Buck or Boost Tracking Power Converter

Pallab Midya, *Senior Member, IEEE*, Ken Haddad, *Member, IEEE*, and Matt Miller, *Member, IEEE*

***Abstract*—A cascade of buck and boost converter is presented here. The control operates in a manner that the converter is either in buck or boost (BOB) mode on a cycle by cycle basis. It transitions between the modes seamlessly to provide a tracking power conversion function for modulating the power supply of a variable envelope radio frequency (RF) power amplifier. The control algorithm and its implementation using switched capacitor circuits is described. Simulation and measured experimental results including converter efficiency, tracking accuracy, and spectrum at the output of the RF power amplifier are provided. This control technique allows seamless transition between the buck and boost modes while tracking RF envelopes with bandwidth greater than 100 kHz, and maintaining extreme accuracy and extremely low ripple. The efficiency of this converter operating at 1.68 MHz is close to 90% over a wide range of conversion ratios. The area of the power converter is extremely small allowing this to be integrated into a cellular telephone. The controller was integrated as part of a larger power management IC as well as a discrete IC.**

***Index Terms*—Buck boost converter, envelope following, supply modulation, tracking power cenverter, two switch buck boost converter.**

I. INTRODUCTION

THE radio frequency (RF) transmitter in certain wireless phones consumes a major portion of the output power. With advances in semiconductor technology, the voltage and power consumption of digital circuits per unit computation is decreasing rapidly. By contrast, the RF transmitter has to transmit and therefore, consume a minimum amount of power. Further, efficient use of the RF spectrum requires the use of RF signals with variable envelope and phase. These signals must be produced with high linearity using class AB amplifiers which are very inefficient. Variation in the battery voltage from fully charged to end of charge makes the class AB amplifier even less efficient. The class AB amplifier has to be biased such that it can provide the peak power without clipping at the lowest battery voltage. Consequently, at the highest battery voltage the efficiency is lowered even for peak-power output. The efficiency of a class AB amplifier operated close to saturation is often close to 50% whereas, the efficiency of the same amplifier operating over the variable RF envelope and variable battery voltage may be about 20%.

If instead the RF amplifier is operated at a supply voltage which tracks the RF envelope the efficiency can be doubled. This is called envelope following and was introduced in [1]. To provide this variable voltage which can be both above or below the supply, without the use of transformers or voltage inversion the buck or boost (BOB) converter was designed. Fig. 1 shows a schematic of the converter. It needs a single inductor and 2 active switches. The circuit in Fig. 1 is not novel and [2] uses a similar circuit to produce a fixed 3.3 V output as the battery voltage varies between 2.5 V and 5.5 V. A second inductor is necessary in this application for suppression of the ripple by 75 dB. Sensorless current mode (SCM) control [3] is a fast control technique suitable for fast tracking power converter applications. In [4] a number of power converters are explored that only need a single switch while providing wide conversion range. However, for integrated applications requiring high efficiency the topology in Fig. 1 is more suitable.

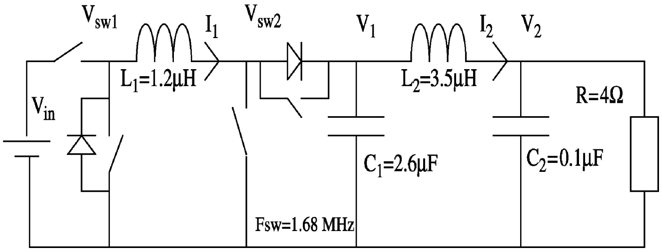

Fig. 1. BOB converter schematic.

For converting between rectified AC mains to a fixed dc voltage for PFC and UPS applications the topology in Fig. 1 has been used in [5]–[7]. In both PFC and UPS applications, one of the source, or load, is a widely varying voltage while the other is a constant dc battery or bus. In this case the source is a constant dc while the load is a widely varying dc output. Control agility required is quite low since the output sine wave frequency lies between 50 Hz and 400 Hz. One of the names for this topology is a two switch buck-boost. The control for these applications is done in [8], [9] by first deciding a buck or boost mode using a comparison between the input and output voltages. This results in a glitch when the system transitions from one mode to the other. In [2] an intermediate mode where both sets of switches are transitioning is introduced between the buck and boost modes. This results in a dip in efficiency which is clearly shown in [2]. Certain aspects of this work is covered by U.S. patent no. 6348781 [10].

II. TRANSITION BETWEEN BUCK AND BOOST MODES

One of the challenges of the design is to transition between the buck and boost modes without any distortion during the transition. Further, to maximize efficiency, the converter must switch only one set of switches (buck or boost) in any one cycle. Previous work [11] actually forbid this to ensure low distortion during the transition.

The transition problem was solved by starting each cycle with the buck switch on (or set) and the boost switch off (or reset).

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P. Midya and M. Miller are with the Freescale Semiconductor, Kemper Lakes Corporate Center, Lake Zurich, IL 60047 USA (email: pallab.midya@freescale.com).

K. Haddad is with Motorola, Schaumburg, IL 60196 USA.

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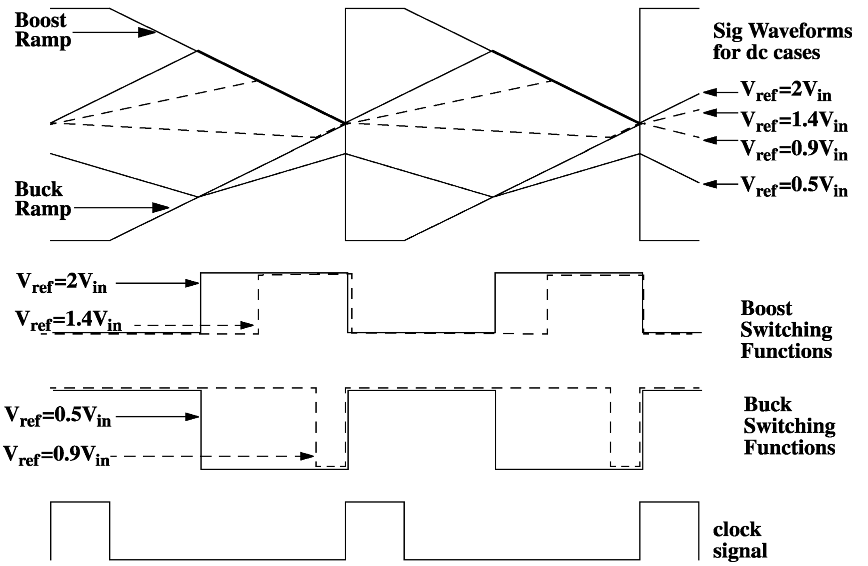

Fig. 2. Ramps and switching waveforms for different buck and boost ratios.

There is a pair of ramps, one for buck and one for boost. The buck ramp rises and the boost ramp falls such that at the end of the cycle they intersect. The error feedback signal must intersect one of the two ramps. If the error signal intersects the buck signal the buck switch is turned off for part of the cycle and the BOB converter is in buck mode. In this cycle the boost switch is never turned on. If the error signal intersects the boost ramp the boost switch is turned on. In this cycle the buck switch is never turned off. There is additional logic to latch the switching signals so that a glitch in the error signal does not cause both sets of switches to transition in a given cycle. In the switched capacitor implementation the duty ratios are quantized with a fairly coarse granularity. Thus, the converter may chatter between buck and boost modes, but the smallest on or off time is at least one cycle of the switched capacitor clock period.

III. SENSORLESS CURRENT MODE FEEDBACK

The feedback structure is a variation of SCM (sensorless current mode) control applied to the BOB converter. SCM has been modified to avoid the use of a switch in the feedback structure. The feedback signal is given by

$$Sig = k_1(V_{\rm ref} - V_1) + \frac{\int \{(V_{sw2} - V_{sw1}) + k_2(V_{\rm ref} - V_1)\}\, dt}{T_S}.$$

For this control, the equal slope criteria (ramp slope equal to current feedback slope) can be easily implemented for the boost mode. In the buck mode the equal slope criteria is met at duty ratio equal to unity and degrades as the duty ratio is reduced. Fig. 2 shows the switching signals, feedback signal and the ramps, under different duty ratios and switching modes. The lowest waveform is the clock signal. Above that are the switching waveforms for the buck and boost waveforms. The buck switch is always on when the boost switch transitions. Similarly the boost switch is always off when the buck switch transitions. Waveforms for the different voltage transfer ratios are drawn all the way from $\rm Vref = 2Vout$ to $\rm Vref = 0.5Vout$.

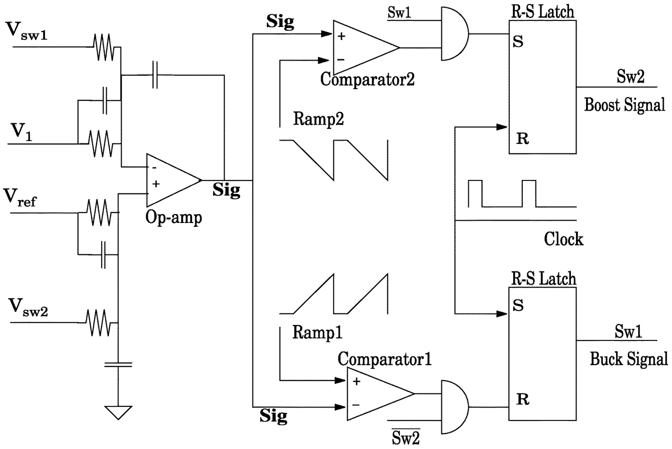

Fig. 3. Continuous-time implementation of BOB feedback control.

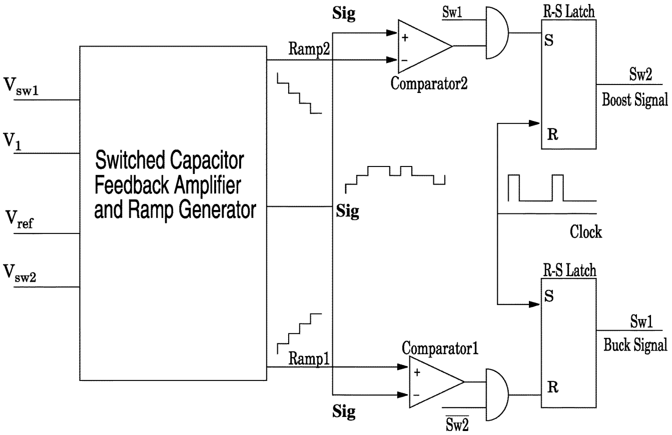

Fig. 4. Switched-capacitor implementation of BOB feedback control.

The use of SCM in this application reduced the gain bandwidth requirement of the feedback opamp significantly. SCM eliminated the need for current sensing and noise issues related to it. At the relatively high switching frequency of 1.68 MHz and the low noise requirements of the load, which is an RF transmitter, these advantages are critical.

IV. INTEGRATED FEEDBACK IMPLEMENTATION

The feedback network was integrated for reducing parts count. The options of a continuous time or switched capacitor implementation are shown in Figs. 3 and 4, respectively. For a continuous time implementation there needs to be a tuning of the RC network to compensate for variation over process and temperature. This would be feasible since a fixed frequency clock is readily available in the radio. However, the continuous time approach was not chosen for the implementation. A switched capacitor implementation was chosen despite the drawback of the noise associated with the quantization of the duty ratio. The extreme spectral requirements of the RF transmitter were met even in the presence of this quantization noise. In the switched capacitor implementation the signal Sig and the ramp are computed every clock cycle and sampled and held till the next cycle.

V. SIMULATION AND EXPERIMENTAL RESULTS

The four switches were implemented in two chipfet packages measuring 3.1 mm × 1.7 mm. The two inductors had dimensions of 2.5 mm × 2.0 mm × 1.5 mm. The peak power out of the BOB converter was about 8 W. The estimated bandwidth achieved in the converter is higher than 300 kHz. In Fig. 5, we see the BOB converter track a reference waveform going both above and below the input voltage. The tracking accuracy is very high as shown by overlaying the reference and output waveforms. The switching functions of both buck and boost switches are also overlaid showing the seamless transition from buck to boost and back. The absence of any buckboost region can also be seen. The envelope shown corresponds to an entire burst of the RF signal. Fig. 6 shows the efficiency of BOB as a function of output voltage for a given input voltage. In comparable implementations that go through a buck-boost region there is a dip in the efficiency when the input and output voltages are close. Also note that this efficiency is achieved at a higher switching frequency than in [2]. The total losses have been optimized such that the conduction losses and switching losses in the switch are approximately equal. The losses in the passive components are less than 3% of the total power.

Fig. 7 shows the spectrum of the RF power amplifier. Linearization has been used to correct for nonlinearity of the power amplifier. The challenge for the BOB design was to make sure that the linearization loop was not disturbed by errors in the switcher output. The efficiency of the RF power amplifier was almost doubled with no significant degradation of the output spectrum. The switching frequency at the switcher output had to be suppressed by more than 70 dB to meet this requirement.

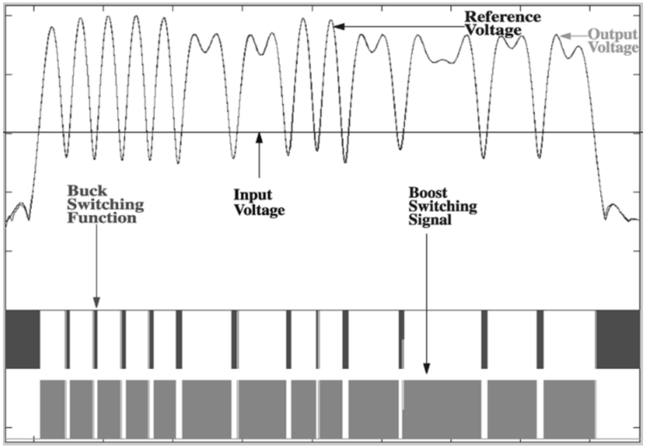

Fig. 5. Signal waveforms tracking RF envelope.

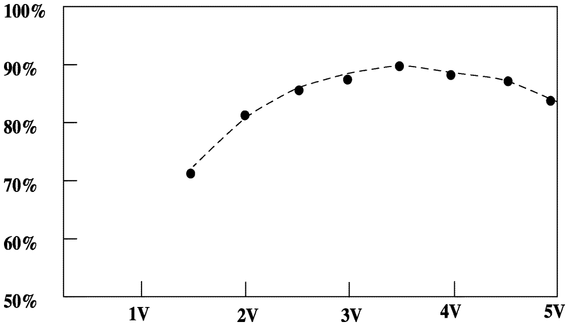

Fig. 6. Measured efficiency of BOB converter.

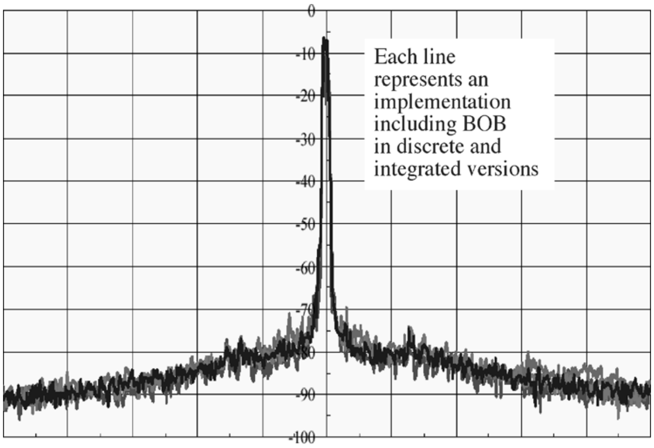

Fig. 7. Spectrum of RF power amplifier with BOB converter providing supply voltage.

Fig. 8 shows measured time domain waveforms of the BOB converter. The reference voltage, converter output voltage, intermediate node voltages, and the variable impedance of the RF power amplifier which is the load for the BOB converter are plotted. The impedance range varies over an order of magnitude being the largest at low voltages and lowest at high voltages. BOB was implemented as part of a larger power management IC as well as a discrete part. Fig. 9 shows a die plot of the discrete part. Note that the total die area is equivalent to 20 mil × 20 mil $(508\ \mu\text{m} \times 508\ \mu\text{m})$.

VI. CONCLUSION

The BOB architecture and control makes it possible to track both above and below the input battery voltage with no polarity inversion. This structure is efficient both from the point of view of power conversion efficiency as well as the size of storage components. Seamless tracking between the buck and boost modes with very high tracking bandwidth and SNR is

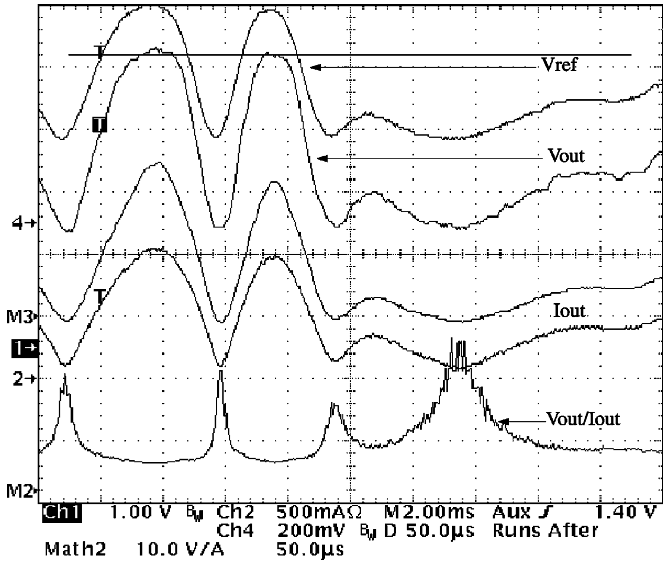

Fig. 8. Measured tracking of BOB converter.

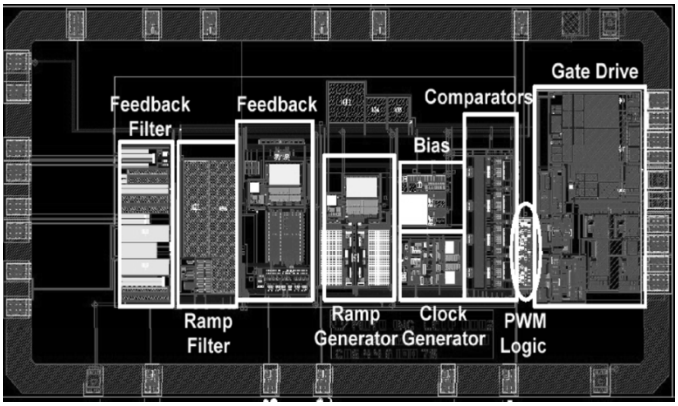

Fig. 9. Die plot of BOB controller.

achieved. The feedback control has been integrated into an IC and combined with an envelope following RF power amplifier to double the efficiency of an RF power amplifier in a handheld radio unit. Switched capacitor circuitry has been successfully used for implementing the feedback control.

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