Switched-Capacitor Filter for Analog Realization of a Sinusoidal Pulse Width Modulated Induction Motor Drive

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ABSTRACT

An analog implementation of a variable amplitude/frequency controller for a single phase DC-AC inverter with emphasis on its application for induction motor speed control is presented. A clocked switched capacitor filter is used along with an operational amplifier integrator and a comparator to generate the bipolar sinusoidal PWM pulses for the output drive. Variable frequency of operation is achieved by controlling the clock of the main controller while effective output voltage is automatically varied by the amplitude modulation ratio. It is demonstrated that the technique used is a novel and cost-effective approach in DC-AC inverter frequency control and has advantages over microcontroller-based and DSP-based methods. This paper describes the basic concepts of the above VVVF-SPWM and preliminary test results of the prototype controller used for the experiment, which was constructed by integrating the controller with the associated driver, full bridge inverter (H-bridge) and deadtime controller.

Index Terms – SPWM, switched capacitor filter, VVVF, DC-AC inverter, amplitude modulation ratio.

I. Introduction

A robust system for varying the frequency of AC drives is needed. The main utilization of this type of inverter is in AC motor drive applications [1] and in controlled rectifier applications for DC-AC conversion devices [2]. AC induction motors are the workhorses of the industry yet there are serious limitations in its characteristics, such as difficulty in controlling its speed. Recently, a number of control methods have been proposed but there are trade-offs in terms of efficiency, simplicity and cost. Pulse Width Modulation (PWM) techniques have been employed for many DC-AC drive applications due to their low ripple current, well-defined harmonic spectrum [3], and control of the output amplitude [4]. We employ the bipolar triangle intersection Sinusoidal PWM (SPWM) technique [5] in our implementation instead of digital pulse programming techniques [6]. Previously, we consider analog-based techniques to have high accuracy and high bandwidth, but require high precision components [7] and is not suitable for additional microprocessor-based implementation when various sinusoidal voltages and frequencies are required in the system [4]. Microprocessor-based methods are free from drift, disturbance, and easily manipulated but online PWM computation is considered laborious and time-consuming [8]. EPROM-based designs, then again, are dependent on a great deal of memory and thus, are characteristically, more expensive and (they) take longer to implement [9].

1.1. The Novel Analog Approach

The proposed analog SPWM controller can be used for generating variable voltage/frequency (VVVF) sinewaves with low-cost and sufficient flexibility for further analog or digital host interfacing. The proposed hardware platform can be used to implement various SPWM techniques, but in this discussion the bipolar triangle intersection method is used. The approach described in this paper will deliver a unified solution to provide a VVVF drive suitable for a motor operating at low speed where both voltage and frequency are simultaneously varied linearly. It will be evident in this discussion that the analog method proposed is more appealing than the use of complicated digital-based techniques. The proposed SPWM scheme will utilize a straightforward analog implementation of the major blocks for the controller. The experimental results obtained will verify that the method described in this paper to be a novel, low-cost, and elegant solution in the design of the controller. The use of waveshaping techniques through simple filtering topologies and will enable fast online variation of the dynamic response suitable to deliver the reference signals needed for the output drive. It will also be shown that the use of a switched capacitor filter (SCF) as a low-pass filter (LPF) is the key to the analog realization of the controller, sufficient in our application to convert a squarewave to a near-perfect sine by filtering out its higher order harmonics. Moreover, its use as a LPF that has a clock-variable cutoff frequency cannot be underemphasized. Novel integrator configurations are readily available and we use the most basic JFET input operational amplifier to implement this. All signals, including inputs for the filter and integrator, are derived from a universal 50% duty squarewave clock and can come from most familiar oscillators (a voltage-controlled oscillator or from microprocessor outputs).

1.2. Brief Review of Bipolar PWM

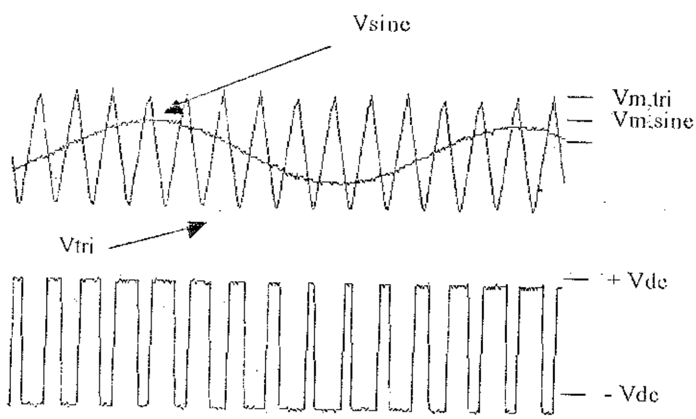

Figure 1. Bipolar SPWM associated waveforms.

Figure 1 illustrates the principle of sinusoidal bipolar pulse-width modulation. The figure shows the associated waveforms where a sinusoidal signal V sine serves as a reference and a triangular wave V tri serves as the carrier signal. Both are instantaneously compared to produce the alternating plus(+) and minus(-) DC supply after driving a full-bridge inverter. We state some definitions and considerations:

1) Frequency modulation ratio m_f: The ratio between the frequencies of the carrier and reference where the m_f is either odd or even and usually greater than 1. Depending on m_f being odd or even, the output will either be a Fourier sine or cosine series.

m_f =f tri / f sine (1)

The Fourier series of the PWM output has a fundamental frequency which is the same as that of the reference sine signal. Harmonics exists at and around multiples of the switching frequencies.

2) Amplitude modulation ratio m_a : This is the ratio between the peak of the reference signal Vm,sine and the peak of the carrier signal Vm,tri.

m_a =Vm,sine / Vm,tri (2)

If m_a is less than 1, the amplitude of the fundamental frequency of the output voltage is linearly proportional to m_a ,i.e. the effective AC output is

$V_{FUNDAMENTAL} = m_a$ Vdc (3)

II. Controller Architecture

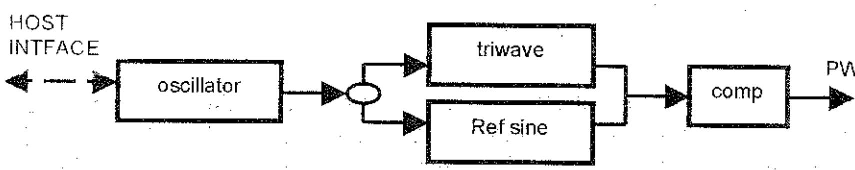

Figure 2. Simplified block diagram of controller

The simplified block diagram of the SCF-based VVVF controller is shown in Figure 2 while a more detailed diagram is shown in Figure 3.

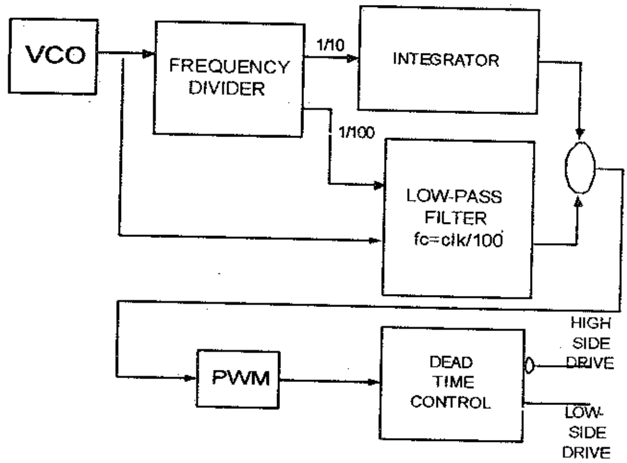

Figure 3. Detailed block diagram of the SPWM controller

2.1. Carrier Triangle Wave Generator

The integrator produces the carrier wave modulating signal. This is implemented using a JFET op-amp (LF353) with appropriate DC-rejection circuits to reshape the input clock-derived squarewave signal into the triangle wave carrier. By using the described integrator circuit, the produced triangle wave will retain its positive-going and negative-going slopes no matter what frequency it operates, such that only the amplitudes/peaks of the output triangle wave changes. Thus, as its input frequency changes from high to low and v.v., so does its output peak vary inversely. Intuitively, when the operating frequency is low enough , clipping will occur such that the output has a voltage swing less than the true peak. We extend the slopes to produce the effective triangle wave and its consequent effective peak Vm,tri. This is illustrated in Figure 4. As the top and bottom of the triangle wave is clipped, it will be of no consequence since the only important part, from the electronic point of view, is its intersection with the reference sinewave as shown in Figure 5. The Vm,tri at sufficiently low frequencies where clipping occurs, can be approximately related to the slope(m), and the triangle wave frequency by:

$$V_{m,tri} = m / 200f \qquad (4)$$

Refer to Figure 6 for the approximation of Vm,tri at low frequencies and the whole frequency range.

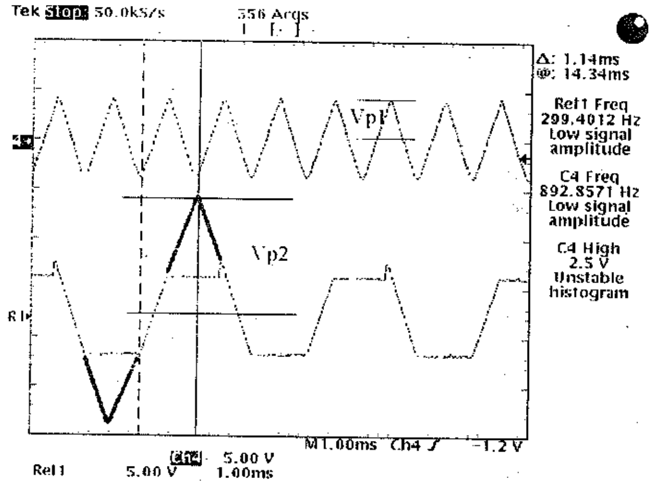

Figure 4. Illustration of acquiring the effective peak even after clipping where Vp1,2 = Vm,tri

2.2. Reference Sinewave Generator Using the Switched Capacitor Filter

An LPF is needed to derive the sinewave reference from the squarewave clock. Again, after AC-coupling another clock-derived squarewave input, the 6 th order Butterworth SCF (MF6-100) is chosen to produce the reference sinewave. Recall that a squarewave is just a superposition of harmonics of sinusoids and that by filtering out the higher order harmonics, the result will be a sufficiently clean sinusoid at the fundamental frequency. Since the MF6 has a clock-tunable corner frequency, with the cutoff having a ratio of 1:100 with respect to the separate clock input. Hence, for our application, since we vary the cutoff as we vary the input, there will be no associated attenuation at the output and we will produce a sinewave that has constant amplitude throughout the operating region. We note further that since the both sinewave and triangle waves are clock-derived, we have a constant *m f* while the *m a* will vary directly with the frequency. The non-changing amplitude of the reference and the subsequent variation of the *m a* will be evident in Figure 7.

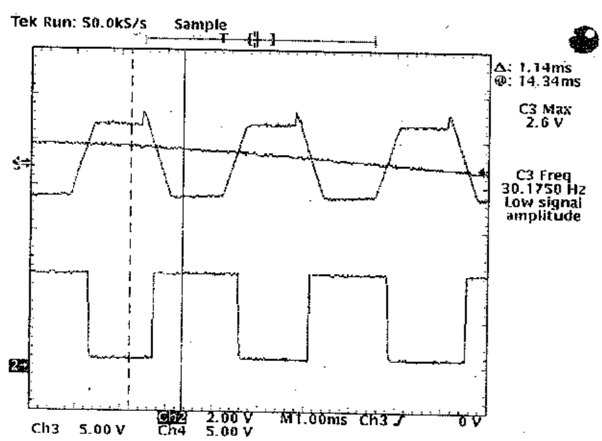

Figure 5. Triangle intersection technique

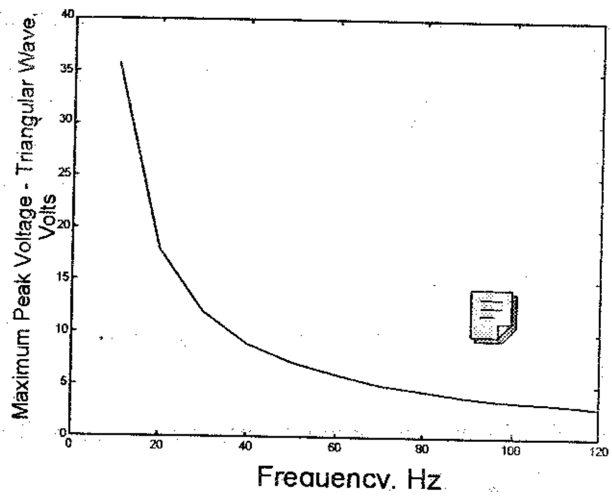

Figure 6. Vm, tri as frequency is varied

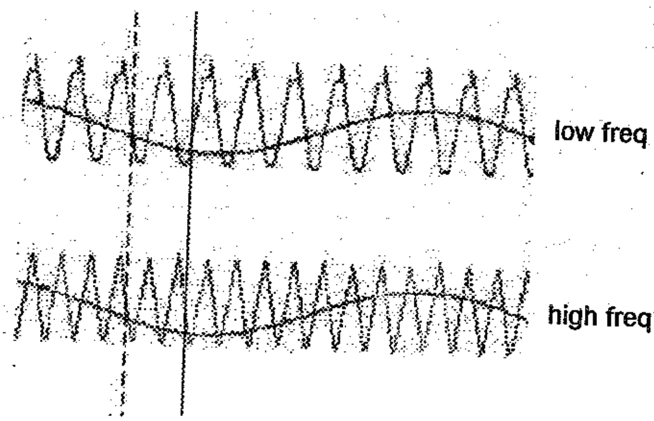

Figure 7. Reference amplitude remains constant while Vp changes inversely with frequency

2.3. Clock Generator and Frequency Divider

Two decade counters (CD4017) are cascaded to produce the frequency divider block which produces the clock÷10 integrator input and the clock÷100 SCF input. The clock frequency itself will drive another SCF input. To ensure 50% duty throughout the operation, a JK flip-flop is used as a frequency divider and as the source of the clock signal. The input of the clock, which can come from a VCO or from an external host microprocessor, is therefore twice the system clock. Although the produced AC output frequencies from 0 to 120Hz are realizable, physical limitations of the motor, however, dictate that we operate the AC drive from 30 to 100Hz only. Operating the controller high enough will tend to make the m_a >1 such that the output will be overmodulated and not vary linearly with the m_a. A number of overmudulation schemes have been discussed [10] but these are not employed in this research.

2.4. Deadtime Controller

Cross-conductance will be prevented by implementation of a simple RCD and Schmitt inverter (74LS14) circuit as shown in Figure 8. For our application, after considering the rise and fall time characteristics of the inverter switches (IRF9530 and IRF840), a minimum deadtime of 1ms will be enough to ensure no cross-conduction. We need to produce complementary SPWM signals to drive the high-side and low-side switches of the inverter bridge. Calculating approximate values for the appropriate deadtime, we solve for RC:

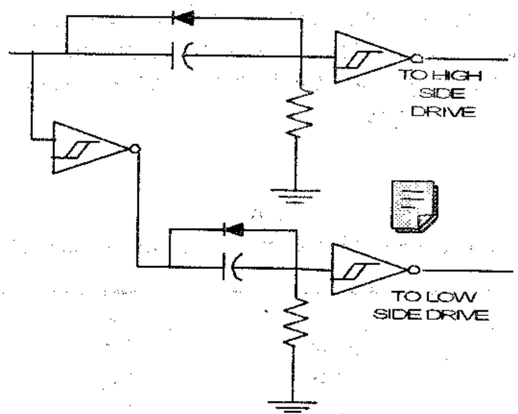

Figure 8. Deadtime control via Schmitt triggers

Minimum pulsewidth = (@*1KHz* switching) *1ms*
Deadtime = t = *1ms*
Von = Schmitt trigger setpoint = *2v*

$$Von = Vf - (Vf - Vi)\exp(-t/RC) \quad (5)$$

The simplified schematic diagram of the bipolar SPWM controller is shown in Figure 9.

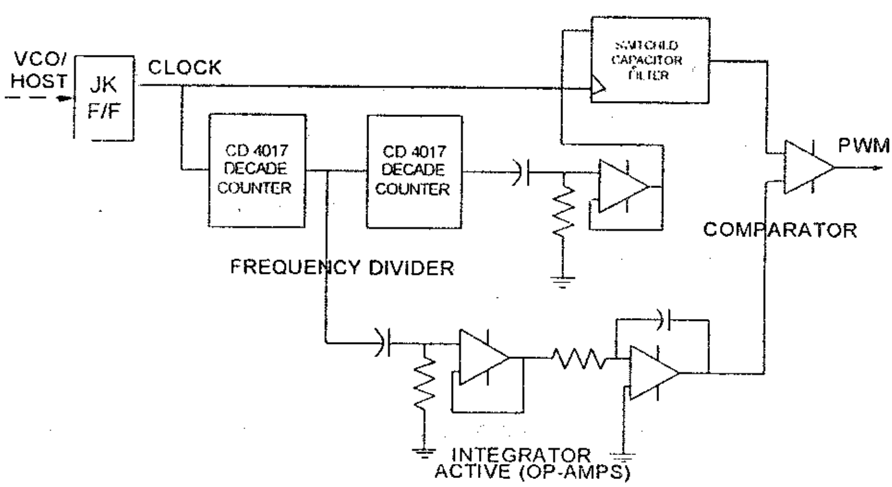

Figure 9. Schematic diagram of controller

III. Discussion of Results

It is not usually needed to provide a pre-filter for motor drives since the motor itself can be considered the output filter. Large harmonics will only occur at very high multiples of the fundamental/output frequency and are easily filtered either by the inherent motor winding inductors or additional output pre-filters as needed. The controller output can be considered to be essentially the output of the drive since their switching patterns are identical. We compare the frequency spectrums of a sinusoid and the SPWM from the controller in Figures 10 - 12 at different frequencies of operation. It will be noticeable that as the operating frequency decreases, the effective output amplitude also decreases and v.v. . The output VAC can be related to m_a by deriving it from equation (3) where $V_{FUNDAMENTAL} = VAC\sqrt{2}$. The m_a and VAC at low frequencies can readily be calculated from equation (4). Refer to Table I for the measured Vm,tri and corresponding VAC with the DC link at 311v, resulting from direct unregulated AC-DC conversion of the 220Vrms mains. The induction motor is a capacitor shunt motor rated at 110V, hence, we choose the VAC for the most part of the operating frequency, not to exceed the rated voltage by more than 50%. From Figure 13, we verify that the effective output voltage drops as frequency decreases--a desirable characteristic of an AC motor drive.

Table 1
Computation for m_a and VAC =Vo/√2 with Vm,sine = 2.24 and Vdc = 311

Freq(Hz)	Vm,tri	m_a	m=slope	VAC= m_a Vdc/√2
90	3.92	0.5714	70560	125
100	3.62	0.6188	72400	136
110	3.24	0.6914	71280	152
120	3	0.7467	72000	164

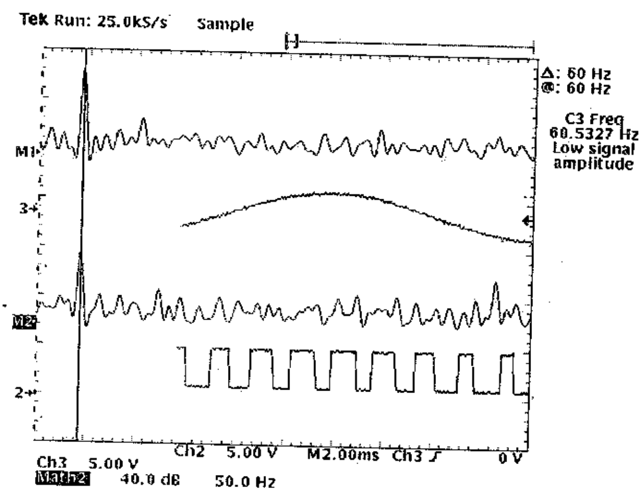

Figure 10. Comparative spectrum between sinusoid reference and SPWM at 60Hz

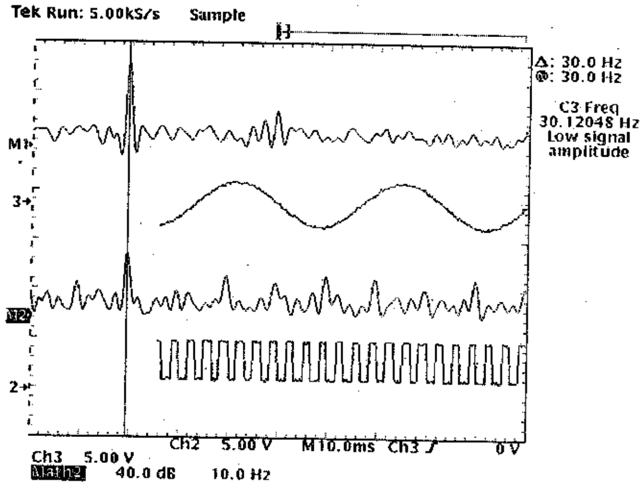

Figure 11. Comparative spectrum between sinusoid reference and SPWM at 30Hz

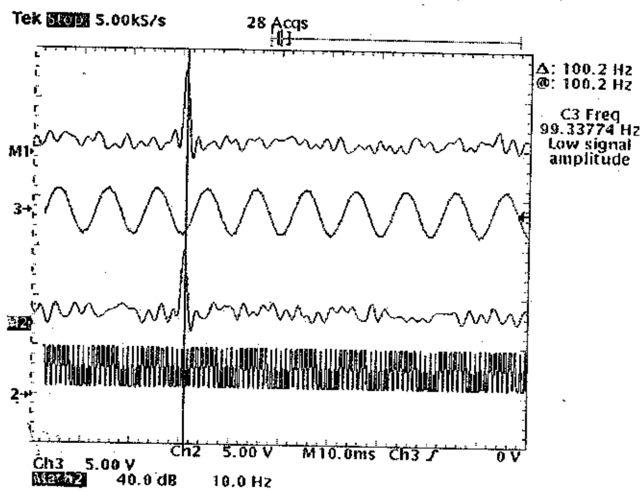

Figure 12. Comparative spectrum between sinusoid reference and SPWM at 100Hz

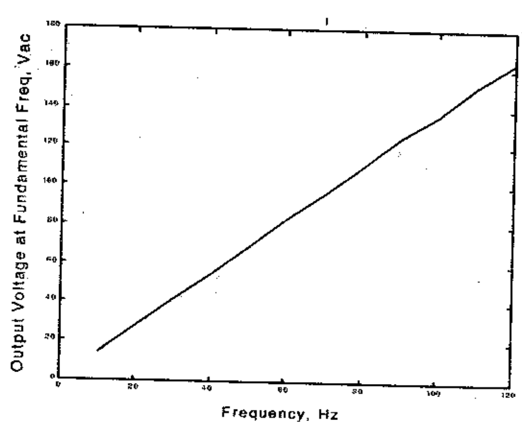

Figure 13. Output voltage related to operating frequency

IV. Conclusions

This paper proposes a novel single-phase VVVF inverter controller that is implemented using low-cost op-amps, SCF, and TTL logic circuitry. It was demonstrated that the output of the controller exhibited close to true sinusoidal output via bipolar SPWM. Features of the circuit include an intuitive and unified approach to variable voltage motor speed control at low frequencies, flexibility of obtaining control and feedback data from either analog/mixed-signal VCO, or microprocessor/digital interfacing. The controller achieves variable frequency operation by modifying the single input clock reference. The proposed circuit architecture has significant advantages over various digital-based techniques in terms of simplicity and cost-effectiveness as per performance. The proposed hardware implementation is a particularly attractive tradeoff between programmability and robustness. It has a reasonably high linearity in the frequency range where there is no overmodulation.

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