A Novel SPWM VVVF AC Drive Using a Discrete Analog Approach with SCF

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ABOUT THE AUTHOR

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This article presents an analog implementation of a variable amplitude/frequency controller for a single-phase DC-AC inverter, with emphasis on an application for induction-motor speed control. The circuit uses a clocked switched-capacitor filter along with an operational amplifier integrator and a comparator to generate the bipolar sinusoidal PWM pulses for the output drive. We demonstrate variable frequency of operation by controlling the clock of the main controller while using the amplitude modulation ratio to automatically vary the effective output voltage. We show that this technique is a novel and cost-effective approach to DC-AC inverter frequency control and has advantages over microcontroller-based and DSP-based methods. This paper also 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 dead-time controller.

Introduction
There is a need for a robust system for varying the AC frequency of a circuit. The main use for this type of inverter is in AC-motor drive applications and in controlled-rectifier applications for DC-AC conversion devices. AC induction motors are the workhorses of the industry, yet there are serious limitations in the characteristics of such motors, such as difficulty in controlling their speed. Recently, a number of control methods have been proposed, but there are tradeoffs 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, and control of the output amplitude. We employ the bipolar triangle-intersection Sinusoidal PWM (SPWM) technique in our implementation in place of digital-pulse programming techniques. We previously considered analog-based techniques to achieve high accuracy and high bandwidth, but these techniques require high precision components and are not suitable for additional microprocessor-based implementation when the system needs various sinusoidal voltages and frequencies. Microprocessor-based methods are free from drift and disturbance, and are easily manipulated, but online PWM computation is considered laborious and time-consuming. EPROM-based designs need a great deal of memory and, thus, are characteristically more expensive and take longer to implement.

A Novel Analog Approach
You can use the proposed analog SPWM controller for generating variable voltage/frequency (VVVF) sine waves at low cost and with sufficient flexibility for further analog or digital-host interfacing. You can use the proposed hardware platform to implement various SPWM techniques, but in this discussion we use the bipolar triangle-intersection method. The approach this paper describes 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. The proposed SPWM scheme will utilize a straightforward analog implementation of the controller's major blocks. The experimental results we obtain will verify that the method described in this paper is a novel, low-cost, and elegant solution in the design of the controller. The use of wave-shaping techniques through simple filtering topologies enables fast online variation of the dynamic response suitable for delivering the reference signals needed for the output drive. We will also show that the use of a switched-capacitor filter (SCF) as a low-pass filter (LPF) is key to an analog realization of the controller, sufficient in our application to convert a square wave to a near-perfect sine wave by filtering out the waveform's higher-order harmonics. Moreover, the controller's use as a LPF that has a clock variable-cutoff frequency cannot be over-emphasized. Novel integrator configurations are readily available and we use the most basic JFET input operational amplifier to implement this function. All signals, including inputs for the filter and integrator, are derived from a universal 50% duty cycle square-wave clock and can come from most familiar oscillators, such as a voltage-controlled oscillator or from microprocessor outputs.

Brief Review of the Bipolar PWM

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 waveforms are compared instantaneously to produce the alternating plus (+) and minus (-) DC supply after driving a full-bridge inverter. Some important definitions and considerations follow:

1. **Frequency-modulation ratio \( m_f \):** The ratio between the frequencies of the carrier and reference
where the $m$ is either odd or even and is usually greater than 1. Depending on $m$ being odd or even, the output will either be a Fourier sine or cosine series. $m = f_{\text{tri}} / f_{\text{sine}} \quad (1)$

The Fourier series of the PWM output has a fundamental frequency that 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 $V_{\text{m,sine}}$ and the peak of the carrier signal $V_{\text{m,tri}}$. $m_a = V_{\text{m,sine}} / V_{\text{m,tri}} \quad (2)$

If $m_a$ is less than 1, the amplitude of the fundamental frequency of the output voltage is linearly proportional to $m_a$; in other words, the effective AC output is $V_{\text{FUNDAMENTAL}} = m_a V_{\text{dc}} \quad (3)$

Controller Architecture

Carrier Triangle-Wave Generator
The integrator produces the carrier-wave modulation signal. This is implemented using a JFET op-amp (LF353) with appropriate DC-rejection circuits to reshape the input clock-derived square-wave 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 at what frequency it operates, such that only the amplitudes/peaks of the output triangle wave change. Thus, as the wave's input frequency changes from high to low and conversely, the output peak varies inversely. Intuitively, when the operating frequency is sufficiently low, 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 $V_{\text{m,tri}}$—this is illustrated in Figure 3. 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 viewpoint, is its intersection with the reference sine wave. The $V_{\text{m,tri}}$, at sufficiently low frequencies where clipping occurs, can be approximately related to the slope ($m$), and the triangle wave frequency by:

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

Refer to Figure 4 for the approximation of $V_{\text{m,tri}}$ at low frequencies and over the entire frequency range.

Reference Sine-Wave Generator Using a Switched Capacitor Filter
You need an LPF to derive the sine-wave reference from the square-wave clock. Again, after AC-coupling, another clock-derived square-wave input, the 6th-order Butterworth SCF (MF6-100), is chosen to produce the reference sine wave. Recall that a square wave is just a superposition of sinusoidal harmonics and that by filtering out the higher-order harmonics, the result will be a sufficiently clean sinusoid at the fundamental frequency. 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 sine wave that has constant amplitude throughout the operating region. We note further that since the both the sine wave and triangle waves are
Clock-derived, we have a constant \( m_a \) while the \( m_a \) will vary directly with the frequency. The non-changing amplitude of the reference and the subsequent variation of the \( m_a \) are evident in Figure 5.

**Clock Generator and Frequency Divider**

Two decade counters (CD4017) are cascaded to produce the frequency divider block that produces the clock10 integrator input and the clock100 SCF input. The clock frequency itself will drive another SCF input. To ensure a 50% duty cycle 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. Operating the controller at a high enough frequency will tend to make the \( m_a > 1 \) such that the output will be over-modulated and not vary linearly with the \( m_a \). A number of over-modulation schemes have been discussed\(^{10}\), but these are not employed in this research.

**Results**

You usually do not need 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 inductance or by additional output pre-filters. You can consider the controller output 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 6 and 7 at different frequencies of operation. Note that as the operating frequency decreases, the effective output amplitude also decreases and conversely. The output VAC can be related to \( m_a \) by deriving it from Equation 3, where \( V_{FUNDAMENTAL} = V_{AC}\sqrt{2} \). The \( m_a \) and VAC at low frequencies can readily be calculated from Equation 4. Refer to Table 1 for the measured \( V_{m,tri} \) and corresponding VAC with the DC link at 311v, resulting from direct unregulated AC-DC conversion of the 220V\(_{rms} \) main voltage. The induction motor is a capacitor-shunt motor rated at 110V, hence we choose the VAC, for most of the operating frequency, not to exceed the rated voltage by more than 50%. From Figure 8, we verify that the effective output voltage drops as frequency decreases—a desirable characteristic of an AC motor drive.

<table>
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<tr>
<th>Freq. (Hz)</th>
<th>( V_{m,tri} )</th>
<th>( m_a )</th>
<th>( m=slope )</th>
<th>VAC=m_a/Vdc/\sqrt{2}</th>
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<td>72000</td>
<td>164</td>
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Conclusions

This article proposes a novel single-phase VVVF inverter controller using low-cost op-amps, SCF, and TTL-logic circuitry. We showed that the output of the controller exhibited close to true sinusoidal output via a bipolar SPWM. Features of the circuit include an intuitive and unified approach to variable-voltage motor-speed control at low frequencies, control flexibility, and feedback data from either an 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. The proposed hardware implementation is a particularly attractive tradeoff between programmability and robustness. The implementation has reasonably high linearity in the frequency range where there is no over-modulation.

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