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MODELLING AND ESTIMATING VOLTAGE AND CURRENT HARMONICS OF VARIABLE SPEED DRIVES (VSD)

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Abstract-This paper presents an analysis on the calculation of harmonic current and voltage components of a variable speed drive (VSD). The requirement for advanced and accurate harmonic mitigating techniques has become essential because of the rapid increase ofnonlinear loads like VSD's in both industrial and commercial applications. A new state-of-the-art MATLABSimulink based harmonic calculator using DiscreteFourier Transform (DFT) was designed to calculate the current and voltage harmonics more accuratelyin order to understand the realistic extra iron loss components inside the rotating machine due to converter switching. This also helpsto optimize the system performance when a converter is coupled with the electric machine.In addition to its harmonic mitigating capabilities, this method can plot harmonic spectrum which helps to design wide spectrum active harmonic filter to eliminate pollutant odd harmonics not entering rotating electrical machines.The harmonic analysis presented in this paper is for a 5hp DC motor connected with the phase controlled rectifier. This model is suitable for virtually any application involving a VSD or similar converters to effectively mitigate voltage and current harmonics.

Keywords: *Harmonics, THD, 3^{rd}& 5^{th} harmonics, current harmonic, voltage harmonic, DFT.*

I. INTRODUCTION

Today the issue of power quality has become prime concern with the increased use of non-linear loads on the supply system. Decade back there were lot of questions and concerns regarding overloaded neutral conductors, overheating and failure of motors and transformers, frequent tripping of circuit breakers and capacitor failures, were often met with limited solutions only. The IEEE 519-1992 [6] standard has been introduced to help improve of power quality. This problem was growing one due to addition of newly introduced equipment in to the supply network. The increased use of VSDs in industry coupled with complaints about VSD shutdowns, along with the above problems stated, this resulted in VSDs becoming one of the first targets as a cause of supply harmonic problems and addition of extra eddy current and hysteresis component losses in rotating machinery. In most cases VSDs are being applied to help save energy even though they also have other benefits which may depend on the specific application. VSD's do have one particular issue that must be evaluated when designing the electrical system. VSD's create electrical distortion (commonly called harmonics) on the system which can be a problem unless it is addressed.

It is easy to see why VSDs were blamed for harmonic problems, as they are normally high power devices, which inject high magnitudes of harmonic currents into the supply network. However we cannot skip other low power devices like computers, portable electronic goods, fluorescent lamps, washing machines, etc. as large number of them can lead to similar impact on the supply system.

Even though more techniques had already introduced in designing filters to reduce harmonic currents from VSDs and to improve system performance, this paper presents live calculation of harmonic currents entering into electrical machine from controlled or uncontrolled rectifier helps in combat with current harmonics.This paper helps in designing intelligent neural network based active filter to eliminate current harmonics by not affecting switching characteristics of power switching devices. Also helps in the finite element method (FEM) based investigation of losses from magnetic devices due to various current harmonics.

This paper explores the relationship between harmonic currents from VSDs and associated supply. Characteristic harmonic currents of VSDs will be shown up to 20^{th} order using developed Simulink model coupled with the VSD. Simulation results of these harmonic current variations can be plotted for three different firing angles of phase controlled VSD along with frequency spectrum.

This paper is prepared in the following way: In section II of this paper, general background of harmonic analysis is presented. Section III introduces the VSD and Fourier modelling; design of phase controlled rectifier, DC motor and Fourier Calculator model. In section IV, simulation results are presented plotting up to 7^{th} order harmonics and discussion about resulted distortion. Finally, some conclusions, recommendations and future scope of this research are provided in section V.

II. BACKGROUND

Harmonics are the odd integral multiples of fundamental frequency resulting in the distortion of supply waveform due to interference by superposition. Harmonic order or harmonic number is a reference to the frequency of the harmonic component e.g. 3rdorder harmonic component refers to a harmonic component having frequency 3 times that of fundamental i.e. for a 50 Hz supply 3rd order component is of 3x50=150Hz.

Generally the sum of even harmonics is less than 1% of fundamental component thus they are not considered also 3rd, 5thand 7thorder harmonics constitute about 97% of harmonic Thus it is most economically suitable to design harmonic filters for these components as these can reduce the pollution level well below the desired limit and being economically justified.

2.1 CAUSES OF HARMONICS

Industrial electronic devices and non-linear loads are the major cause of harmonic generation. As the currentdrawn from the supply no longer remains sinusoidal thus the resultant waveform is made up of a number of different waveforms of different frequencies.

2.2 EFFECTS OF HARMONICS

Harmonics are a major cause of power supply pollution lowering the power factor and increasing electrical losses. This results in premature equipment failure and higher rating requirement for equipment.

2.3 HARMONIC FILTERS

A harmonic filter is a device used to 'filter out' components of different harmonic order from reaching and harming the load thus the name 'harmonic filter'.

2.4 APPLICATION OF HARMONIC FILTERS

Harmonic Filters are applied at different points where power pollution due to harmonics is observed above the desirable limits as recommended by IEE 519 standards.[7] These are used in parallel to load thus providing a bypass low impedance path for the flow of Harmonic currents of specific frequency or harmonic number. Thus a separate harmonic filter branch is required for each harmonic order to be removed. Thus a 3 branch filter might be used to filter out 3rd, 5th and 7thharmonic component.

When non-linear equipment like a VSD draws current, harmonics of various frequencies are created. See Figure 1, 2 & 3. This figure shows the fundamental wave form, then the 5th order wave form, or 5thorder harmonic. When these harmonics are added together with the fundamental current waveform, the resulting waveform upstream of the drive becomes distorted as shown by the last waveform. In reality, additional odd ordered harmonics are also created which include e.g. 3rd, 7th,9th, 11th,13th,15th, and 17th.

The most pre-dominate order harmonics are the 5thand the 7th.

HARMONIC ORDERS & MAGNITUDES

$h = kn \pm 1$ and $I_h = I_1 / h$

h = harmonic number

k = an integer

n = pulse number of circuit (2, 3, 6, 12, 18, 24)

I_h = estimated harmonic current magnitude

I_1 = fundamental current

For a 2 pulse rectifier (standard on fully controlled VSD's)

h=3, 3rdharmonic = 3 * 50 Hz = 150 Hz (I3=1/3)

h=5, 5th harmonic = 5 * 50 Hz = 250 Hz (I5=1/5)

e.g.: Sine wave of a fundamental waveform f(x) = sin(x)

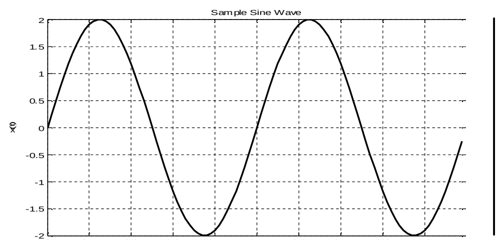

Figure.1a

plus a "5th" harmonic sine wave of $f(x) = \frac{\sin(5x)}{5}$

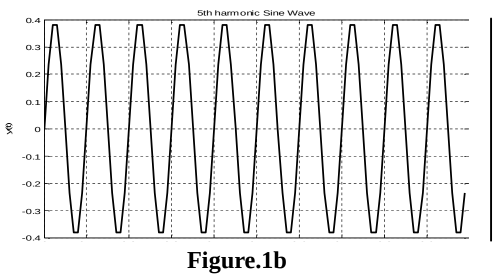

Figure.1b

results in a harmonic rich, distorted, non-linear wave shape of f(x) = sin(x)+$\frac{\sin(5x)}{5}$

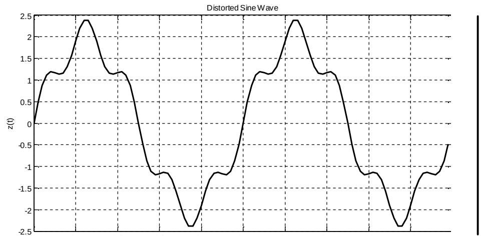

Figure.1c

III. VSD AND FOURIER CALCULATOR MODEL

The harmonics are determined by the method of Fourier analysis. General expression for Fourier series, periodic function f (t) of any complex wave over the period of 2π can be written as follows:

$$f(x) = a_0 + \sum_{n=1,2,\ldots}^{\infty}(a_n \cos nwt + b_n \sin nwt) \quad (1)$$

Where a_0 is the DC component of the original wave, $(a_n \cos nwt + b_n \sin nwt)$ is the nth harmonic of the function.

The values of a_0, a_n and b_n can be determined by the following relations.

$$a_0 = \frac{1}{2\pi}\int_0^{2\pi} I_d dwt \quad (2)$$

$$a_n = \frac{2}{\pi}\int_{\alpha}^{\pi+\alpha} I_d Cos\, n\, wt\, d(wt) \quad (3)$$

$$b_n = \frac{2}{\pi}\int_{\alpha}^{\pi+\alpha} I_d Sin\, n\, wt\, d(wt) \quad (4)$$

Equation (1) further can be written as under:

$$f(x) = a_0 + \sum_{n=1,2,\ldots}^{\infty}(A_n \operatorname{Sin}(nwt + \emptyset n)) \quad (5)$$

Where $A_n = \sqrt{a_n^2 + b_n^2}$ and $\emptyset n = \tan^{-1}\frac{a_n}{b_n}$

A_n *is* magnitude of n[th] harmonic component, $\emptyset n$ is phase angle of the n[th] harmonic component and I_d is current input to the motor.

A Fourier analyzer model has been designed using equations (1) & (2) for calculation of various orders of harmonics in the MATLAB Simulink. The data calculated in the Simulink model has been exported to the MATLAB m-file program which generates GUI based harmonic analysis plots with various order of harmonics and frequency spectrum.

The signal which is going to be analyzed for the measurement and investigation of total harmonic distortion was given from the input of the D.C. motor. A fully controlled 5hp, 240V, 1200rpm, 30N-m VSD was selected for the analysis (Appendix). This Simulink based Fourier calculator can be used for the analysis of any controlled, uncontrolled, 1-phase and 3-phase converters.This also can be utilized for the design of active harmonic filters using neural network technique.

The Simulink model of harmonic calculator is as in Figure.2. The Fourier calculator was designed based on extraction of non-stationary Sinusoids tracking algorithm and Phase-Dictated Sinusoid Tracking Algorithm [6]

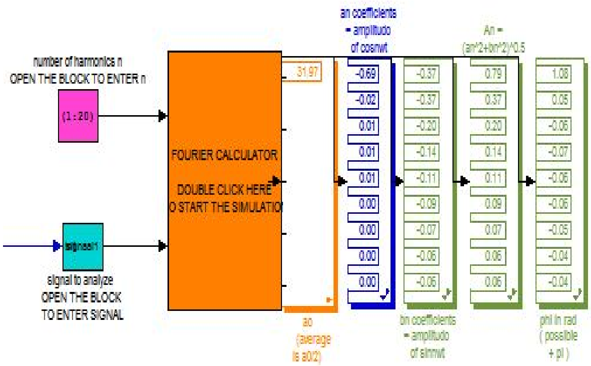

Figure.2 Fourier Calculator

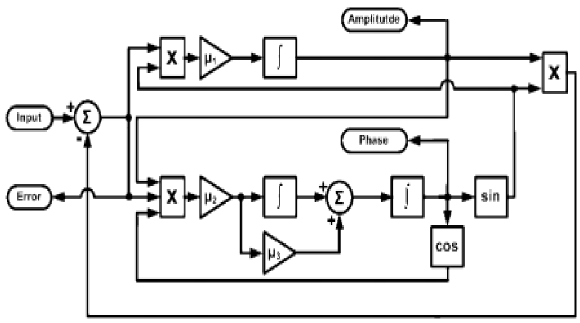

Figure.3 Block diagram of the sinusoid tracking algorithm

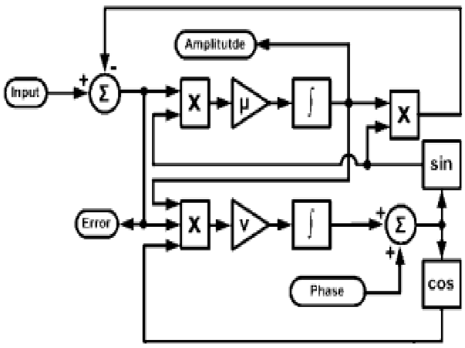

Figure.4 Block diagram of the phase dictated sinusoid tracking algorithm

A simple GUI based MATLAB program also can be run in order to plot frequency spectrum and total harmonic distortion wave.

The design and modelling of 1-∅ fully controlled bridge rectifier drive can be as follows:

Electrical system equation:

$$Va = Ra.ia + \frac{dia}{dt} + eb \quad (6)$$

where eb = K.wm

Mechanical system equation:

$$Te = \frac{Jdwm}{dt} + Tl.signum(wm) + f(wm) \quad (7)$$

whereTe = K.ia

The Simulink model of the drive connected to the above Fourier calculator is as in Figure.3

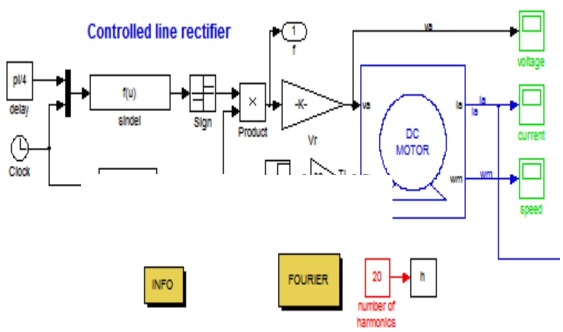

Figure.5 Phase controlled variable speed drive

IV. RESULTS AND DISCUSSION

Harmonic analyzer simulated for firing angle $=\frac{\pi}{6}$. The fundamental current harmonic of VSD and the corresponding frequency spectrum generated by the MATLAB program in time domain was as shown in Figures.6 to 10 and Table.1 shows the calculated values of harmonic data by simulator.

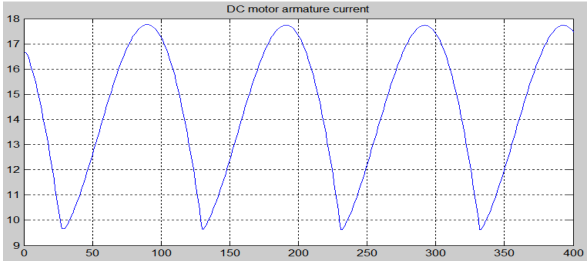

Figure.6 Motor armature current (Ia)

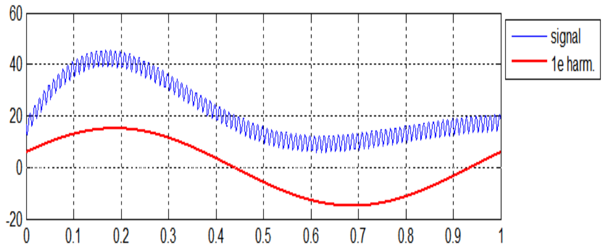

Figure.7 Signal and fundamental current

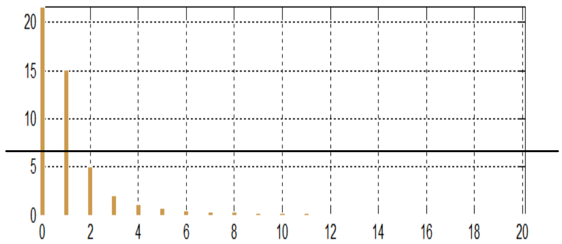

Figure.8 amplitude versus f/f1

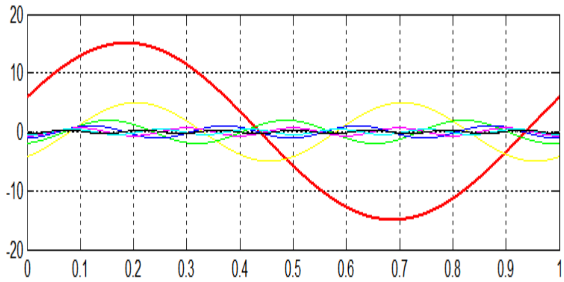

Figure.9 Higher harmonics (max. the first 7)

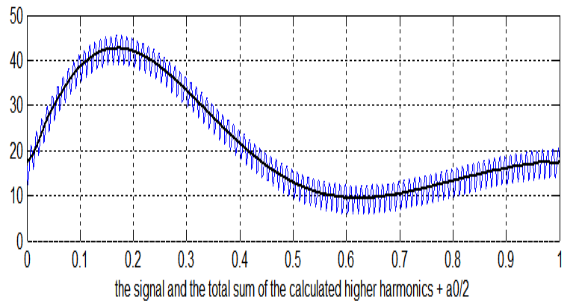

Fig.10 the signal and the total sum of the calculated higher harmonics + a0/2

Simulation time (ms)

The average value of a_0 obtained for the assumed VSD i.e.$\frac{a_0}{2}$ = 21.6928

f/fn	an	bn	An	∅n
1	5.7735	13.8817	15.0345	0.3941
2	-4.2220	2.6373	4.9780	-1.0125
3	-1.9185	0.4644	1.9739	-1.3333
4	-1.0619	0.0966	1.0663	-1.4801
5	-0.6727	-0.0043	0.6727	4.7060
6	-0.4643	-0.0381	0.4658	4.6306
7	-0.3398	-0.0498	0.3434	4.5670
8	-0.2594	-0.0530	0.2648	4.5107
9	-0.2046	-0.0528	0.2113	4.4597
10	-0.1655	-0.0512	0.1733	4.4125
11	-0.1367	-0.0489	0.1452	4.3685
12	-0.1147	-0.0465	0.1238	4.3271
13	-0.0977	-0.0442	0.1072	4.2879
14	-0.0842	-0.0419	0.0941	4.2509
15	-0.0733	-0.0398	0.0834	4.2156
16	-0.0644	-0.0378	0.0747	4.1821
17	-0.0571	-0.0359	0.0674	4.1502
18	-0.0509	-0.0343	0.0613	4.1199
19	-0.0457	-0.0327	0.0562	4.0909
20	-0.0412	-0.0313	0.0517	4.0632

Table.1

APPENDIX

DC Motor parameters:
Shaft power – 5 hp
Rated voltage(va) – 240 V
Armature resistance(Ra) – 0.6 Ohms
Armature inductance(La) – 0.1 H
Field resistance(Rf) – 240
Field inductance(Lf) – 120 H
Total inertia (J) – 0.6 kgm2
Viscous friction coefficient (B) – 0.02 Nms
Coulomb friction torque (Tf) – 1e-5 Nm

V. CONCLUSION

An analytical method has been proposed to investigate the harmonics generated by the dc drives fed by full controlled converters. This method precludes the time consuming calculations which are needed by the numerical method. A more accurate estimation on the harmonic contents becomes feasible. From the calculated results, the distorted current waveforms are found to be far from those of conventional used ones. The harmonic distortions vary significantly with the load current and the speed. The intrinsic small time constant in armature circuit of a dc machine results in not only a higher ripple current that will deteriorate the performance of the dc machine but also more serious harmonic pollution in the power system. The problem of the harmonics can be alleviated by adding a large inductor in the armature circuit. Consequently, this will increase a considerable cost and introduce additional losses. Throughout this research, useful information is provided for the harmonic load flow and the filter design in the power system.

. The complete VSD system model is coupled with SIMULINK Fourier calculator which provides extracted harmonic data from the input signal by running m-file code and import/export configuration settings. Both m-file and SIMULINK model must be in the same directory.

Using the proposed Simulink model, harmonics from AC/DC drives of 1-phase/3-phase type can be measured and easily combined for coupled simulation. With the developed simulation environment, this model calculated current harmonics are very closely agreed with the theoretical values. This also can be coupled to the FEM model in order to compute motor losses, but FEM model [2], [4] is needed for detailed analysis of the saturation and frequency dependence of the motor parameters. This presented model can also be utilized for the design of high power harmonic active filters in order to nullify supply system pollution using MATLAB, but this model mustbe connected at input of the drive system [8]. In general, the simulation results with the Fourier model are very accurate and reliable, which leads to benefits in the system optimization of VSD with an improved estimation of iron losses in rotating electrical machines [6].

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