

Reinventing the Power Amplifier - BCA

THE BALANCED CURRENT AMPLIFIER - A NEW PARADIGM FOR THE 21ST CENTURY

In 1931 Loy Barton, a research worker employed by David Sarnoff, unearthed the paradigm that has dominated all electronic power amplifiers used for audio reproduction and industrial power to this present day. Many incremental additions have embellished Loy's original invention since its inception. The embellishments have many names, ultra-linear, Williamson, full complementary, quasi-complementary, quasi-linear, class-G, class-H, grounded-bridge, class-D, etc.

One common thread in all of the above is the use of push-pull circuitry. Loy did not invent push-pull circuitry. Class-A push-pull amplifiers were around before 1931 and were used whenever larger output powers were needed than could be derived from a single device vacuum tube output stage. Loy was the first to describe class-B push-pull amplifiers which he developed to power both the large audio modulators of AM broadcast stations and the output stages of home radios. Both applications had a common need, the need to produce more high-quality power output with less electricity and natural resources.

In 1931 Loy Barton published "High Audio Output from Relatively Small Tubes" in the Institute of Radio Engineers proceedings. The very theme of the article is in harmony with the goals of every designer who has ever wrestled with the power amplifier problem of wanting unlimited output power from a small box of affordable cost. There are some things which do not change.

One thing has changed since 1931 and that is the variety of electronic devices which are available to implement circuits. The original electronic power devices were vacuum tubes which were characterized by large output impedance's and high saturation resistance's. They made poor power switches and were most useful when used with transformers to match their output impedance's to lower impedance loads such as loudspeakers. Today's solid-state devices such as power MOSFETs offer characteristics which are most appropriate to make high-speed switches, not linear output stages as practiced by Loy.

Loy's genius was to operate the two tubes of his class-B output stage in strict time alternation. To produce one polarity of output current he would turn on one tube; to produce the other polarity of output current he would turn on the other tube. Previously with class-A designs, both tubes were always turned on and even at no signal were dissipating large amounts of quiescent power. By

careful selection of the class-B bias point, he was able to produce essentially undistorted output without having a massive quiescent power loss. This greatly increased the power output that could be obtained from a pair of tubes and reduced the wastage of electricity.

While many variations on this basic theme have been developed since 1931, Loy's class-B paradigm has survived unchallenged. Operation of the push-pull power devices in time alternation has been part of all high performance designs for the last 66 years. Even when the devices became class-D PWM (Pulse Width Modulation) switches, they were operated using the class-B paradigm, first one on and then the other, in strict time alternation.

While switching and PWM methods are the methods of choice to all modern power electronics engineers, PWM amplifiers have remained relatively useless for precision power amplification. Ironically the class-B paradigm lies at the heart of the problem.

To produce a class-D PWM amplifier with low amounts of distortion near zero output current, it has been necessary to operate the time alternating power switches with very precise sequencing of the two switches. If the switches have any dead time (no switch on) between their activation large amounts of distortion will form. If they overlap, the circuitry would self-destruct with large amounts of shoot-through current. The circuitry has been designed around the paradigm and is therefore not tolerant of any violation of time alternation.

So pervasive has been the paradigm that it has gone unchallenged until now. While Loy's class-B paradigm has served us all well for most of a century, its days are numbered.

With a marked bifurcation in design concept, the paradigm for the next century uses simultaneous activation of its push-pull switches and has been appropriately dubbed a "Balanced Current Amplifier". This is the very antithesis of the time alternation paradigm.

In the Crown BCA design, when there is no intended output signal, the power switches are being turned on and off simultaneously with a 50% duty cycle. The result is the formation of two balanced and canceling high-frequency output currents with no output at the no-signal condition.

To produce an output signal the output of one of the switches is increased in duty while the remaining switch

is decreased by the same amount. Both pulses remain centered on each other or balanced in time. The result is that the difference ripple current has a minimum frequency which is twice the operating frequency of the individual switches.

The frequency doubling character of the output is remarkable and further allows advancement towards Loy Barton's goal of more from less. The switching losses are effectively halved by this property as it is only necessary to switch at 250KHz to make a 500KHz amplifier! The result is that the operating frequency is taken to its theoretical maximum of N (the number of switches) \times f_s (the switching frequency). This is a full factor of two faster than any known previous design.

The modulation process makes two decisions per switching cycle for each switch, as both the turn-on time and the turn-off time are independently controlled by the modulator. A 250KHz Crown BCA design thus has one million switch decisions made each second. This is what is required for full bandwidth audio operation. Previous to the BCA the conventional wisdom correctly held that any full-bandwidth audio amplifier would need operate at 500KHz. Low quality or limited bandwidth PWM designs have operated at lesser frequencies.

The result of the new paradigm is a convection cooled 2.5KW amplifier which mounts in two rack spaces. This is approximately an order of magnitude larger amplifier than could have been built previously in the same space without any cooling fan. With no fan there is no need for filter maintenance, no fan noise and no contamination of the unit resulting from normal use.

The Crown K2 amplifier has all of the nearly ideal power converter attributes of class-D PWM amplifiers in that reactive loads such as loudspeakers are easily driven. The reactive energy returned from the load to the amplifier is reabsorbed and reoutput with little loss. Non-switching amplifiers are forced to dissipate all of the returned energy plus much more (the latter ratio is a function of the topology used) and is typically three fold or more.

Difficult loads are driven with grace and ease. Current overload is smooth and sonically identical to voltage overload. Thermal overload is rendered a thing of the past as it is difficult to produce large amounts of heat. Conventional amplifiers tackling the same difficult loads become overloaded within minutes

and become sonically dysfunctional with either large amounts of distortion or shutting off entirely. The result is that a BCA output Watt is operationally larger than that of previous amplifier designs.

Real-world high power operation of most large amplifiers reveals that rated bench Watts and distortion ratings often bear little if any relationship to what can be sustained under normal field conditions by the typical user using loudspeakers and music.

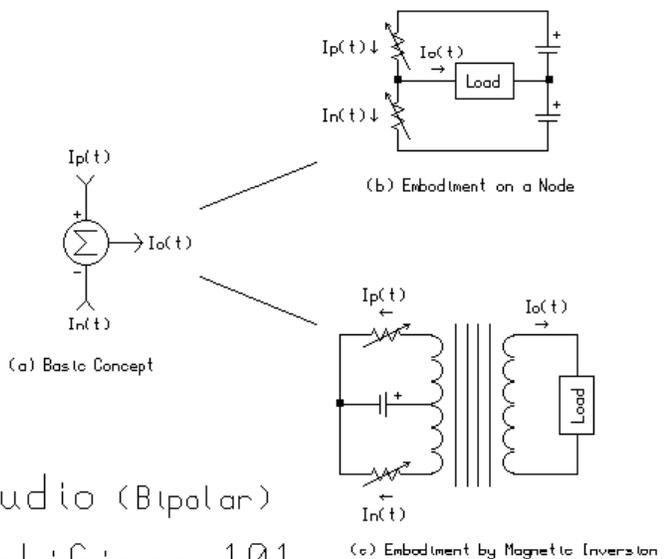
In critical studio environments the K2 is sonically flawless and will outperform the best large studio amplifiers in that it does not have the one sonic flaw that any unit with a low-speed fan has fan noise. The K2's over 100dB of electrical signal to noise (A-weighted) is not rendered superfluous by fan noise.

With a low-frequency damping factor of over 10,000 and low distortion ($<0.1\%$ THD), the K2 is ready to give your music the quality of presentation that it deserves.

One final footnote: One (the larger) of Loy Barton's 1931 design examples was a 2.5KW amplifier. Ironically there are some things that do not change, no matter which century's paradigms are in force.

PUSH-PULL

The basic concept of push-pull amplification is quite old (1920's) and can be described as an amplifier in which there are two similar signal branch circuits operating in phase opposition and whose outputs are combined in a difference (summing) circuit to produce an increased power output.

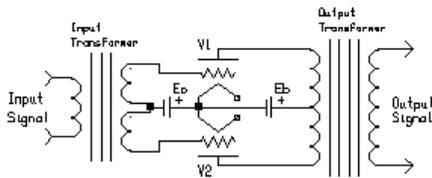
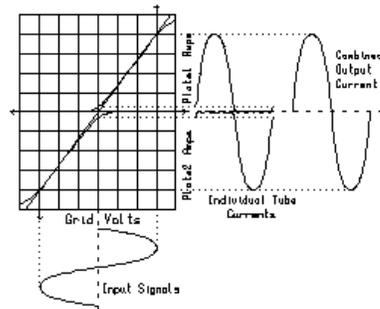


Audio (Bipolar)
Amplifiers 101

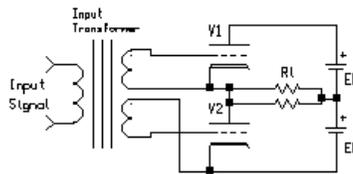
The simplest combining method is to join the output signals at a single circuit node. This is the method used in all power stages that are referred to in the jargon as a totem-pole, half-bridge or single-ended push-pull design. While combining at a node is the simplest method, it was not the method first used to produce push-pull power amplifiers.

The second and original method of combining the push-pull output signals was to use a magnetic device, a transformer with a center-tapped primary, to perform the differencing. Transformers had been in use previously to adapt the high output impedance of vacuum tubes to lower impedance loads. Power output was obtained at such a high cost that it was rarely permissible to operate a power stage with impedance mismatching.

Push-pull operation using a transformer with a center-



Class-B Push-Pull
(1931 Loy Barton)



Class-B Push-Pull
Totem-pole
(1944)

tapped primary as the combiner was particularly attractive as it also solved a problem implicit to transformer-coupled designs. It was now possible to minimize (cancel) the DC magnetizing force produced by the quiescent bias currents in the primary. The output transformer became smaller and less expensive as a consequence. Larger low-frequency outputs were possible before core saturation would cause significant distortion.

The invention of the half-bridge power stage was not documented until the 1940's. Vacuum tubes were still the only power devices available, but applications and circuit design were continuously becoming more diverse. Fundamental things were slowly but surely coming to the fore.

PARADIGMS

The push-pull paradigm is part of the Crown BCA design while the class-B paradigm is not. The distinction is that the class-B paradigm is taken to include both the push-pull concept and the notion of strict time alternation of the active devices used to effect the push-pull power stage.

Push-pull operation is possible with the output of a power stage being a signal statistic and not an expression of the immediate state of the power devices used to create the signal statistic. Such is the case within the Crown BCA power stage.

Note that push-pull concepts in no way imply the operating efficiency of a power stage. The first push-pull amplifiers were very inefficient because they were class-A linear designs which by nature have large quiescent power losses. Loy Barton's class-B designs were still inefficient by switch-mode standards as the vacuum tubes were conductivity modulated to effect the power output of the stage. Large voltages were evident on the tubes during most of their conduction cycle and thus they dissipated (wasted) much power.

When the output signal becomes a signal statistic as in a PWM power stage, it is not necessary to retain the class-B paradigm to retain push-pull operation.

So then is there a class designator for the BCA paradigm? This author suggests class-I as a possible designator. Such a choice has a mnemonic tag in that the Crown BCA is implicitly an interleaved power stage. The chosen name for the overall

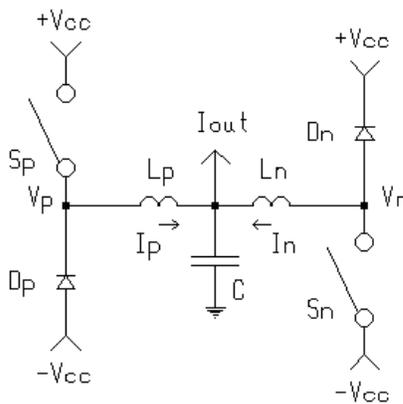
technology where interleaving is taken to its logical conclusions has been named OCIA (Opposed Current Interleaved Amplifier) technology.

BCA OPERATION

The following figures show the fundamental operation of the basic Crown BCA power amplifier. The switch commutation sequence is depicted by the Sp and Sn waveforms and the Vp and Vn waveforms are the switched voltages which are input to the main output inductors Lp and Ln. The currents Ip and In are the currents flowing in Lp and Ln respectively.

The quiescent switching sequence is for both output switches to enable and disable in unison (50% duty

Balanced Current Amplifier Output Stage



The converter is always biased such that current continuously flows in the output inductors which means that either a FET (S_p or S_n) or its companion free-wheeling diode (D_p or D_n) are conducting. The converter is said (in power conversion jargon) to be operating in CCM (continuous current mode). As such the V_p and V_n nodes are either at the $+V_{cc}$ or $-V_{cc}$ potential.

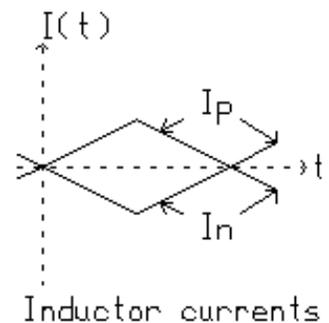
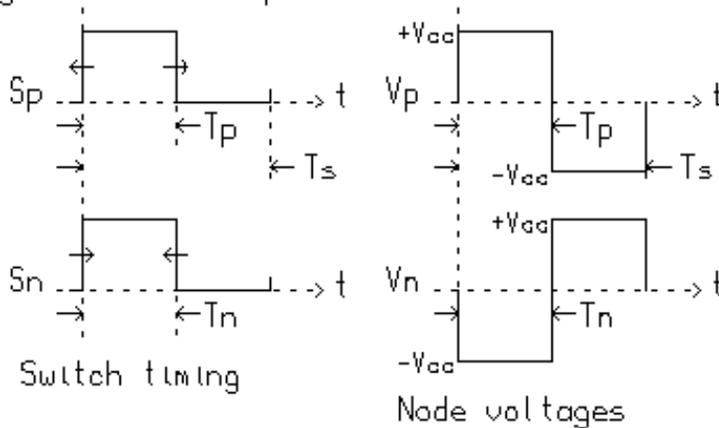
There is an equivalent circuit that can enlighten one's understanding of the circuit's operation. There are four state permutations of the MOSFET switches that can exist.

Two are states with one FET on, one with no FETs on and one with both FETs on. The equivalent circuit is composed of a three position switch which can either output $+V_{cc}$, ground or $-V_{cc}$ to an output inductor of value $L/2$ where $L=L_p=L_n$. This equivalent circuit will be switched to ground whenever both S_p and S_n switches are in the same state (on or off). If only one of the S_p and S_n switches is on, the equivalent circuit switch will be set to the supply polarity of the S_p or S_n switch which is on.

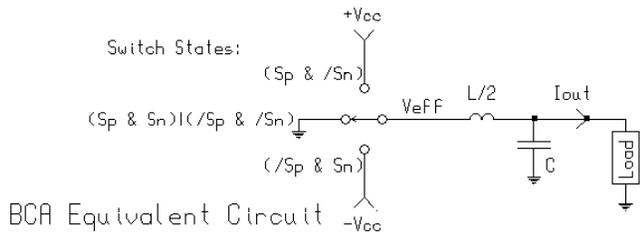
cycle). When the S_p and S_n switches are both closed during interval T_p (or T_n) the main output inductor current magnitudes increase at a rate of V_{cc}/L where $L=L_p=L_n$. When the switches are both off during the interval following T_p (equal to $T_p=T_s-T_p$), the inductor voltage is reversed and the output currents ramp down at the same magnitude. I_p and I_n are of equal magnitude but of opposite polarity, thus the output currents are said to be balanced and therefore the name Balanced Current Amplifier or BCA.

with no FETs on and one with both FETs on. The equivalent circuit is composed of a three position switch which can either output $+V_{cc}$, ground or $-V_{cc}$ to an output inductor of value $L/2$ where $L=L_p=L_n$. This equivalent circuit will be switched to ground whenever both S_p and S_n switches are in the same state (on or off). If only one of the S_p and S_n switches is on, the equivalent circuit switch will be set to the supply polarity of the S_p or S_n switch which is on.

Arrows on pulse edges indicate timing changes for (+) output



BCA Modulation



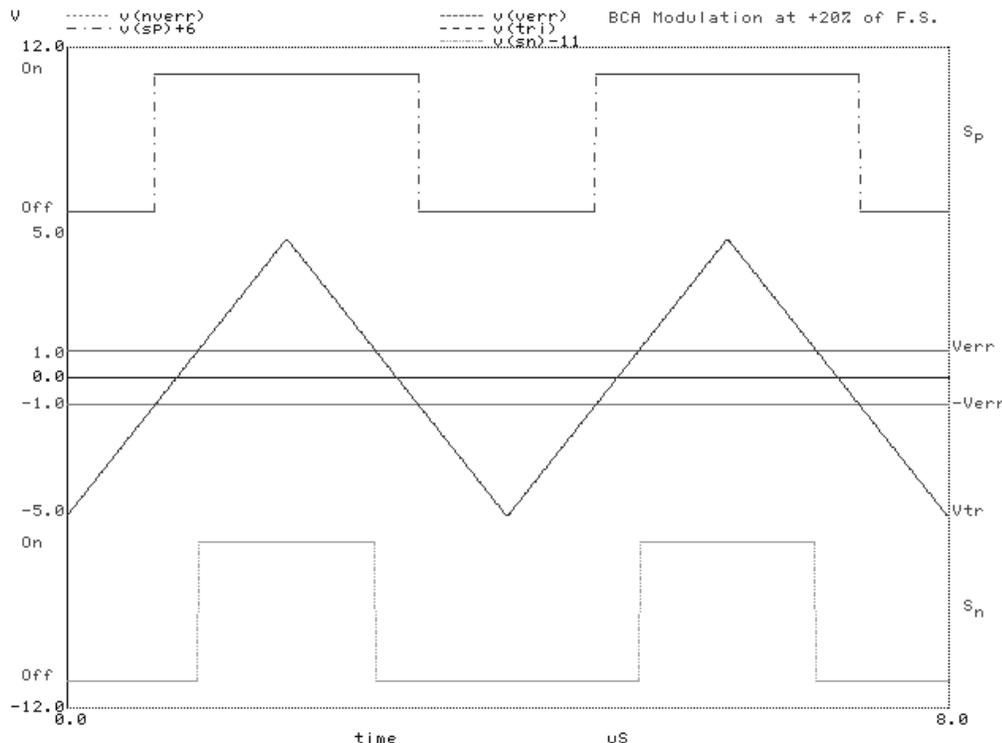
When the amplifier is at quiescent state with no output voltage, the equivalent switch will always be at the ground position as the switches are operating in unison, either being on or off with a 50% duty cycle. In other words $T_p = T_n = T_s/2$ where T_s is the inverse of the switching frequency, the switching period. If T_p is the period that S_p is on and T_n is the period that S_n is on, then $T_p + T_n = T_s$.

When the output is programmed to be positive, the S_p switch will enable before the S_n and disable after the S_n switch. The width of S_p (T_p) increases as the width of S_n (T_n) decreases. The total duty cycle of both switches is still set to 100% ($T_p + T_n = T_s$). When the S_p switch is on and the S_n is not, the equivalent output switch is set to $+V_{cc}$. Not until negative output is programmed will there be a case of having the S_n switch on and not the S_p switch. Therefore when producing a positive output,

the effective input voltage to the output inductor ($L/2$) is a unipolar pulse sequence at twice the basic switch operating frequency.

When a negative output is to be produced, there will not be a time when the S_p switch is on and not the S_n , thus the output will be a unipolar negative double frequency pulse sequence.

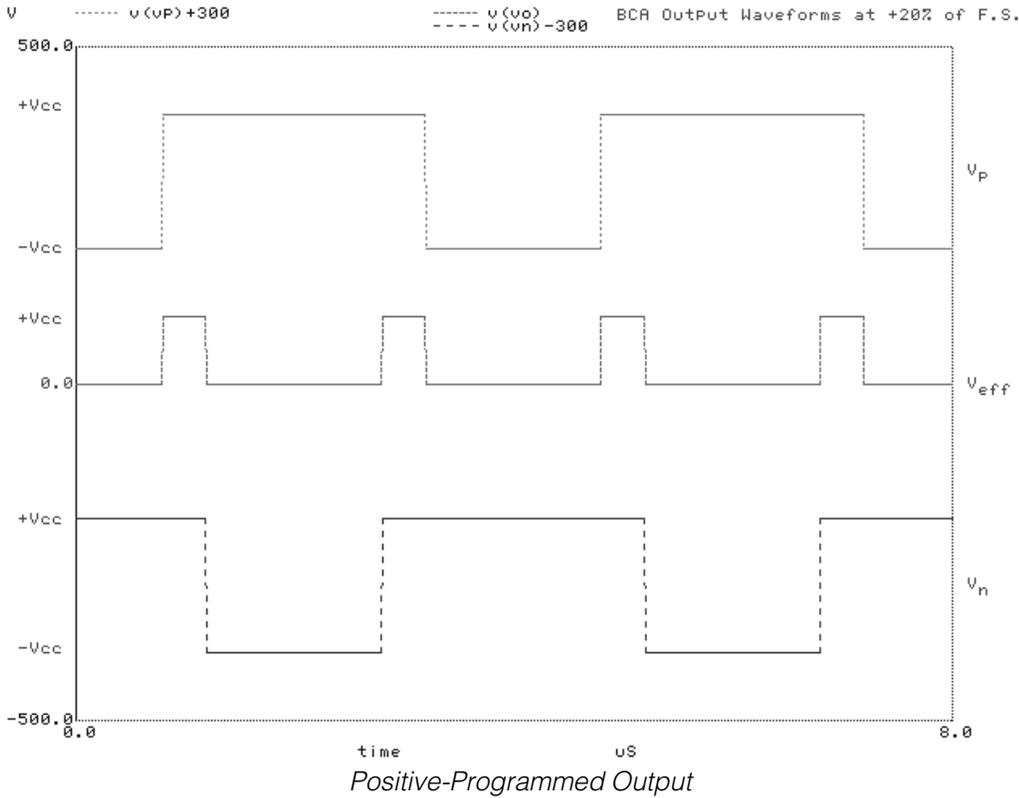
The suggested equivalent circuit reveals the low output ripple nature of the Crown BCA. A full null in the output ripple current occurs at zero output, the very state which is most commonly occupied by audio (and many other) signals. The effective output frequency is doubled without operating any switch at double frequency. Bridged output circuits are commonly understood to double the ripple frequency but note that they use four switches to obtain a doubling of frequency. When the BCA's output stages are used in a full-bridge, the output ripple frequency can be quadrupled. The trick is to operate the second half of the full bridge with phase quadrature modulation. The Crown BCA amplifier operates the two channels in phase quadrature which allows the balanced monaural output to have a 1MHz ripple frequency, yet no switch is operating at other than 250KHz. Since any given effective output pulse has two modulation decisions (one on each edge), the effective control sampling rate is 1Ms/S (Mega-samples per Second) for each channel; but when operated in balanced monaural mode, that effective rate rises to 2Ms/S.



Positive-Programmed Output

The methods used to design the modulation of the Crown BCA are those of interleaved power converter design. Interleaved power conversion is one of a number of cutting-edge technologies being explored in the larger venue of power electronics. A classification system exists in power electronics capable of describing most circuits. The Crown BCA's power stage is properly classified as a fully interleaved buck-derived power converter.

Crown has chosen to give the generic names of OCA and OCIA (Oh-see-yuh) to these new

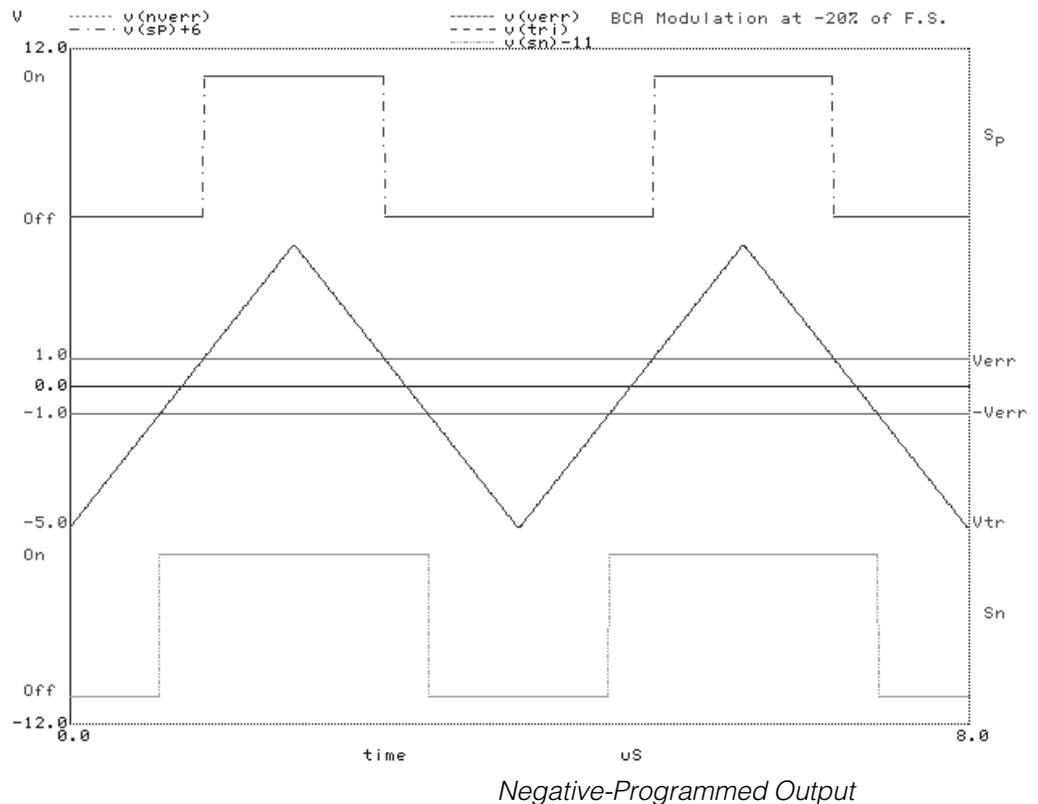


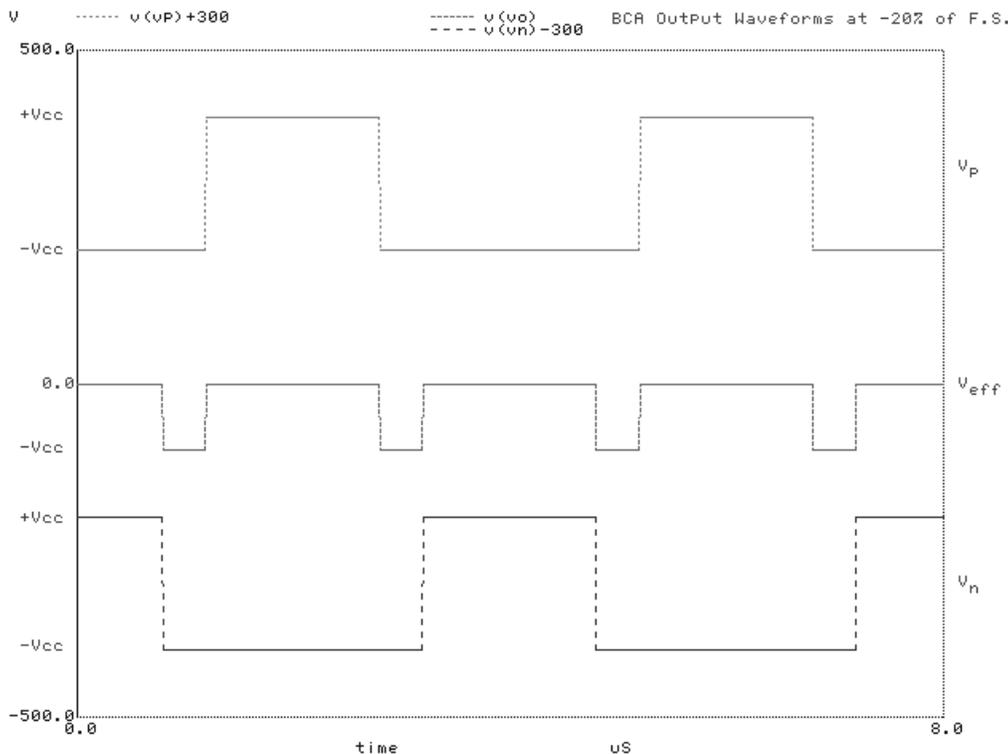
quired to eliminate the switching signal from the output. Since ripple currents simultaneously increase in frequency while decreasing in amplitude, the filtering requirements are multiply relaxed.

Note that no matter how many balanced current power stages are interleaved, total ripple rejection will always occur at zero signal. Additional total nulls of the output ripple will occur at evenly spaced levels intermediate to full scale. If N is the number of total switches in the design, there will be $N+1$ output levels which

designs of power converters. OCA is the acronym for Opposed Current Amplifier while OCIA is short for Opposed Current Interleaved Amplifier. The OCIA designation is for designs which achieve additional interleaving by using paralleled and seriesed OCA power stages.

Interleaved power converters have the highly desirable property that converter speed is enhanced with increased converter size. As additional power stages are paralleled, the ripple frequencies are increasing proportional to the number of switches. This reduces the amount of low-pass filtering re-



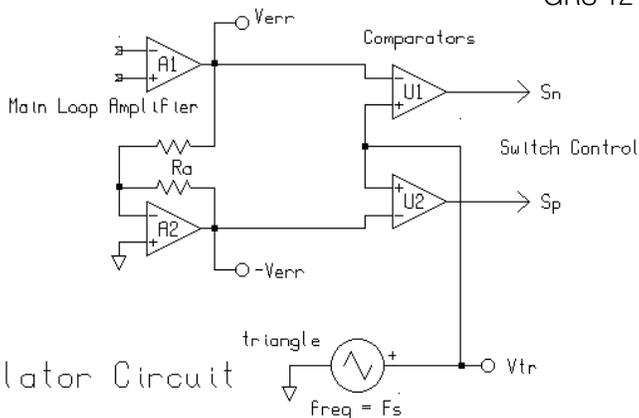


Negative-Programmed Output

exhibit total ripple cancellation. In standard PWM class-D designs which use interleaving there are $(N+2)/2$ ripple nulls. Thus $N/2$ more ripple nulls result from OCIA design.

Power converters that use OCIA design principles can be used for both inverter and rectifier applications. This is the natural consequence of being a full four-quadrant power converter. Much more could be said, however it is not the intent of this document to be a textbook on state-of-the-art amplifier design.

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BCA Modulator Circuit

The modulator for the basic Crown BCA power stage is simpler than one might at first imagine. Having twice the standard amount of resultant information, it has two high-speed comparators driven from three signals, V_{err} , $-V_{err}$ and V_{tr} . The same triangle waveform source can be used by both comparators.

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