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System Efficiency using PWM Switching Strategies

Mohammed Hussein Baqir

Abstract— ***Pulse Width Modulation (PWM) is the technique of using switching devices to produce the effect of a continuously varying analogue signal; this PWM conversion generally has very high electrical efficiency. In controlling either a three-phase synchronous motor or a three-phase induction motor it is desirable to create three perfectly sinusoidal current waveforms in the motor windings, with relative phase displacements of 120°.***

The production of sinewave power via a linear amplifier system would have low efficiency, at best 64%. If instead of the linear circuitry, fast electronic switching devices are used, and then the efficiency can be greater than 95%, depending on the characteristics of the semiconductor power switching.

Keywords- it is desirable to create three perfectly sinusoidal current waveforms in the motor windings, with relative phase displacements of 120°.

I. INTRODUCTION

Controlling an A.C. induction motor by the technique of sinewave-weighted pulse-width modulation (PWM), switching gives the benefits of smooth torque at low speeds and also complete speed control from zero up to the nominal rated speed of the motor, with only small additional motor losses. Traditional power switches such as thyristors need switching frequencies in the audible range, typically between 400 and 1500Hz. In industrial environments, the small amount of acoustic noise produced by the motor with this type of control can be regarded as insignificant. By contrast, however, the same amount of noise in a domestic or office application, such as speed control of a ventilation fan, might prove to be unacceptable.

Now, however, with the advent of power MOSFETs three-phase PWM inverters operating at ultrasonic frequencies can be designed. A three-phase motor usually makes even less noise when being driven from such a system than when being run directly from the mains because the PWM synthesis generates a purer sinewave than is normally obtainable from the mains.

The carrier frequency is generally about 20 kHz and so it is far removed from the modulation frequency, which is typically less than 50Hz, making it economic to use a low-pass filter between the inverter and the motor. By removing the carrier frequency and its sidebands and harmonics, the waveform delivered via the motor leads can be made almost perfectly sinusoidal [1]. RFI radiated by the motor leads, or conducted by the winding-to-frame capacitance of the motor, is therefore almost entirely eliminated. Furthermore, because of the high carrier frequency, it is possible to drive motors which are designed for frequencies higher than the mains, such as 400Hz aircraft motors. This section describes a three-phase A.C. motor control system which is powered from the single-phase. It is capable of controlling a motor with up to 1kW of shaft A.C. Mains output power. Before details are given, the general principles of PWM motor control are outlined.

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II. SINUSOIDAL PULSE WIDTH MODULATION INVERTER

The phase reference voltages Va, Vb and Vc of a variable amplitude Am are compared in three separated comparators with a common isosceles triangular carrier wave VT of a fixed amplitude Ac, as shown in figure 1. The modulation is called sinusoidal PWM by which the output wave sinusoidal pulse width distortion can be kept in maximum degree of symmetry for any frequency changing and so a nearly distortion free sinusoidal output can be obtained [2]. The frequency of the fundamental component of the load terminal voltage is nearly the same as that of the reference sinusoidal voltages. The output waveform contains harmonics, which are odd multiple of the carrier frequency Fc (that is Fc, 3Fc, 5Fc,……, and so on). The harmonics which are even multiples of the carrier frequency are zero, and also contain side bands centered around multiples of Fc given by:

$$Fu = K_1 F_c + K_2 F_m - - - - - - - - - - - (1)$$

$$F_1 = K_1 F_c + K_2 F_m - - - - - - - - - - - - (2)$$

Where Fu, F1 and Fm are frequencies of the side bands and the reference signal [3], andK1, K2 are constants. Switching frequency can be determine by equation,

$$f = \frac{1}{R_T C_T} - - - - - - - - - - - - - - - - - (3)$$

The modulation is said to be synchronous when frequency ratio (FR) is an integer and the carrier wave is symmetrical with respect to the three phase reference voltages Va, Vb, and VC. These condition will be satisfied when FR is an integer multiple of three. When this condition is satisfied the modulation is called asynchronous or free running.

When FR (frequency ratio) is large the D.C and subharmonic components in the output waveform have negligible magnitude. Hence the torque and speed fluctuations are also negligible. When FR (frequency ratio) is small they have appreciable magnitudes. With an increase in the frequency of switching operation, the machine losses decreases but the inverter switching losses increase. Thus beyond a certain frequency, the drive efficiency falls. The increasing in switching losses also derate the switching devices and the associated components in the snubber and commutation circuits. The MOSFET is the best according to the above considerations (very low switching loss and additional advantages). The modulation technique can be implemented easily by the microcomputer based implementation [2], since the widths of the pulses are not given by analytic expressions.

For using microcomputer based implementation, therefore various techniques, such as regular sampling, natural sampling, optimum PWM and otter method are used for calculating the pulse widths, and harmonic elimination method has been proposed for digital implementation [3].

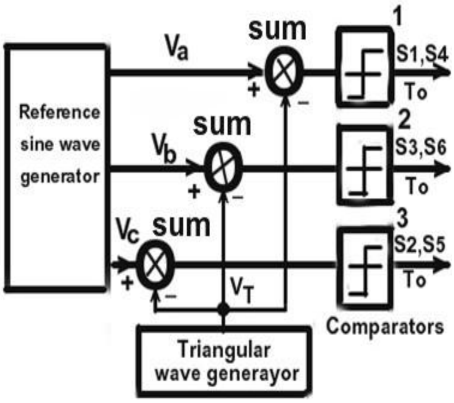

Fig.1Block diagram of generation pulse width modulation

The production of sinewave power via a linear amplifier system would have low efficiency, at best 64%. If instead of the linear circuitry, fast electronic switching devices are used, and then the efficiency can be greater than 95%, depending on the characteristics of the semiconductor power switching.

In practice, the frequency of the modulation is usually between zero and 50Hz. The switching frequency depends on the type of power device that is to be used, until recently the only devices available were power thyristors or the relatively slow bipolar transistors, and therefore the switching frequency was limited to a maximum of about 1kHz, With thyristors, this frequency limit was set by the need to provide forced commutation of the thyristor by an external commutation circuit using an additional thyristor a diode, a capacitor, and an inductor, in a process that takes at least 40ms. With transistors, the switching frequency was limited by their switching frequency and their long storage time.

The ratio of carrier frequency to modulation frequency was only about 20:1. Under these conditions the exact duty ratio and carrier frequencies had to be selected so as to avoid all sub-harmonic torques, that is, torque components at frequencies lower than the modulation frequency.

This was done by synchronizing the carrier to a selected multiple of the fundamental frequency; the HEF4752V, an excellent IC purpose-designed for A.C. motor control, uses this particular approach.

The 1kHz technique is still extremely useful for control of large motors because whenever shaft output powers of more than a few kW are required three-phase mains input must be used, and there are, as yet, few available switching devices with combined high voltage rating, current rating, and switching speed[4].

With using MOSFETs switching times of much less than 1µs, the carrier frequency can be raised to the ultrasonic region, that is, to 20 kHz or more.

There are obvious system benefits with this higher frequency, but there are also several aspects of PWM waveform generation that become easier.

It is possible to use a fixed carrier frequency because the sub-harmonics that are produced as a result of the non-synchronization of the carrier frequency with a multiple of the fundamental are insignificant when the ratio of the carrier frequency to the fundamental frequency is typically about 400:1.

There is a further advantage to be obtained from the high ratio of carrier to modulation frequency: by adding a small amount of modulation at the third harmonic frequency of the basic fundamental modulation frequency, the maximum line-to-line output voltage obtainable from the inverter can be increased, for the following reason [5].

The effect of the third harmonic on the output voltage of each phase is to flatten the top of the waveform, thus allowing higher amplitude of fundamental while still reaching a peak modulation of100%.

When the difference voltage between any two phases is measured, the third harmonic terms cancel, leaving pure sinewave at the fundamental frequency.

This allows the inverter output to deliver the same voltage as the mains input without any significant distortion, and thus to reduce insertion losses to virtually zero.

II. PRACTICAL SYSTEM

The principles outlined above are applied to a typical system shown in Figure.2.

The incoming A.C. mains is rectified and smoothed to produce about 300V and this is fed to the three-phase inverter via a current-sensing circuit.

The inverter chops the D.C. to give 300V peak-to-peak PWM waves at 20 kHz, each having low-frequency modulation of its mark-space ratio, The output of the inverter is filtered to remove the 20 kHz carrier frequency, and the resultant sinewave are fed to the A.C. motor.

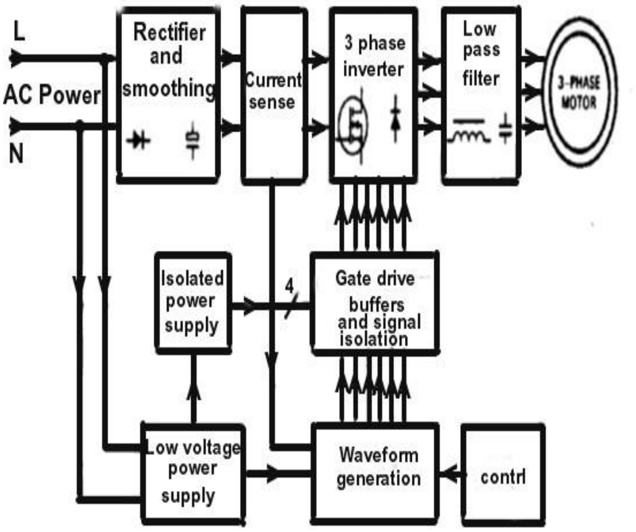

Fig.2 Blok diagram A.C motor control by using 3 phase inverter for 20 kHz

The six switches in the inverter are under the command of a waveform-generation circuit which determines the conduction time of each switch.

Because the control terminals of the six switches are not at the same potential the outputs of the waveform-generation circuits must be isolated and buffered. A low-voltage power supply feeds the signal processing circuit, and a further low-voltage power supply drives a switch-mode isolating stage to provide floating power supplies to the gate drive circuits [6].

III. SIGNAL PROCESSING

Fig.3 shows a block diagram of the circuit which generates the PWM control signals for the inverter.

The input to the system is a speed-demand voltage and this is also used for setting the required direction of rotation: the analogue speed signal is then separated from the digital direction signal.

The speed-demand voltage sets the frequency of the voltage-controlled oscillator (VCO). Information to determine the modulation depth is derived from the speed-control signal by a simple non-linear circuit and is then converted by an analogue-to-digital converter into an 8- bit parallel digital signal [7].

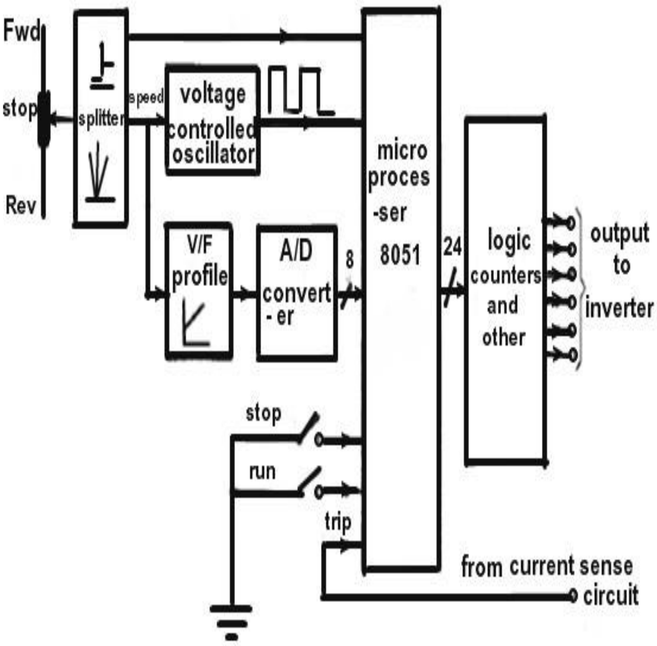

Fig.3 Block diagram of generation PWM waveform

A dedicated IC, type MAB8051, receives the clock signals from the VCO, the modulation-depth control number from the A/D converter, the direction-control logic signal and applying digital multiplication processes to internal look-up table values, the microcomputer calculates the 'on-time' for each of the six power switches, and this process is repeated at regular intervals of 50ms, giving a carrier frequency of 20kHz.

The pulses from the VCO are used for incrementing the pointers of the look-up table in the microcomputer, and thus control the motor speed.

The output signals of the microcomputer are in the form of three 8-bit parallel numbers:

each representing the duty-ratio for the next 50ms switching cycle for one pair of inverter switches, on a scale which represents 0% to 100% on-time for the upper switch and therefore also 100% to 0% on-time for the complementary lower switch.

A dedicated logic circuit applies these three numbers from the microcomputer to digital counters and converts each number to a pair of pulse-widths.

The two signals produced for each phase are complementary except for a small underlap' delay. This delay is necessary to ensure that the switch being turned off recovers its blocking voltage before, its partner is turned on, thus preventing 'shoot-through.

Other inputs to the microcomputer are the on/off switches the motor direction logic signal, and the current-sensing signal. Each input triggers a processor interrupt, causing the appropriate action to be taken. The STOP switch and the overcurrent sense signals have the same effect that of causing the microcomputer to instruct all six power switches in the inverter to turn off. The RUN switch causes the microcomputer to start producing output pulses. Any change in the direction signal first stops the microcomputer which then determines the new direction of rotation and adjusts its output phase rotation accordingly [8].

IV. PROGRAMMABLE SWITCHING FREQUENCY

The internal saw-tooth wave which samples the error input can be adjusted by connecting a resistor and capacitor to ground on the RT and CT pins (pins 4 and 7). In our application we, used single-ended output by connected the output transistors in parallel.

For single-ended output (as opposed to a push-pull output transistor configuration), the switching frequency is determined by the equation,

$$f = 1/R_T C_T$$

The maximum duty cycle of the PWM signal coming from 97%, this can be decreased by applying a voltage to the DTC pin (pin 4), see figure 4.

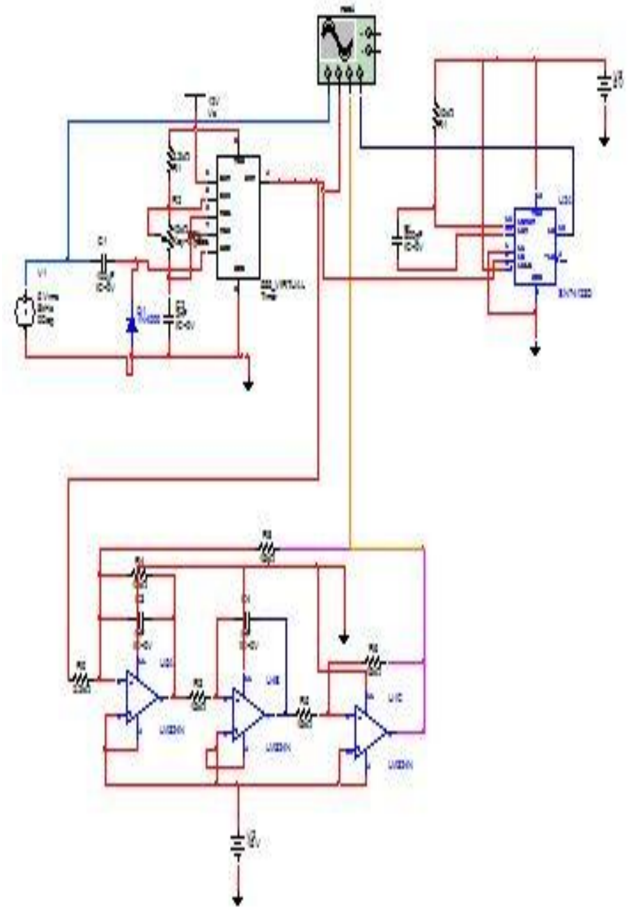

Fig. 4 Blok diagram of generating PWM from the simulating

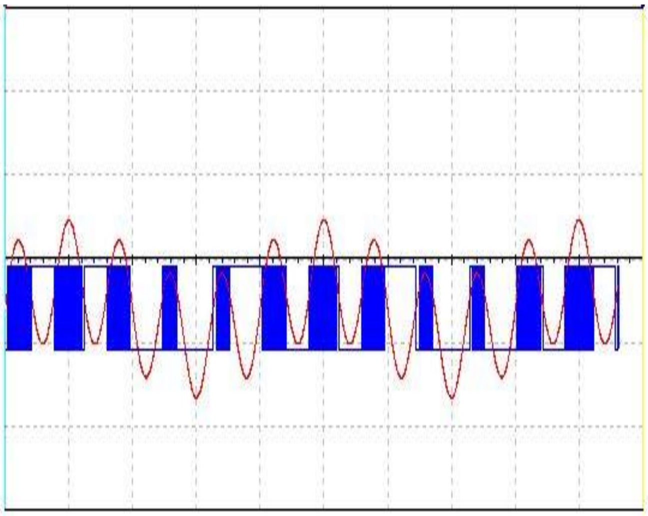

Fig.5 Frequency variation from switching frequency is 5Hz at maximum modulation index

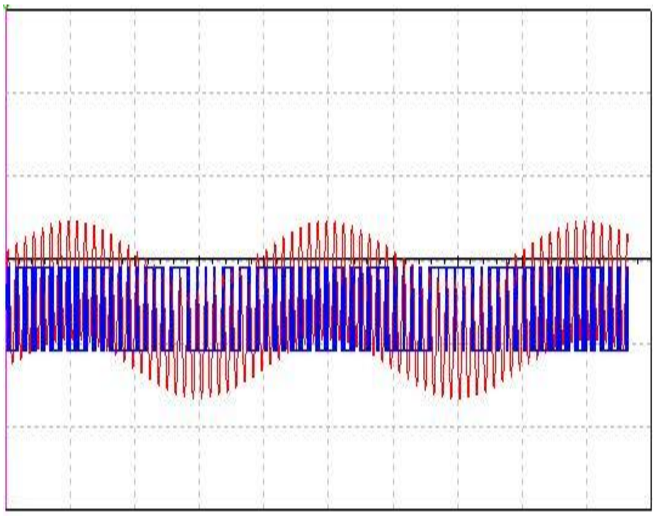

Fig.8 Frequency variation from switching frequency is 30Hz at maximum modulation index

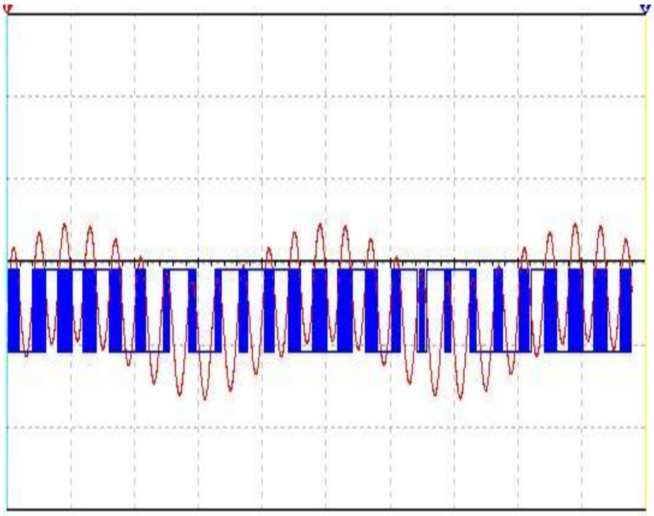

Fig.6 Frequency variation from switching frequency is 10Hz at maximum modulation index

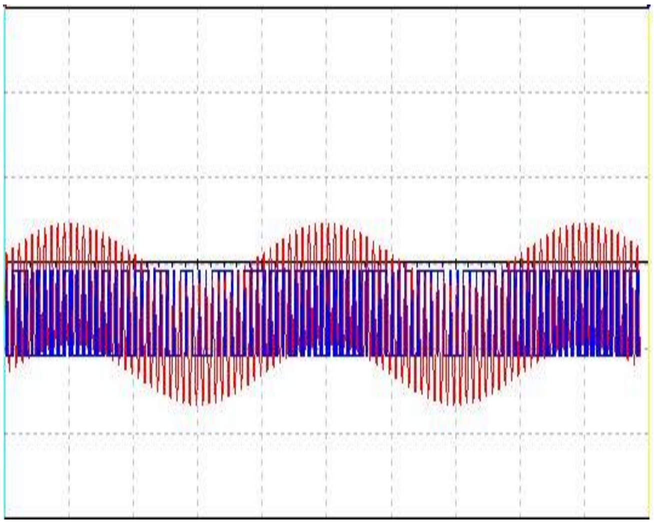

Fig.9 Frequency variation from switching frequency is 40Hz at maximum modulation index

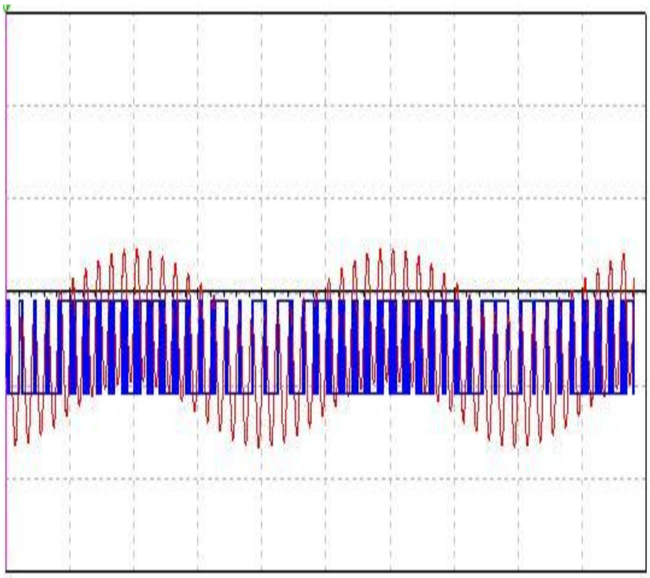

Fig.7 Frequency variation from switching frequency is 20Hz at maximum modulation index

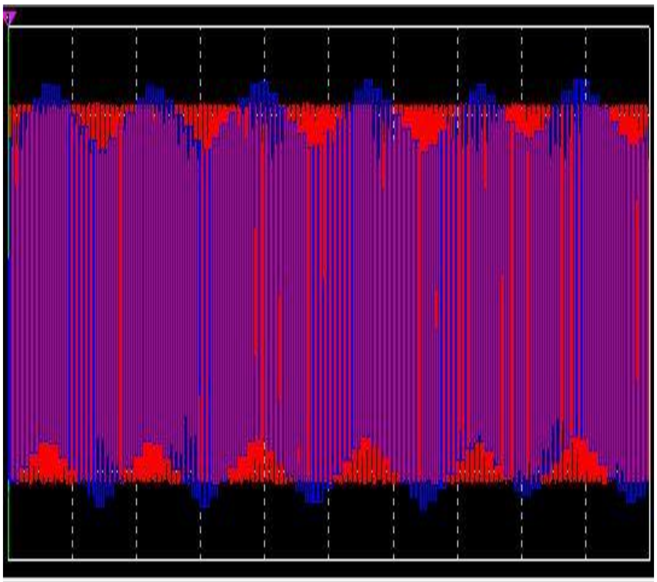

Fig.10 Frequency variation from switching frequency is 60Hz at maximum modulation index

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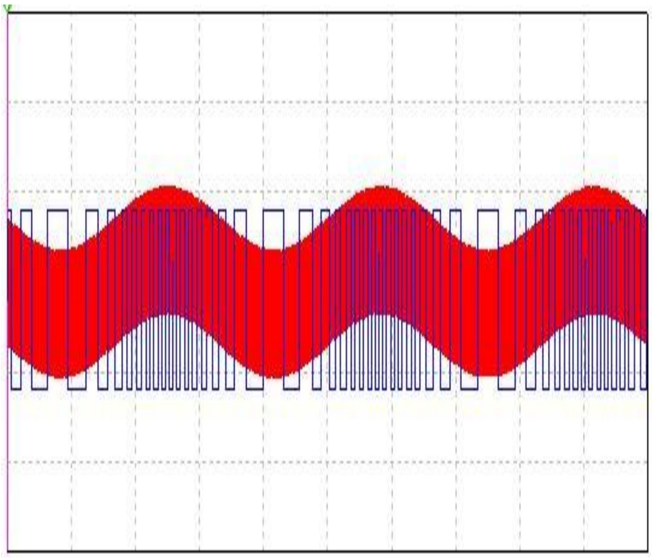

Fig 11 Frequency variation from switching frequency is 166Hz at maximum modulation index

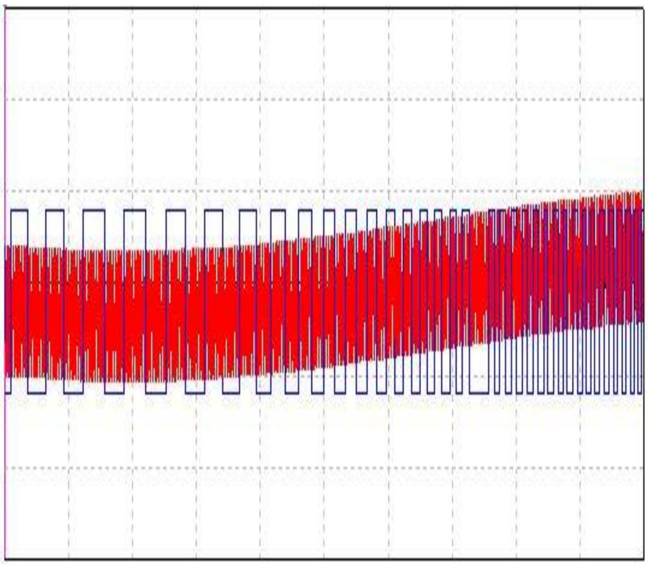

Fig 12 Frequency variation from switching frequency is 600Hz at maximum modulation index

V. DECISION RESULTS

The PWM switching frequency has to be much faster than what would affect the load, which is to say the device that uses the power. Typically switching's have to be done several times a minute in an electric stove, 120 Hz in a lamp dimmer, from few kilohertz (kHz) to tens of kHz for a motor drive and well into the tens or hundreds of kHz in audio amplifiers and computer power supplies.

switching frequency speed has extended power conversion switching bipolar transistor to beyond 100kHz, in hard switching. With soft switching techniques such as zero voltage switching (ZVS) and zero current switching (ZCS), the switching frequency can exceed Mega Hertz. As switching frequency moves upward power MOSFET parasitic parameters such as inductance and capacitance should be well defined and understood in order to optimize the particular power conversion design. This design tip focuses on explaining the power MOSFET output capacitance Coss and how it actually affects the power conversion circuit.

Other capacitance's such as input capacitance Ciss, and reverse transfer capacitance Crss, and the related gate charges have been well explained in previous.

An International Rectifier publication in hard switching circuits, Coss is used, to calculate the additional power dissipation of power MOSFET due to discharging this output capacitor every switching cycle.

In soft switching circuits, Coss may be used to calculate the resonant frequency or transition time which is critical in establishing ZVS and/ or ZCS conditions. Unfortunately the value of Coss varies non-linearly as a function of drain to source voltage Vds The value of Coss specified in most.

Vds of the device under test (DUT) starts rising, Coss is being charged by the 100kW to Vdd of 600V The time it takes for Vds to rise from zero to 480V, which is 80% of rated Vdss, tc is measured. Coss effective is then calculated per following equations,

$$Vc \;=\; Vdd\left(1 - e^{-t/RC}\right) = 480\,\mathrm{V} - - - - (4)$$

Where t is the measured tc, R = 100kW and C is Coss effective. Solving for Coss effective:

Coss effective = 6.21* t_c pF, t_c is in µs------------------ (5)

The classical LC resonant frequency equation,

$$f_r = \frac{1}{2\pi}\sqrt{L_r C_r} - - - - - - - - - - - - - - (6)$$

Equation (6) is used in many modern power converter circuits where the MOSFET Coss effective may be whole or part of the resonant capacitance.

Each time the MOSFET turns on, the energy stored in the output capacitance will be dissipated in the device, with Coss at the Vds voltage prior to turning on this energy equal to,

$$E \;=\; ½\, Coss\, Vds^2 - - - - - - - - - - - (7)$$

As the switching frequency goes up the power dissipation, equation (8) in the MOSFET due to discharging this energy increases proportionately, which may become a limiting factor in hard switching topologies.

$$Pd \;=\; E\; x\; fs - - - - - - - - - - - - - - - (8)$$

VI. CONCLUSION

The ultrasonic PWM – MOSFET inverter offers advantages compared with the inverters switched frequency at a few Hz. These advantages are a small filter component for input of inverter, elimination of low order harmonics and therefore reduction torque pulsation, when used to drive electric motors and a minimal acoustic noise.

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