Frequency Domain Analysis of Adjustable Speed Drive Systems Based on Transfer Switching Function

V. Mohan[1] J. Raja[2] S. Jeevananthan[3]

Abstract – A frequency domain analysis (FDA) is proposed to build an accurate model of the front end rectifier and pulse width modulated (PWM) inverter in an ac-ac conversion scheme, in order to analyze the harmonic currents generated by the adjustable speed drive (ASD) systems. The harmonic currents cause detrimental effects, such as an abrupt termination of the load power or oscillations, which may impose higher stresses on all the components of the power path. The impact of the interaction between non-linear loads and the power sources need to be characterized, which necessitates the accurate model. Simulation and experimental results of the suggested approach are compared with those obtained using time domain simulation, to highlight its validity.

Keywords - Frequency domain analysis, PWM inverter, transfer switching function.

I. INTRODUCTION

The present day systems are powered by non-ideal sources whose output impedance is not negligible, besides most of the loads are non-linear in nature [1]. The analysis of harmonic components is an inevitable part of the study, due to the requirements of higher power quality. Numerical techniques offer a good representation of the non-characteristic waveform distortion generated by the converters. The most widely used method to calculate the harmonic components is a numerical time domain simulation method, in which the various components are analyzed by solving differential equations.

The time domain methods are easy to use and allow verification of system operation under any number of different operating states. However they do not provide an analytical insight required for optimal design; besides frequency dependence cannot be accurately modeled [2-3]. An alternative method for calculating the harmonic currents of a power converter uses the Fourier series and the switching functions. With a frequency domain model, the closed loop frequency responses can be established, which will facilitate the analysis of system stability and design optimization. The frequency response test is cumbersome to perform, for systems with large time constants, as the time required for the output to reach the steady state for each frequency of the test signal is exceedingly long. However frequency domain modeling is significant for power electronic circuits, which offer a faster response.

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Sakui et al. have proposed an analytical method to calculate the harmonic currents of three-phase rectifier with a dc filter by accounting the ac side reactance [4]. They have further improved it by including the ac side resistance for continuous and discontinuous modes of conduction [5]. Hu and Yacamini have developed another analytical method to show how harmonics are transferred in the both directions through three phase bridges [6]. Larsen et. al have proposed a three-port network and analyzed the low order harmonic interactions on HVDC systems [7]. Wood and Arrillaga have developed a three-port model and used it to predict the composite resonant frequency. The same authors have shown that HVDC rectifiers and other nonlinear power electronic switching devices are almost completely linear in frequency domain [2].

This paper presents a transfer switching function (TSF) based frequency domain analysis (FDA) for adjustable speed drive (ASD) system consisting of an uncontrolled inverter and pulse width modulated (PWM) inverter. The developed FDA results are compared with time domain analysis (TDA) and experimental results.

II. FDA OF UNCONTROLLED RECTIDIERS

A typical single phase diode rectifier (SPDR) is shown in Fig 1. Generally the rectifier operates as a modulator, since its primary function is to convert the fundamental power frequency ac (50 or 60 Hz) to dc. The modulation is achieved by the alternate switching action of the diodes. The instantaneous output voltage, V_{dc} shown in Fig.2(c), is expressed in terms of the rectifier switching function 'S' and ac source voltage, V_{ac} as in (1). Fig 2 (b) shows the TS) of the SPDR, which represents the switching of the alternate diode pairs, to connect the supply voltage to the dc-bus. This switching function operates as a frequency transfer function in that it describes the way an ac side frequency signal is transferred to the dc side [8,9,10]. The Fourier series of switching function is given in (2).

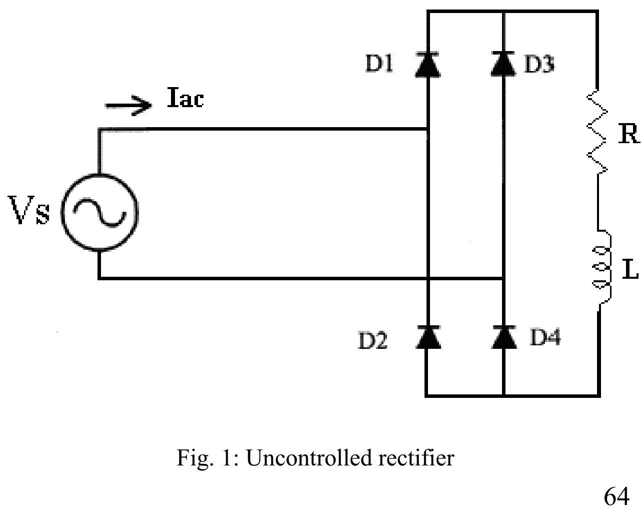


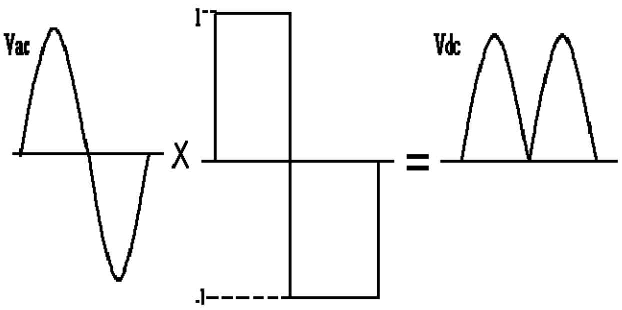
Fig. 1: Uncontrolled rectifier

$$V_{dc} = V_{ac} * S \qquad (1)$$

$$S = a_0 + \sum_{n=1} a_n \cos(n\omega t) + \sum_{n=1} b_n \sin(n\omega t) \qquad (2)$$

As the switching function is symmetrical, the Fourier coefficients a_o and a_n are zero and the switching function S is

$$S = \sum_{n=1,3,..} \frac{4}{n\pi}\sin(n\omega t) \qquad (3)$$



(a) (b) (c)

Fig. 2 (a): Rectifier input (b): Switching function and (c): Rectifier output

Substituting (3) in (1) gives

$$V_{dc} = \sum_{n=1,3,..} \frac{4}{n\pi}\sin(n\omega t) * V_m \sin(\omega t) \qquad (4)$$

$$= \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\sum_{n=2,4,...} \frac{\cos(n\omega t)}{n^2-1} \qquad (5)$$

The final rectifier output is given by (5) and the rectifier load side current is given by

$$I_{dc} = \frac{2V_m}{\pi R} - \frac{4V_m}{\pi}\sum_{n=1,2,3...} \frac{\cos(2n\omega t)}{(4n^2-1)*Z_{2n}} \qquad (6)$$

where, Z_{2n} is the impedance offered to even order harmonic components. The rectifier source side current can also be obtained by using the same switching function (S) and the load side current, expressed as

$$I_{ac} = I_{dc} * S \qquad (7)$$

By substituting (6) and (3) in (7)

$$I_{ac} = \frac{8V_m}{\pi^2 R}\sum_{n=1,3,5...} \frac{\sin(n\omega t)}{n} - \frac{16V_m}{\pi^2}\sum_{n=1,2,3...} \frac{\cos(2n\omega t)}{(4n^2-1)*Z_{2n}} * \sum_{n=1,3,5...} \frac{\sin(n\omega t)}{n} \qquad (8)$$

III. FDA OF PWM INVERTERS

The typical single-phase inverter is shown in Fig 3. The typical switching function 'S_I' of the inverter is shown in Fig 4 (b) which is derived from comparison of sine reference and triangular carrier. Figs 4(a) and 4(b) show the inverter input and output respectively. The switching angles are found using following expressions [11].

$$P_i^{th}\ \text{intersection},\ \alpha_m + \frac{\pi}{2M_f} M_a \sin\alpha_m - \frac{2j}{2M_f} = 0$$

$$P_{i+1}^{th}\ \text{intersection},\ \alpha_m - \frac{\pi}{2M_f} M_a \sin\alpha_m - \frac{2j}{2M_f} = 0 \qquad (9)$$

The Fourier coefficients for a pair of pulse is given as

$$B_n = \frac{4}{n\pi}\sin\left(\frac{n\delta_m}{4}\right)\left[\sin n\left(\alpha_m + \frac{3\delta_m}{4}\right) - \sin n\left(\pi + \alpha_m + \frac{\delta_m}{4}\right)\right] \qquad (10)$$

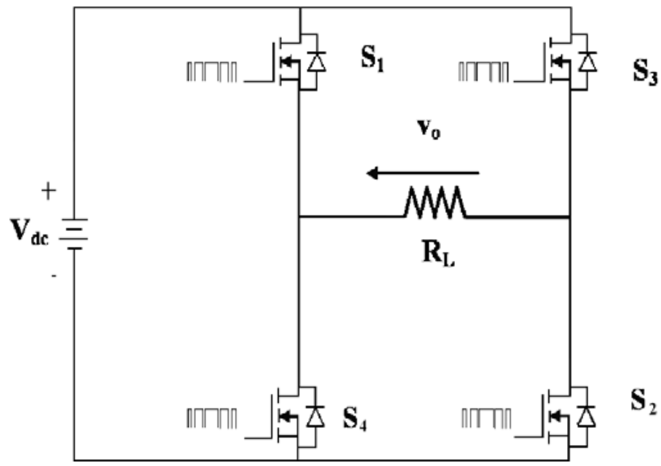
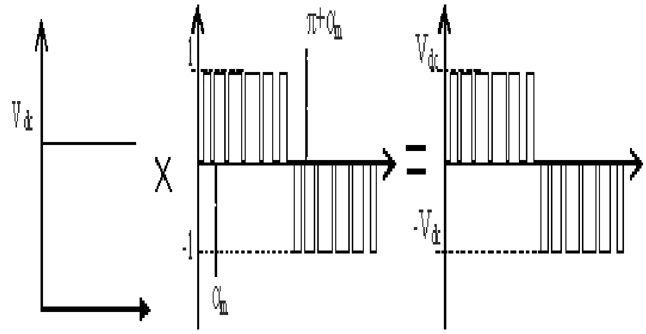


Fig. 3: Single-phase full-bridge inverter



(a) (b) (c)

Fig. 4 (a): Inverter input, (b): Switching function and (c): Inverter output

Where, α_m is the starting point of the pulse and δ_m is the width of each pulse. The over all switching function is given as

$$S_I = \sum_{n=1.3.5..}\sum_{m=1}^{p} \frac{4}{n\pi}\sin\left(\frac{n\delta_m}{4}\right)\begin{bmatrix}\sin n\left(\alpha_m + \frac{3\delta_m}{4}\right) \\ -\sin n\left(\pi + \alpha_m + \frac{\delta_m}{4}\right)\end{bmatrix}\sin(n\omega t) \qquad (11)$$

The output of the inverter is given by

$$V_o(t) = V_{dc} * S_I$$

$$V_o(t) = \sum_{n=1.3.5..}\sum_{m=1}^{p}\left(\frac{4V_{dc}}{n\pi}\sin\left(\frac{n\delta_m}{4}\right)\begin{bmatrix}\sin n\left(\alpha_m + \frac{3\delta_m}{4}\right) \\ -\sin n\left(\pi + \alpha_m + \frac{\delta_m}{4}\right)\end{bmatrix}\right)\sin(n\omega t) \qquad (12)$$

The inverter output current is the ratio between the output voltage and the load resistance, expressed as

$$I_o(t) = \sum_{n=1.3.5..}\sum_{m=1}^{p}\left(\frac{4V_{dc}}{n\pi R}\sin\left(\frac{n\delta_m}{4}\right)\begin{bmatrix}\sin n\left(\alpha_m + \frac{3\delta_m}{4}\right) \\ -\sin n\left(\pi + \alpha_m + \frac{\delta_m}{4}\right)\end{bmatrix}\right)\sin(n\omega t) \qquad (13)$$

The inverter input current is obtained by using the inverter output current and the same switching function (S_I), given by

$$I_i(t) = I_o(t) * S_I \tag{14}$$

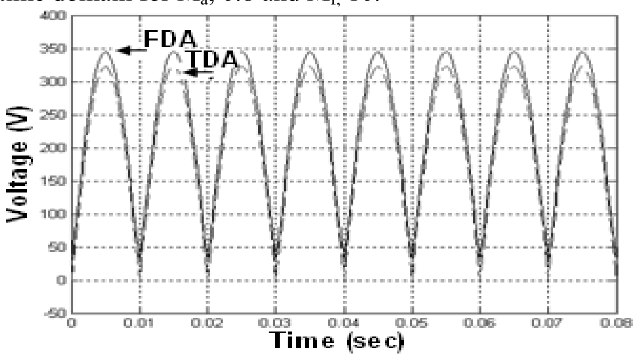
$$= \frac{V_{dc}}{R}\left[\sum_{n=1.3.5..}\sum_{m=1}^{p}\left(\frac{4}{n\pi}\sin(\frac{n\delta_m}{4})\begin{bmatrix}\sin n(\alpha_m+\frac{3\delta_m}{4}) \\ -\sin n(\pi+\alpha_m+\frac{\delta_m}{4})\end{bmatrix}\right)\sin(n\omega t)\right]^2 \tag{15}$$

IV. Problem formulation

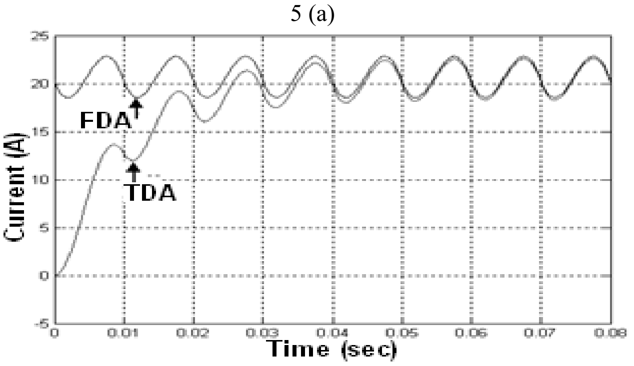
It is envisaged to develop a frequency domain based model of a single phase uncontrolled rectifier and a SPFB inverter, in order to evaluate the performance of the ac-ac conversion system, suitable for variable frequency system through MATLAB simulation and FPGA based hardware implementation. The simulation results are to be validated by comparing with those obtained using time domain analysis. Besides, the analytical (FDA) and experimental results are to be compared.

V. Simulation results

The simulation is performed on a SPWM inverter using MATLAB both in time and frequency domain for various values of M_a and M_f. However the results obtained by the analytical method are compared with those available in the time domain for M_a, 0.8 and M_f, 10.



5 (a)



5 (b)

Fig. 5 (a): Output voltage (b): Output current waveform FDA - calculated, TDA-simulated

The results are obtained for a rectifier of load resistance of 10Ω and inductance of 0.1H. The FDA results are shifted in the Y-axis scale for clarity. Fig 5 shows the dc voltage of the rectifier. It follows that the frequency domain analysis output voltage and time domain simulation output are almost the same, but the output dc current shown in Fig 5 (b) reveals that the time domain analysis takes a longer time to reach steady state. The source side current of the rectifier is seen in Fig 6. The output voltage of inverter and fundamental component of the output are depicted in Figs 7 (a) and (b) respectively. Fig 8 shows the simulated harmonic spectrum of the inverter output voltage. The dominant harmonic components of PWM controlled inverter are pushed to higher frequency as expected. It is seen that the inverter output current waveform is the same as that of the voltage for a resistive load.

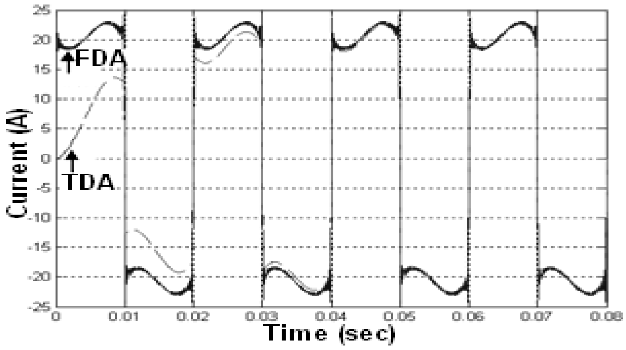
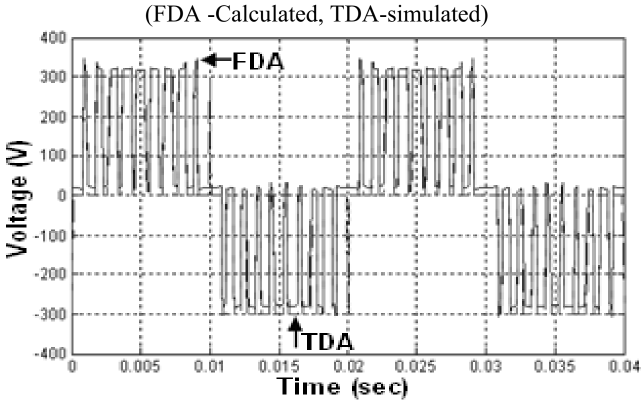
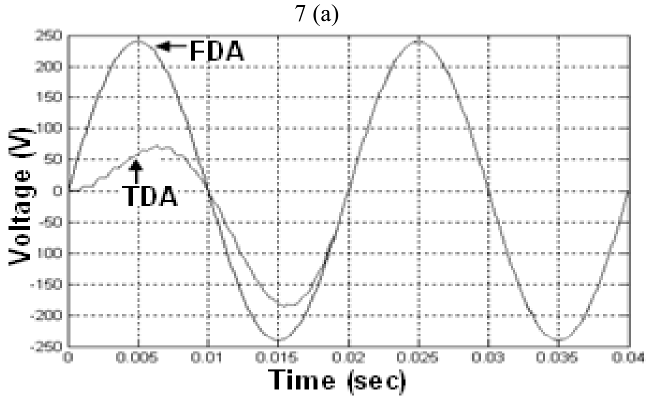


Fig. 6: Source side current waveform of rectifier (FDA -Calculated, TDA-simulated)



7 (a)



7 (b)

Fig. 7 (a): Output voltage and (b): Fundamental of output (M_a= 0.8, M_f=10, Vdc=300V)

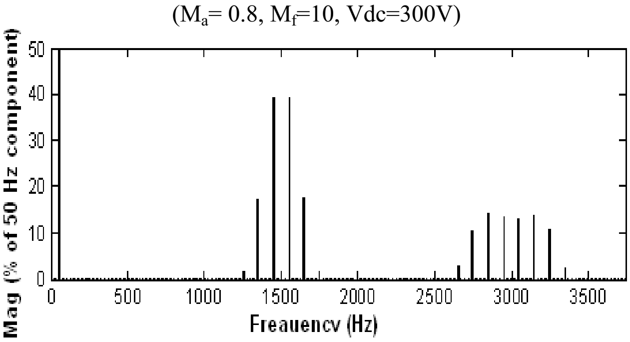


Fig. 8: Harmonic spectrum of output voltage -SPWM M_a=0.8, M_f=15 and V_{dc}= 300V

VI. HARDWARE IMPLEMENTATION

The SPWM strategy is implemented on a SPFB inverter using FPGA architecture (Xilinx-Spartan-3 xc3s400-4-pq208). The design is complied, simulated using ModelSim and finally downloaded to the device through Xilinx software. The PWM pulses are generated using TRR algorithm, in which the basic idea is to generate carrier waves of any frequency, acquired by fetching the triangular samples while the reference of any magnitude is obtained through a suitable multiplying factor [12]. The FPGA processor acquires the values of M_a, M_f, base reference wave (at M_a=1) and base carrier wave (at M_f =1) as inputs. The first step is to modify the base reference to the given M_a and obtain the actual reference wave. The base reference samples are multiplied by a transitory M_a (ten times the actual M_a) and later divided by ten. The values of the actual reference wave are stored in an array of fresh adjacent locations. The second step is to compare the reference and carrier waves. The subroutine determines the actual carrier wave from the base carrier wave. The modified sine pointer (MSP) and formed pattern pointer (FPP-where the PWM pattern is to be stored) are initialized and thereafter the carrier pointer (CP) is calculated recursively.

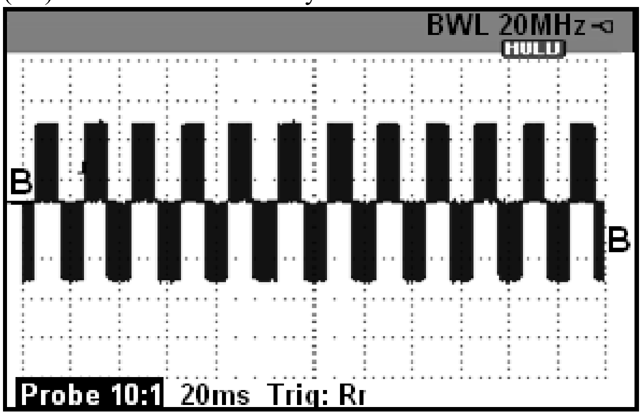


Fig. 9: Experimental output voltage waveform with SPWM

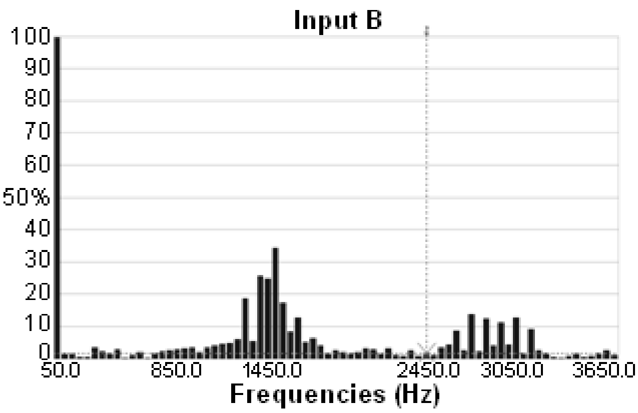


Fig. 10: Frequency spectrum with SPWM (M_a=0.8, M_f=15)

Fig. 9 shows the typical output waveform resulted in hardware testing. The corresponding harmonic spectrum is presented in Fig. 10. A detailed comparison of analytical and experimental results is presented in Fig.11 in terms of total harmonic distortion (THD) as a function of M_a. Tables 1 and 2 shows similar comparison for M_a=0.8 and M_f=15 highlighting the dominant harmonics. Fig 12 shows the FDA and time domain analysis results of dc link current while Fig 13 gives similar results of representative dominant harmonics.

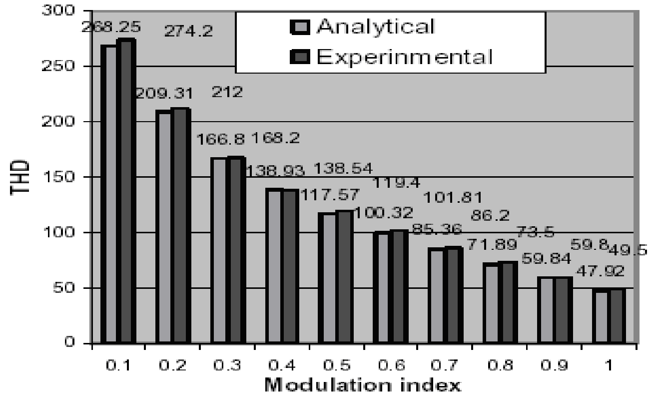


Fig.11: Comparison of analytical (FDA) and experimental values

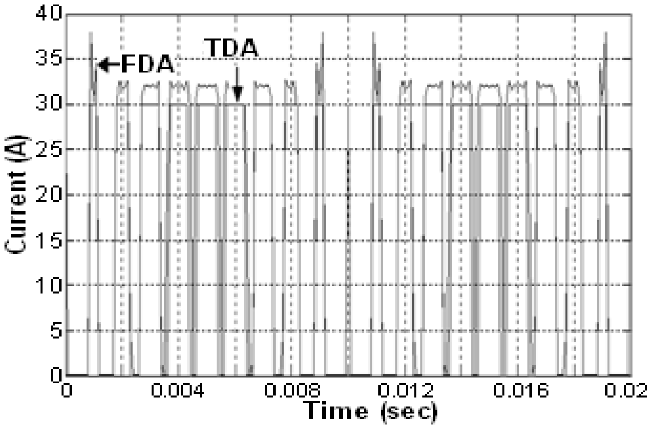
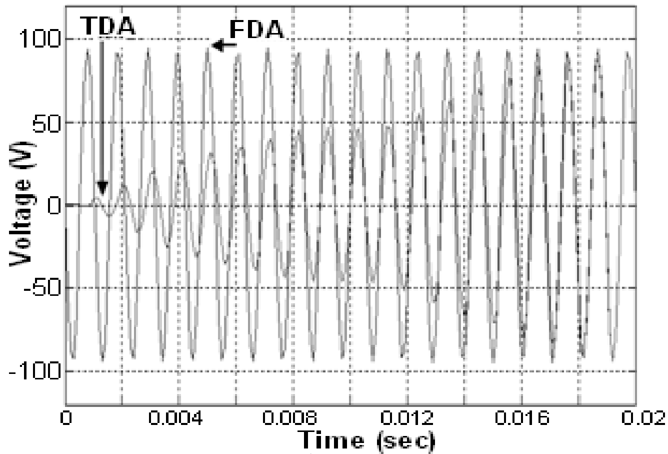
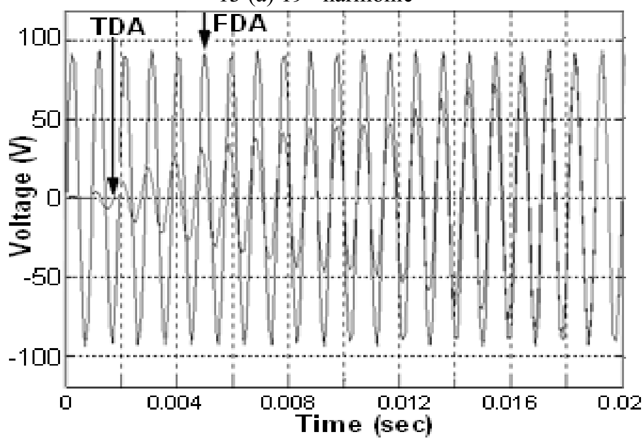


Fig. 12: Input current of inverter (M_a= 0.8, M_f=10, Vdc=300V, R=10Ω)



13 (a) 19[th] harmonic



13 (b) 21[st] harmonic

Fig. 13: Dominant harmonic components of SPWM inverter (M_a= 0.8, M_f=10, Vdc=300V, R=10Ω)

Table 1: THD fundamental and lower order harmonics

Method	THD 9%)	V_3 (%)	V_5 (%)	V_7 (%)
TDA	76.68	12.45	8.62	2.28
FDA	68.02	0.18	0.12	0.03
Experimental	69.68	1.45	0.62	0.28

Table 2: Comparison of carrier frequency harmonics

Method	$2M_f$-3 V_{27} (%)	$2M_f$-1 V_{29} (%)	$2M_f$+1 V_{31} (%)	$2M_f$+3 V_{33} (%)
TDA	27.20	51.48	43.41	9.63
FDA	17.55	38.92	38.86	17.55
Experimental	19.20	40.48	36.41	13.63

VII. Conclusion

The approach has served to develop accurate FD models of the front end rectifier and PWM inverter. The importance of switching functions has been illustrated through the analysis. The scheme has created a new dimension in the harmonic analysis of power converters. The results show that TDA is very accurate and reflects the circuit behavior right from the first cycle of its working. The frequency domain modeling has highlighted a technique by which the linear operating range of the PWM inverters can be identified. The close comparison of the simulated and implemented results reveals the superiority of the proposed method. This idea will go a long way in exploring newer variable speed techniques suitable for ac drives to meet state- of-the- art applications.

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Biographies

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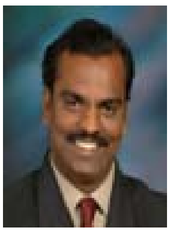

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