input current is dependent on the size and type of the line filter, switching frequency, selected control and modulation schemes and the waveform of the line voltage. Harmonics have a negative effect on the operation of the electrical system and the power factor as well therefore; an increasing attention is paid to their generation and control. . Unity power factor with lower harmonic current or low input current total harmonic distortion (THD) and fixed DC output voltage with minimum ripple are the important parameters in rectifier. A pulse width modulation (PWM) approach serves all these purposes. The PWM is a very advance and useful technique in which width of the gate pulses are controlled by various mechanisms. PWM shift the frequency of the dominant harmonics to a higher value, so that they can easily filter harmonics by employing a small passive filter [1]-[8]. Most commonly used PWM technique is SPWM in which a triangular carrier wave is compared with sinusoidal wave to generate PWM switching pulses [9]. Recently, new control approaches such as virtual flux based direct power control (VF-DPC) PWM technique have been the topic of research due to its high-performance. Structure of VF-DPC contains the DC voltage outer loop and power control inner loop. It selects switching states from the switching table according to the AC-side instantaneous power, to achieve unity power factor, low total harmonic distortion (THD) and fast response [14], [15].

Sinusoidal Pulse Width Modulation (SPWM)

In sine-triangle PWM, three phase sinusoidal reference modulating signals are compared against a common triangular carrier to generate PWM switching gate triggering pulses for the three phases. The rectifier switching frequency is governed by the frequency of the triangular waveform and this carrier frequency is very high compared to the frequency of modulating signal. The frequency of reference signal controls the modulation index m, rms voltage V_{rms} and output voltage V_o. The number of pulses per half cycle depends on carrier frequency. The triangle waveform frequency or switching frequency controls the speed at which the switches are turned off and on. The magnitude and frequencies of the fundamental component in the line side are controlled by changing the magnitude and frequency of the modulating signal. It is simple and linear between 0% and 78.5% of six step voltage values, which results in poor voltage utilization [10]-[13].

Fig. 1 shows block diagram of sinusoidal PWM rectifiers. Generally, the control structure of a three-phase six-switch PWM boost converter consists of double close loop with an inner current control loop and an outer voltage control loop. The line inductors provide energy storage and allow the rectifier to operate in a boost configuration. The switching pulses are generated by current mode control scheme which is shown in Fig. 2.
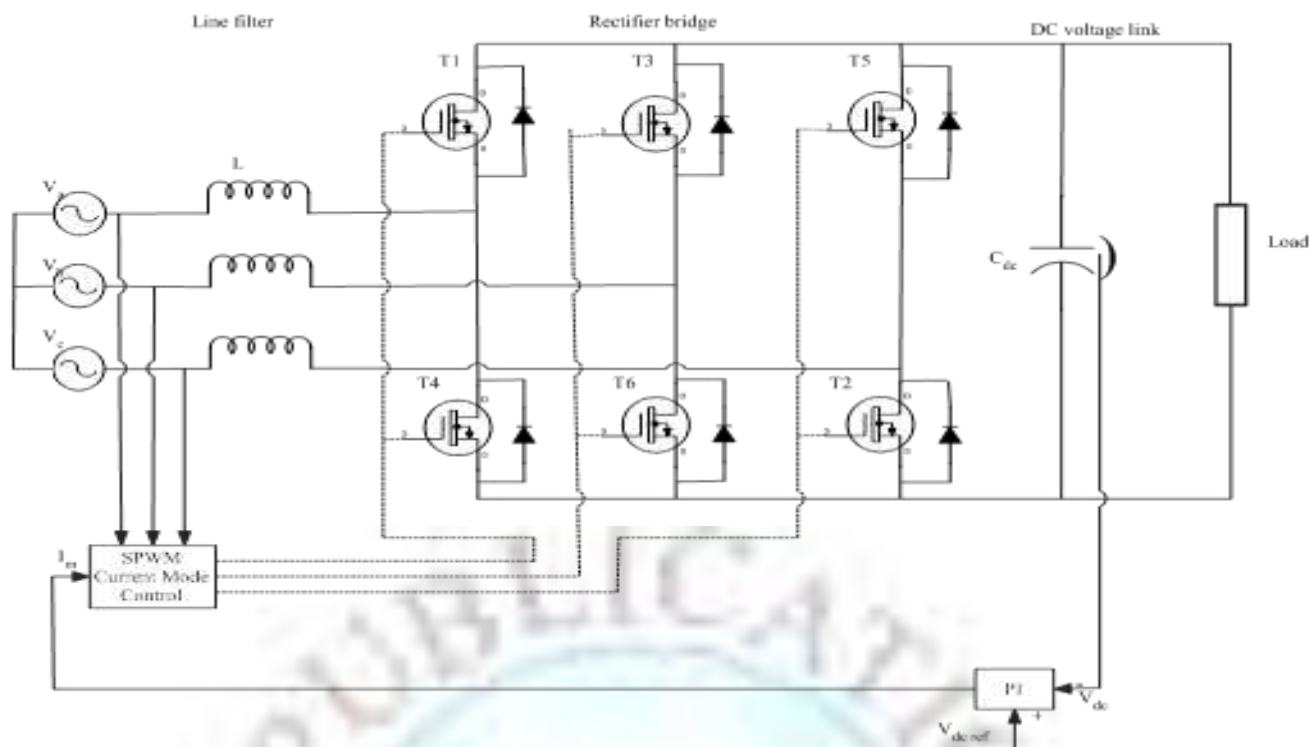
Figure 1: Block diagram of three-phase sinusoidal PWM boost rectifier
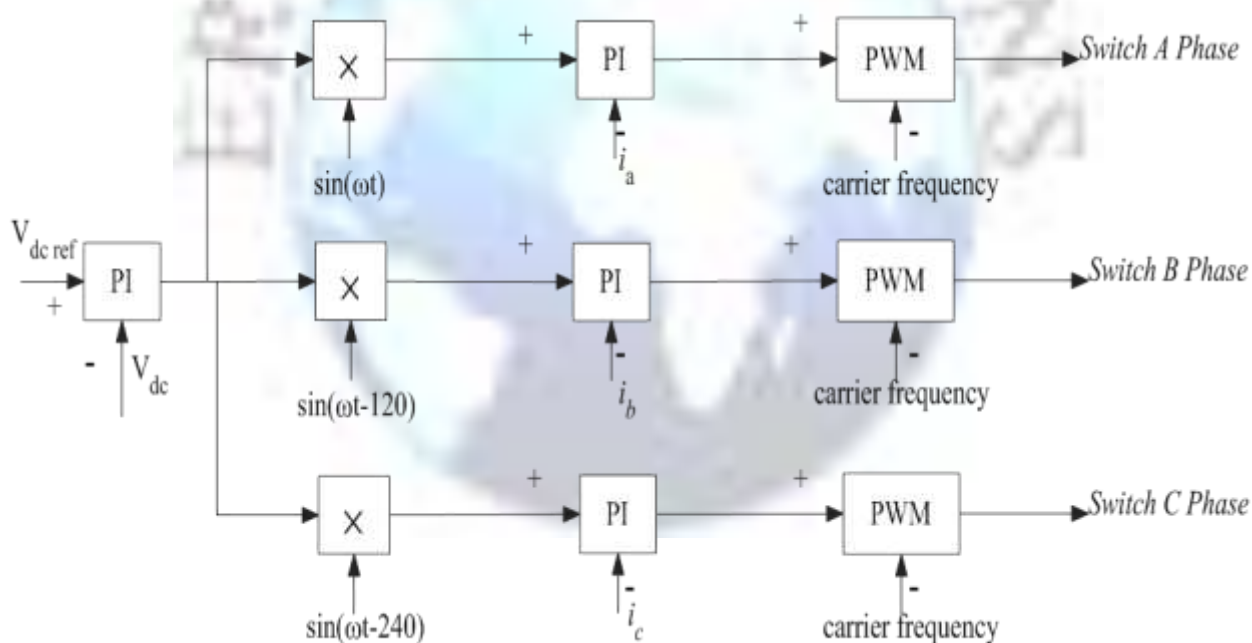

Figure 2: Control circuit of current mode control scheme for SPWM rectifier

A current-mode control scheme is required for the line currents. The DC bus voltage is controlled by comparing of measured DC voltage to the reference DC voltage. This error signal is passed through a PI controller which then forms the current amplitude reference required for all three inner current control loops. The current controller senses the input current and compares it with sinusoidal reference currents. The current amplitude reference is multiplied by three sinusoidal templates each with a 120° phase apart to form the true current references. For unity power factor operation it is required that each sinusoidal reference is in phase with the respective supply phase voltage. The inductor current is measured and compared to a reference signal. The error is passed through a proportional and integral (PI) controller providing high gain at low frequencies, but having a filtering effect on the high-frequency ripple current. The constants

of the PI controllers are set by hit and trial method to produce a stable system with good response. Now, this signal is compared to a triangular carrier wave to generate the required PWM signal to control the switches. This technique has excellent features, like real-time control and easily obtained drive signals. Merits are simple to implement, easy to control etc. Demerits are dc link voltage ripple introduces additional output ripple, high THD, low input power factor at low and medium power applications.

Virtual Flux-DPC PWM Technique

VF-DPC is a new technique which is based on estimated virtual flux vector instead of the line voltage vector in the control. VF-DPC control technique is similar to direct power control technique in respect to the control, switching table, sector selection and control by hysteresis band but instantaneous power is calculated from virtual flux. It provides sinusoidal line current and lower harmonic distortion. VF-DPC does not perform sinusoidal current when the line voltage is distorted. However in this scheme the switching frequency does not remain constant which increases the switching losses of the converter. Consequently, voltage line power estimation is less noisy; thanks to the natural low-pass behavior of the integrator used in the calculation algorithm used for VF-DPC and differentiation of the line current is avoided in this technique. Therefore, the use of the virtual flux (VF) signal for power estimation leads to the following advantages: [16]-[19]

> ➢ Compared to the DPC, there is lower sampling frequency, a simpler voltage and power estimation algorithm, easy implementation of the unbalanced and distorted line voltage compensation to obtain sinusoidal line currents [low total harmonic distortion (THD)] with unity power factor operation.
> ➢ No need of current control loops, coordinate transformation and separate PWM voltage modulator. There is no need for decoupling between control of the active and reactive components and also provides better dynamics.

A. Power Estimation Based On Virtual Flux [16]-[21]

1) Virtual flux estimator [14]

The voltages imposed by the line power in combination with the ac-side inductors are assumed to be quantities related to a virtual ac motor. Thus, R and L represent the stator resistance and the stator leakage inductance of the virtual motor [Fig. 3(a)] and line-to-line voltages are U_{ab}, U_{bc}, U_{ca} which is induced by a virtual air-gap flux or the integration of the voltages leads to a virtual flux (VF) vector $\overline{\psi_L}$, stationary α-β coordinates [Fig. 3 (b)].
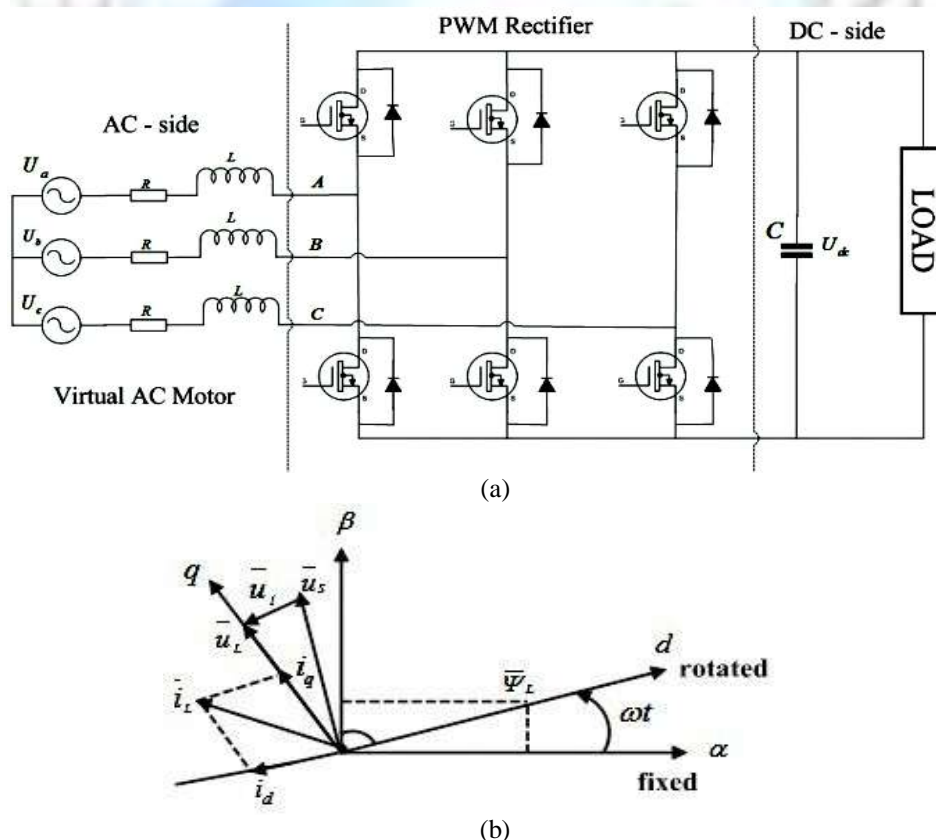

(a)

(b)

Figure 3: **(a) Three-phase PWM rectifier system with AC side presented as virtual AC motor**
(b) Reference coordinates and vectors [5]

$\overline{\psi_L}$ -Virtual flux vector of line; $\overline{u_L}$ -line voltage vector; $\overline{u_S}$ -converter voltage vector; $\overline{u_I}$ -inductor voltage vector; $\overline{i_L}$ - line current vector.

From the relation of voltage and flux vector, we can write

$$\psi_L = \int u_L dt \qquad (1)$$

Where

$$\overline{u_L} = \begin{bmatrix} u_{L\alpha} \\ u_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{ab} \\ u_{bc} \end{bmatrix} \qquad (2)$$

$$\overline{\psi_L} = \begin{bmatrix} \psi_{L\alpha} \\ \psi_{L\beta} \end{bmatrix} = \begin{bmatrix} \int u_{L\alpha} dt \\ \int u_{L\beta} dt \end{bmatrix} \qquad (3)$$

Based on the measured dc-link voltage U_{dc} and the converter switch states S_a, S_b and S_c, the rectifier voltages are estimated in as follows [5]:

$$u_{S\alpha} = \sqrt{\frac{2}{3}} U_{dc} \left(S_a - \frac{1}{2}(S_b + S_c) \right) \qquad (4)$$

$$u_{S\beta} = \frac{1}{\sqrt{2}} U_{dc} (S_b - S_c) \qquad (5)$$

Then, the virtual flux $\overline{\psi_L}$ components are calculated from equations 3, 4 & 5 in stationary (α-β) coordinates system as

$$\psi_{L\alpha(est)} = \int \left(u_{s\alpha} + L \frac{di_{L\alpha}}{dt} \right) dt \qquad (6)$$

$$\psi_{L\beta(est)} = \int \left(u_{s\beta} + L \frac{di_\beta}{dt} \right) dt \qquad (7)$$

2) Active and reactive power estimator

Using complex notation, the instantaneous power can be calculated as follows:

$$p = \text{Re}(\overline{u_L} . \overline{i_L}^*) \qquad (8)$$

$$q = \text{Im}(\overline{u_L} . \overline{i_L}^*) \qquad (9)$$

Where * denotes conjugate of the line current vector.

Line current vector

$$i_L = \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{3}{2} & 0 \\ \frac{\sqrt{3}}{2} & \sqrt{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix} \qquad (10)$$

For sinusoidal and balanced line voltage the derivatives of the flux amplitudes should be zero. So the instantaneous active and reactive powers can be computed as [9]

$$p = \omega.(\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha}) \qquad (11)$$

$$q = \omega.(\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta}) \qquad (12)$$

B. Block Diagram of VF-DPC PWM Rectifier

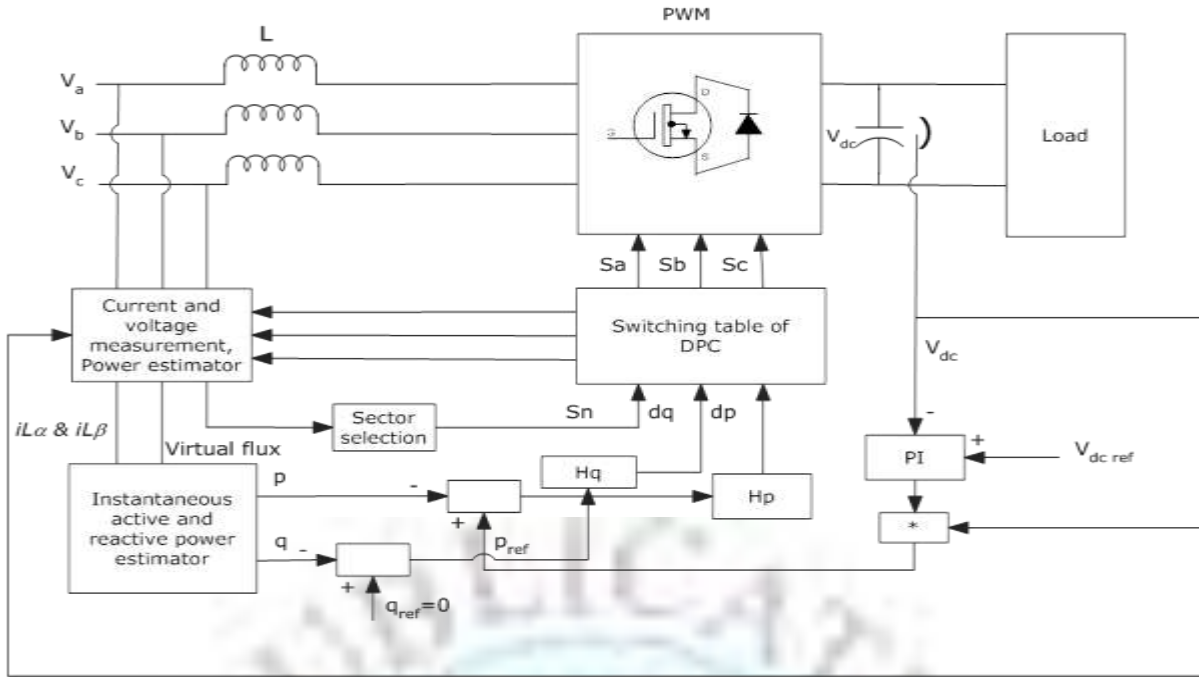The block diagram of the VF-DPC PWM rectifier is shown in Fig. 4.

Figure 4: Block diagram of VF-DPC technique

This block diagram has three main blocks power estimator, sector estimator and switching table. The output voltage is compared with reference voltage in the PI controller (I_m). The power estimator block has two inputs (input supply & I_m) and it estimates iLα & iLβ. The 12 sector are calculated from estimated $V_α$ and $V_β$. These reference currents are wished to be the actual in the next switching period. VF-DPC block calculates instance real power, reactive power and iLα & iLβ. The real power trigger are compared between instantaneous real power is calculated from dc side. As similarly, reactive power trigger are compared between instance reactive power and null because of set to obtain unity power factor. Finally firing pulses are selected through sector number, real power trigger and reactive power trigger. The real power and reactive power are estimated from equations 11 & 12. The real power trigger is get from comparison between the real power and calculated dc link power. As similarly, the reactive power trigger is estimated from comparison between the instance relative power and null value.

The measured line currents i_a, i_b, i_c and the estimated virtual flux components $\Psi_{Lα}$, $\Psi_{Lβ}$ are delivered to the instantaneous power estimator block (PE). The commands of reactive power qref (set to zero for unity power factor) and active power pref (delivered from the outer PI dc voltage controller) are compared with the estimated q and p values, in q and p hysteresis controllers, respectively. Errors between the commands and the estimated feedback power are input to the hysteresis comparators and digitized to the signals d_p and d_q. The digitized output signal of the reactive power controller is defined as:

$$d_q = 1 \text{ for } q < q_{ref} - H_q \qquad (13)$$
$$d_q = 0 \text{ for } q > q_{ref} + H_q, \qquad (14)$$

Similarly for the active power controller

$$d_p = 1 \text{ for } p < pref - Hp \qquad (15)$$
$$d_p = 0 \text{ for } p > pref + Hp \qquad (16)$$

Where Hq & Hp are the hysteresis bands.

The digitized variables d_p, d_q and the voltage vector position θ_{uL} = arc tan ($u_{Lα}/u_{Lβ}$) or flux vector position $\theta_{\Psi L}$ = arc tan ($\psi_{Lα}/\psi_{Lβ}$) can form a digital word. For this purpose, the stationary coordinates are divided into 12 sectors, as shown in Fig. 5, and the sectors can be numerically expressed as [16]-[19]:

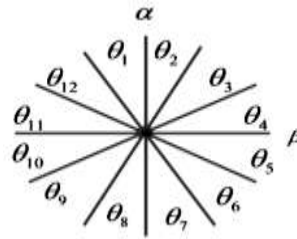$$(n-2)\,\pi/6 \le \theta_n < (n-1)\,\pi/6 \qquad (17)$$

Where n = 1, 2...12

Figure 5: Sector selection for VF-DPC technique [20]

The digitized error signals d_p and d_q and digitized voltage phase θ_n are input to the switching table in which every switching state, S_A, S_B and S_C, of the converter is stored, as shown in Table 1 [21].

Table 1: Switching Table for VF-DPC

Sp	Sq	θ1	θ2	θ3	θ4	θ5	θ6	θ7	θ8	θ9	θ10	θ11	θ12
1	0	101	111	100	000	110	111	010	000	011	111	001	000
1	1	111	111	000	000	111	111	000	000	111	111	000	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
0	1	100	110	110	010	010	011	011	001	001	101	101	100

According to the combination of the digitized input signals, using this switching table, the optimum switching state of the converter can be selected uniquely in every specific moment. The selection of the optimum switching state is performed so that the power errors can be restricted within the hysteresis bands. VF-DPC technique deals with the instantaneous variables. The estimated values contain not only fundamental but also harmonic components and this improves the total power factor and efficiency of rectifiers. The instantaneous active and reactive power depends on position of converter voltage vector. It has indirect influence on inductance voltage as well as phase and amplitude of line current. Therefore, different pattern of switching table can be applied. It influences control condition as instantaneous power and current ripple, switching frequency and performance of converter. For drives, there exist more switching table techniques because of wide range of output frequency and dynamic demands. Problems related to this technique are variable switching frequency and requirement of fast microprocessor and A/D converters.

Simulation and Results

The simulation has been done using MATLAB/SIMULINK software which it is easy to implement.
Various Parameters Used for Simulation Study:
AC input voltage (peak) = 230V
Supply frequency = 50Hz
Rated output power =7.5 kW (Load resistance = 40Ω, Load inductance = 2mH)
DC reference voltage = 550V

C. Sinusoidal PWM
The output DC link voltage is measured from voltage and current meter block. The DC link and source side voltage and current waveforms of the SPWM for a switching frequency of 10 KHz are shown in Fig. 6 and Fig. 7 respectively. The input current THD is taken from POWERGUI block of SIMULINK. The FFT analysis of the source current is depicted in Fig. 8. The total harmonic distortion of the source current comes out to be 3.68% so satisfied IEEE standard. The input power factor is calculated from functional block active and reactive power from the SIMULINK model.
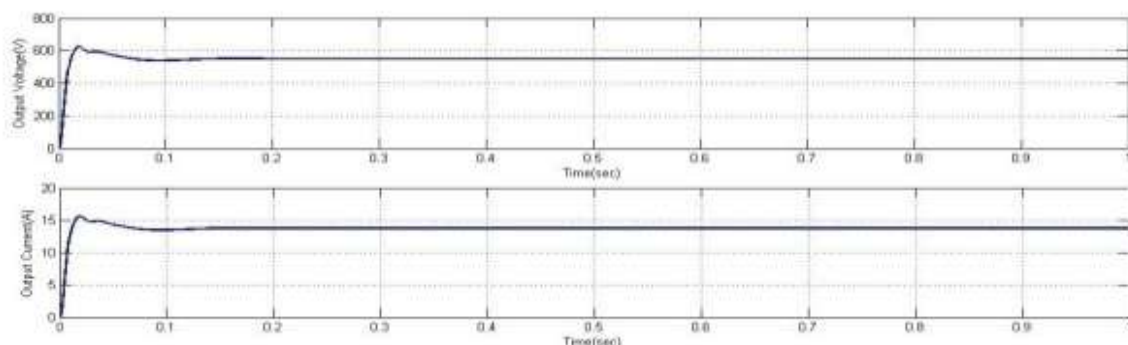

Figure 6: Output voltage (V) & output current (A) waveform of SPWM at rated load with switching frequency fs=10 kHz
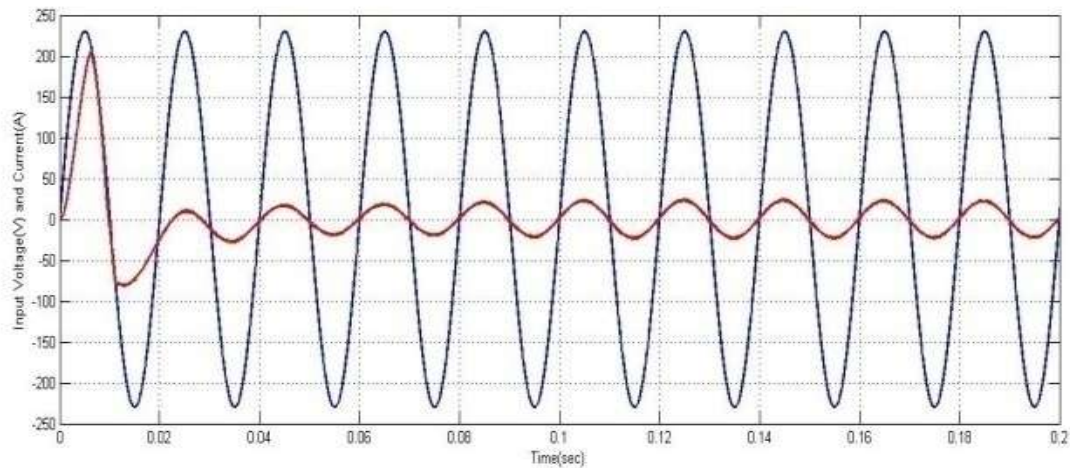
Figure 7: Input voltage (V) & input current (A) waveform of SPWM at rated load with switching frequency fs=10 kHz
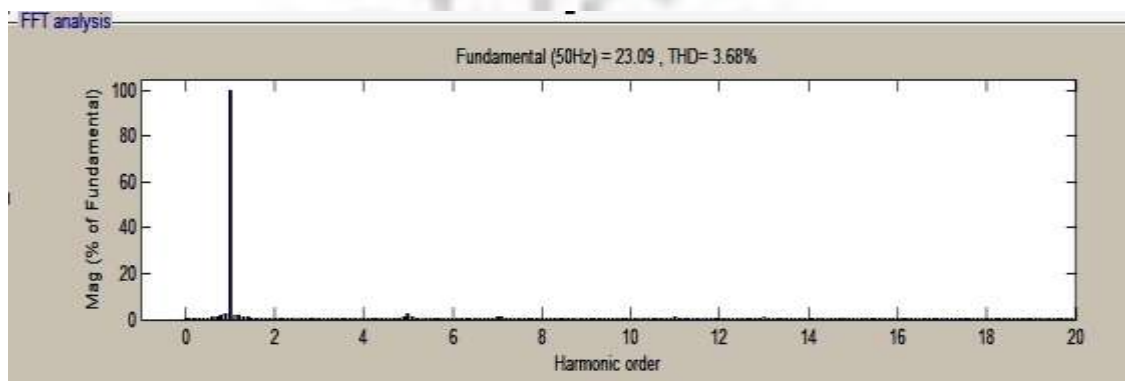

Figure 8: FFT analysis of input current (A) of SPWM at rated load with switching frequency f_s=10 kHz

D. Virtual flux based DPC

Fig. 9 shows block diagram of instantaneous active and reactive power estimator in MATLAB.
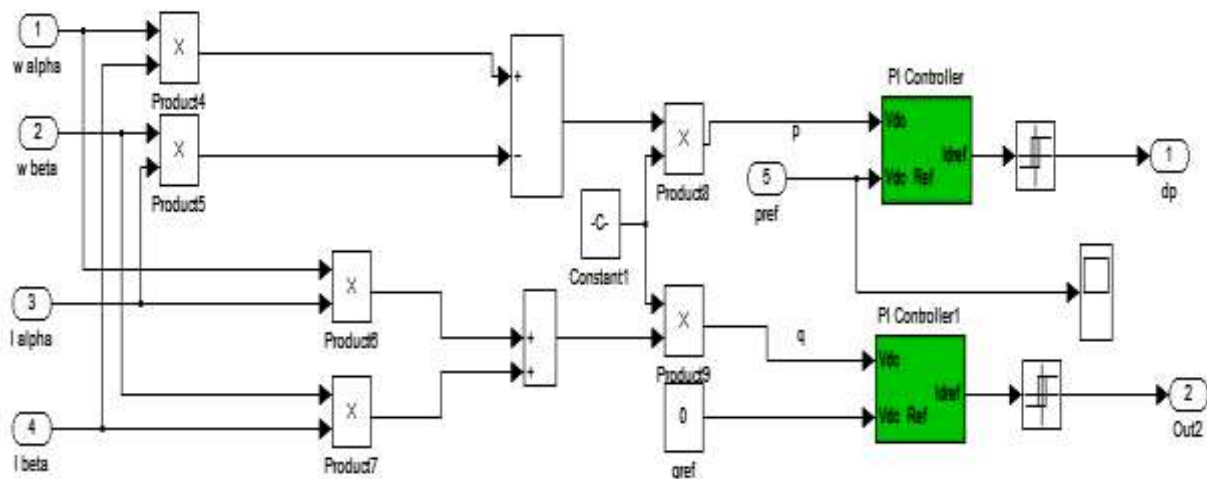

Figure 9: Simulink block diagram of instantaneous active and reactive power estimator for VF-DPC

The output DC link voltage is measured from voltage and current meter block. The DC link and source side voltage and current waveforms of the SPWM for a switching frequency of 10 KHz are shown in Fig. 10 and Fig. 11 respectively. The input current THD is taken from POWERGUI block of SIMULINK. The FFT analysis of the source current is depicted in Fig. 12. The total harmonic distortion of the source current comes out to be 0.57% so satisfied IEEE standard. The input power factor is calculated from functional block active and reactive power from the SIMULINK model.
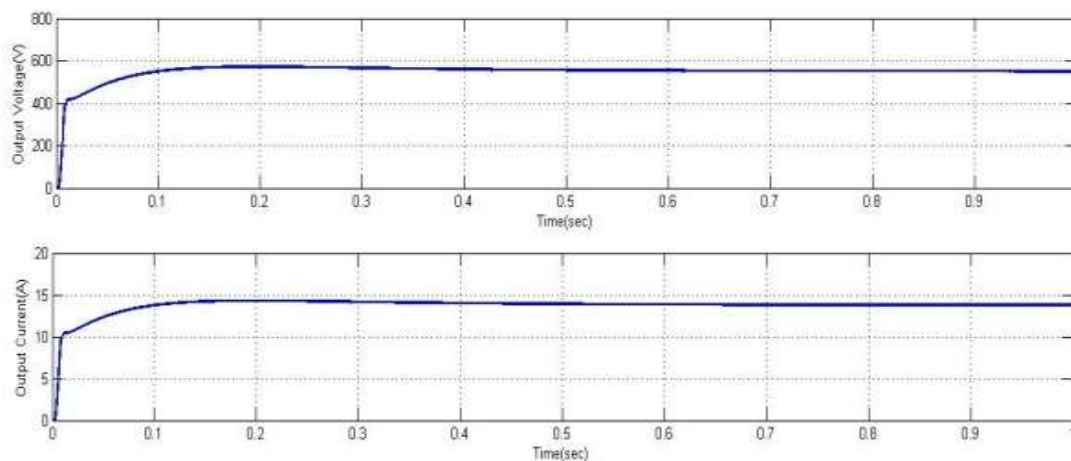
Figure 10: Output voltage (V) & output current (A) waveform of VF-DPC at rated load condition
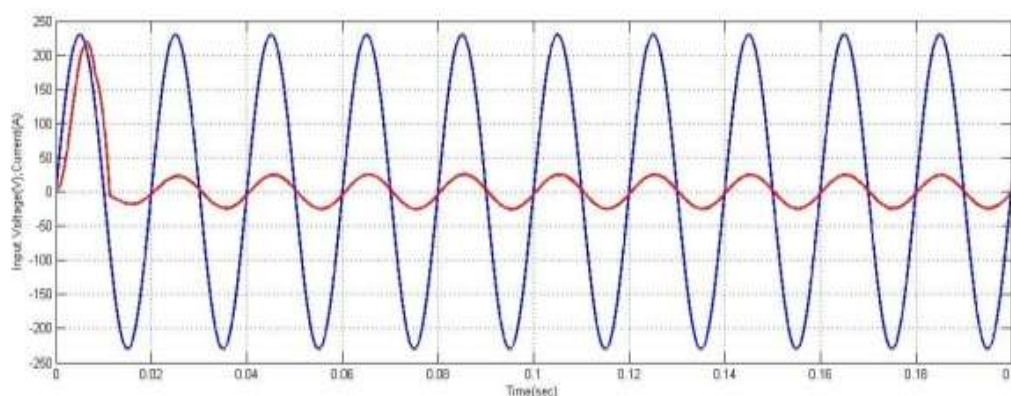

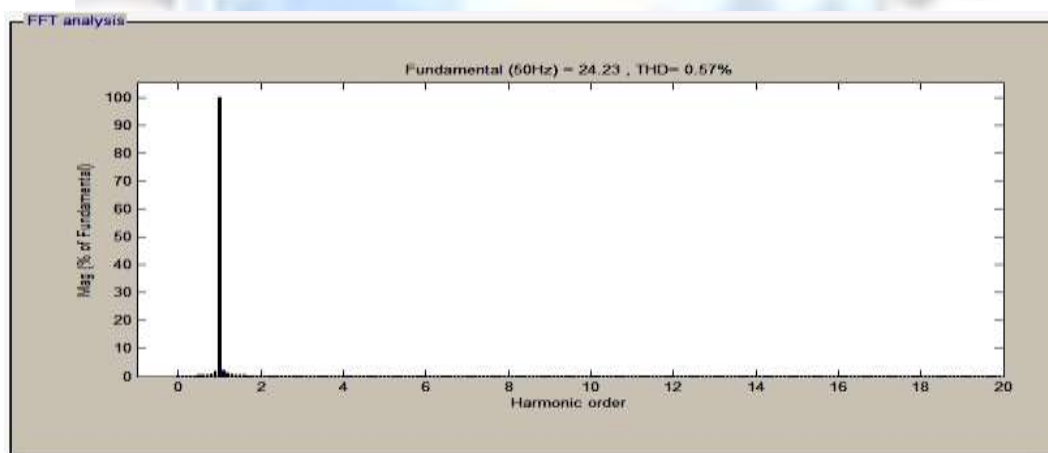**Figure 11: Input voltage (V) & input current (A) waveform of VF-DPC at rated load condition**

Figure 12: FFT analysis of input current (A) of VF-DPC at rated load condition

Conclusions

The proposed work presents the comparison of SPWM and VF-DPC based three-phase AC to DC PWM converters. Both techniques are simulated using MATLAB/SIMULUINK software and their performance is compared in terms of input power factor and input current THD value at rated load condition. From the simulation results, at rated load condition, the power factor obtained for SPWM is 0.9972 and unity power factor for VF-DPC technique. Harmonic analysis for input current THD is done by using FFT tool at rated load condition. The input current THD obtained for SPWM is 3.68% and 0.57% for VF-DPC technique which is very low. From these simulation results, it is concluded that unity power factor operation with minimum THD is obtained by VF-DPC technique so that it gives better performance compared to SPWM.

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