



5 METHOD AND APPARATUS FOR
COMPENSATING FOR DELAYS IN MODULATOR LOOPS

BACKGROUND OF THE INVENTION

The present invention relates to delay handling
10 in modulator loops. More specifically, the present
invention provides a filter in the modulator loop which
compensates for delays introduced by, for example, a
power switching stage or an output filter.

With pulse width modulation (PWM) and other
15 modulation techniques, the delay introduced by switching
and output filter stages must be effectively dealt with
to alleviate the adverse effects such delays have on
circuit stability. This is particularly true for
modulators which have relatively high power switching
20 stages because the delays can become very large with
respect to the pulse repetition frequency of the loop. A
traditional solution to the problem of delay handling
will be described with reference to Figs. 1 and 2.

Fig. 1 is a block diagram of a typical
25 modulator loop 100. The logic output of modulator 102
drives an inverting power stage 104 the output of which
is filtered by output filter 106. A feedback resistor
108 and attenuation resistor 112 are provided for the
purpose of introducing negative feedback from the output
30 of the loop to modulator 102. Fig. 2 shows two waveforms
202 and 204 from the modulator loop of Fig. 1 without
delay compensation. As shown, due to the delay
introduced by the switching and filter stages, the
positive swing of waveform 204 (i.e., the output filter
35 106) is nearly in phase with the positive swing of
waveform 202 (i.e., the logic output of modulator 102).

Thus, where the original design of the loop
contemplates negative feedback, the delay converts it to
positive feedback and therefore loop instability (not



shown) results. For this reason, a filter capacitor 110 is provided in parallel with feedback resistor 108 for delay compensation. Capacitor 110 produces a zero in the feedback loop, effectively bypassing the attenuation
5 caused by resistors 108 and 112 for high frequencies.

Unfortunately, because this type of delay compensation is performed after the delay has been introduced into the loop, it is difficult to correct all of the delay's negative consequences with regard to loop
10 stability. In fact, this type of compensation technique has had only limited success and, as a result, has limited the delay tolerance and the overall performance of today's modulators. One solution is to use feedback signals directly from the logic output of the modulator,
15 i.e., before the delay is introduced, in combination with the output of the power stage and/or the output filter. Unfortunately, while the output of the modulator (202) and the filter output (204) have similar characteristics there are significant differences in content in the
20 modulator loop's frequency range of interest due to the non-ideal nature of the power stage as discussed in U.S. Patent Application No. 08/898,544 for METHOD AND APPARATUS FOR PERFORMANCE IMPROVEMENT BY QUALIFYING PULSES IN AN OVERSAMPLED, NOISE-SHAPING SIGNAL PROCESSOR
25 filed on July 22, 1997, the entire specification of which is incorporated herein by reference. This makes it very difficult to achieve high fidelity operation while feeding these signals back.

In view of the foregoing, it is desirable to
30 provide an improved technique for compensating for delays in modulator loops such that greater delays may be tolerated without adversely affecting loop stability.

SUMMARY OF THE INVENTION

35 According to the present invention, a feedback technique for modulator loops is introduced which addresses the difficulties discussed above. The feedback technique described herein uses the output of a low

voltage modulator stage to compensate for the delay introduced by subsequent power and filter stages while, at the same time, achieving a high level of fidelity notwithstanding the differences in signal content as discussed above. The invention achieves this result by filtering the output of the modulator stage such that its frequency components outside of the modulator loop's frequency range of interest are transmitted to the feedback path while its frequency components inside the loop's range of interest are attenuated. Thus, the stability of the loop is enhanced due to the feeding back of some portion of the modulator output, while the fidelity of the output spectrum of the loop is not adversely affected by undesirable modulator output components within the range.

Depending upon the type of modulator, the frequencies attenuated and transmitted by the feedback filter of the present invention vary. For example, for a baseband modulator, the filter attenuates frequencies in the baseband and transmits higher frequencies such as, for example, a high pass filter. For a bandpass modulator, the feedback filter may behave like a notch filter, attenuating frequencies within the relevant band.

Similarly, for a band reject modulator, the filter may behave like a bandpass filter, while for a high pass modulator, the filter may behave like a low pass filter.

In a modulator loop which tolerates a 250 ns delay without the improvements of the present invention, the addition of the feedback technique described herein has been shown to increase the delay tolerance level to greater than 500 ns. This means that, according to the present invention, very large power devices may be employed with low voltage modulators despite the troublesome delays associated with such power devices. For example, a specific embodiment of the invention is capable of delivering more than 1000 W (> 1 hp!) into a 4 ohm load with very high fidelity. For a 1 ohm load (e.g., an industrial motor) this is the equivalent of

more than 5 hp! This is a significant improvement over currently available high fidelity modulator loops and is sufficient for many relatively high power industrial applications.

5 Thus the present invention provides a modulator loop designed to operate in a frequency range of interest. The loop includes a loop output terminal and a switching stage, the output of which is coupled to the loop output terminal. The switching stage has a first
10 delay associated therewith. The output of a modulator stage is coupled to the input of the switching stage. A first feedback path is coupled between the loop output terminal and the feedback input of the modulator stage. A feedback filter is coupled between the output of the
15 modulator stage and the feedback input of the modulator stage which compensates for the first delay. The feedback filter is operable to transmit frequencies outside the frequency range of interest and attenuate frequencies in the frequency range of interest.

20 A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and the drawings.

25 BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a modulator loop designed according to the prior art;

Fig. 2 shows two waveforms from the modulator loop of Fig. 1;

30 Fig. 3 is a block diagram of a modulator loop designed according to a specific embodiment of the invention;

Fig. 4 is a block diagram of a modulator loop designed according to a more specific embodiment of the
35 invention;

Fig. 5 is a block diagram of a modulator loop designed according to a still more specific embodiment of the invention;

Fig. 6 is a block diagram of a modulator loop designed according to an even still more specific embodiment of the invention; and

Fig. 7 is a block diagram of a generalized embodiment of a modulator loop designed according to the invention.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Fig. 3 is a block diagram of a modulator loop 300 designed according to a specific embodiment of the invention. Modulator stage 302 may be any of a wide variety of modulator types including, for example, a pulse width modulator, or an oversampled mixed-signal modulator such as the one described in commonly assigned, copending U.S. Patent Application No. 08/667,925 for METHOD AND APPARATUS FOR OVERSAMPLED, NOISE-SHAPING, MIXED-SIGNAL PROCESSING filed on June 20, 1996, the entire specification of which is incorporated herein by reference for all purposes. According to specific embodiments, modulator stage 302 comprises a plurality of filters in parallel and/or in series. Switching stage 304 receives a control signal from the output of modulator 302. Switching stage 304 may be any of a wide variety of switch configurations and power levels. Switching stage 304 may also be either inverting or noninverting. For an inverting switching stage, an inverter is inserted in the modulator output feedback path in front of feedback filter 308. Output filter 306 may also be implemented according to any of a wide variety of techniques as appropriate for the desired output signal content in a particular application.

As with previous designs, negative feedback may be provided to modulator 302 from the outputs of switching stage 304 and/or output filter 306 via summing junction 310. For purposes of this description, junction 310 is assumed to be ideal and therefore, no additional feedback circuitry is shown. However, it will be understood that summing junction 310 must, of necessity,

be implemented using actual circuit components such as, for example, resistors. Therefore, specific embodiments of the invention showing some actual implementations of summing junction 310 are described below with reference to Figs. 4-6. The frequency content of the feedback from the switching stage and output filter is both inside and outside of the loop's frequency range of interest.

Unlike previous designs, the modulator loop 300 also employs feedback from the output of modulator 302 via feedback filter 308 to further enhance loop stability. However, to avoid the negative consequences for output fidelity discussed in the Background of the Invention, this feedback is filtered by filter 308 such that its frequency content is largely outside of the modulator loop's frequency range of interest. Thus, stability is increased without loss of fidelity.

Fig. 4 is a block diagram of a baseband modulator loop 400 designed according to a more specific embodiment of the invention. Modulator 402, switching stage 404, and output filter 406 operate substantially similarly to the corresponding loop elements discussed above with reference to Fig. 3. Feedback is provided to the feedback input of modulator 402 from the output of switching stage 404 via a divider network comprising resistors 412 and 414. Feedback is also provided to the feedback input of modulator 402 from its logic output via filter capacitor 408 and series resistor 410. The value of capacitor 408 is selected to attenuate the logic output's signal content in the baseband range of interest while passing higher frequencies to the feedback path for combination with the attenuated switching stage signal. Significant increases in delay tolerance have been achieved with this configuration.

However, because the filtered modulator logic signal is not combined with the feedback path using an ideal filter and an ideal summer, an additional pole and zero are introduced to the transfer function of the loop by the actual circuit elements, i.e., capacitor 408 and

resistor 410. This can be seen from a network analysis perspective by treating the logic output of modulator 402 as ground and observing that capacitor 408 adds delay to the loop by low pass filtering the switching stage output. This delay represents a limitation on the performance enhancements made possible by the use of the filtered modulator output as feedback. Therefore, further embodiments of the invention are described below introducing enhancements to the loop of Fig. 4 which address this limitation.

Fig. 5 is a block diagram of a baseband modulator loop 500 designed according to a still more specific embodiment of the invention. Modulator 502, switching stage 504, and output filter 506 operate substantially similarly to the corresponding loop elements described above with reference to Fig. 3. As with the corresponding elements of loop 400, feedback is provided to the feedback input of modulator 502 from the output of switching stage 504 via a divider network comprising resistors 512 and 514. Feedback is also provided to the feedback input of modulator 502 from its logic output via filter capacitor 508 and series resistor 510. The value of capacitor 508 is selected to attenuate the logic output's signal content in the baseband range of interest while passing higher frequencies to the feedback path for combination with the attenuated switching stage signal.

An additional capacitor 516 is provided from the output of switching stage 504 to node 1 which cancels the pole introduced into the switching stage's feedback path by capacitor 508. This may be understood from a network analysis perspective by again treating the logic output of modulator 502 as ground and analyzing the feedback path from the output of switching stage 504. If the ratio of resistors 512 and 514 is made equal to the ratio of capacitors 508 and 516, the attenuation of the switching stage output seen at node 1 is the same as that seen at node 2, i.e., the voltage level should be the

same. Because the voltages at nodes 1 and 2 are equal, there is no current through resistor 510 which can therefore be treated like an open circuit, effectively removing capacitor 508 and its corresponding pole from the switching stage feedback path. This makes the modulator loop extremely stable as well as delay tolerant.

Fig. 6 is a block diagram of a modulator loop 600 designed according to an even still more specific embodiment of the invention. Modulator 602, switching stage 604, and output filter 606 operate substantially similarly to the corresponding loop elements described above with reference to Fig. 3. Resistors 610, 612 and 614 and capacitors 608 and 616 operate substantially similarly to the corresponding loop components described above with reference to Fig. 5. In fact, the embodiment of Fig. 6 includes all of the circuitry of Fig. 5 with the addition of a feedback path from the output of filter 606 to the feedback input of modulator stage 602, the additional feedback path being implemented with a resistor 620. Capacitor 622 is also included from the output of filter 606 to node 1 for the purpose of canceling the pole in the new feedback path introduced by capacitors 608 and 616. As discussed above with reference to the embodiment of Fig. 5, if the ratio of resistor 620 and resistor 614 in parallel with resistor 612 is made the same as the ratio of capacitor 608 in parallel with capacitor 616 and capacitor 622, no current flows in resistor 610 and thus, capacitor 608 is effectively removed from either feedback path.

Fig. 7 is a block diagram of a generalized embodiment of a modulator loop 700 designed according to the invention. Replacing the feedback filter and signal combining circuitry of the previously described embodiments is a 4-port network 708 to which modulator stage 702, switching stage 704, and output filter stage 706 are connected. Network 708 takes the modulator logic output signal and attenuates its frequency content within

the range of interest of modulator loop 700. It also combines the resulting signal with the fed back outputs of the switching and filter stages for use as feedback by modulator stage 702. Network 708 may be implemented in a variety of ways depending upon the technology used to
5 implement modulator loop 700.

Moreover, for modulators having amplitude dependent stability (e.g., oversampled and pulse width modulators), it may be desirable to control the magnitude
10 of the modulator feedback with respect to the feedback from the power and/or filter stages to maintain an optimal stability point. Therefore, an optional gain control 710 is provided before the feedback filter (included in 4-port network 708) to allow gain matching
15 of the modulator logic output signal and the power output. According to a specific embodiment, gain control 710 is implemented using a digital-to-analog converter (DAC) with a variable output amplitude.

While the invention has been particularly shown
20 and described with reference to specific embodiments thereof, it will be understood by those skilled in the art that changes in the form and details of the disclosed embodiments may be made without departing from the spirit or scope of the invention. For example, the specific
25 embodiments described above with reference to Figs. 4 and 5 show the use of analog components (i.e., resistors and capacitors) to both filter the modulator output and combine the resulting filtered feedback signal with the feedback path from the output of the switching stage. It
30 will be understood, however, that, where, for example, the modulator stage is implemented using digital techniques, the circuitry and techniques used to filter and combine the feedback signal could be digital. Similarly, with a mixed-signal modulator, mixed-signal
35 circuitry and techniques may be used to implement the feedback.

It should also be understood that, depending upon the degree to which the contents of the modulator

- and power outputs in the modulator loop's frequency range of interest are dissimilar, and the degree to which degradation of the loop's output may be tolerated, varying levels of attenuation of the modulator output's
- 5 components in the range may be appropriate. That is, the frequency components in the modulator stage output which are within the loop's frequency range of interest need not be completely rejected to maintain reasonable fidelity and remain within the scope of the invention.
- 10 Therefore, the scope of the invention should be determined with reference to the appended claims.
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WHAT IS CLAIMED IS:

1. A modulator loop designed to operate with a frequency range of interest, comprising:
 - 5 a loop output terminal;
 - a switching stage having an input and an output, the output of the switching stage being coupled to the loop output terminal, the switching stage having a first delay associated therewith;
 - 10 a modulator stage having an output and a feedback input, the output of the modulator stage being coupled to the input of the switching stage;
 - a first feedback path coupled between the loop output terminal and the feedback input of the modulator stage; and
 - 15 a feedback filter coupled between the output of the modulator stage and the feedback input of the modulator stage for compensating for the first delay, the feedback filter being operable to transmit frequencies outside the frequency range of interest and attenuate frequencies in the frequency range of interest.
2. The modulator loop of claim 1 wherein the modulator loop is a baseband modulator loop and the
25 feedback filter comprises a high pass filter.
3. The modulator loop of claim 1 wherein the modulator loop is a band pass modulator loop and the feedback filter comprises a notch filter corresponding to
30 the frequency range of interest.
4. The modulator loop of claim 1 wherein the modulator loop is a high pass modulator loop and the feedback filter comprises a low pass filter.
- 35 5. The modulator loop of claim 1 wherein the modulator loop is a band reject modulator loop and the feedback filter comprises a band pass filter.

6. The modulator loop of claim 1 wherein the modulator stage comprises a plurality of filters in parallel.

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7. The modulator loop of claim 1 wherein the modulator stage comprises a plurality of filters in series.

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8. The modulator loop of claim 1 wherein the feedback filter generates a feedback signal using analog techniques.

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9. The modulator loop of claim 1 wherein the feedback filter generates a feedback signal using digital techniques.

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10. The modulator loop of claim 1 wherein the feedback filter generates a feedback signal using mixed signal techniques.

11. The modulator loop of claim 1 wherein the feedback filter comprises a capacitor and a resistor.

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12. The modulator loop of claim 1 wherein the feedback filter comprises a digital signal processor.

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13. The modulator loop of claim 1 further comprising additional circuitry coupled to the feedback filter for compensating for an undesirable contribution to the first feedback path by the feedback filter.

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14. The modulator loop of claim 13 wherein the additional circuitry cancels a pole associated with the high pass filter.

15. The modulator loop of claim 14 wherein the additional circuitry comprises a capacitor coupled

between the loop output terminal and the feedback filter.

16. The modulator loop of claim 1 further comprising an output filter coupled between the output of
5 the switching stage and the loop output terminal, the output filter having a second delay associated therewith, the feedback filter also compensating for the second delay.

10 17. The modulator loop of claim 16 further comprising a second feedback path from the output of the switching stage to the feedback input of the modulator stage.)

15 18. The modulator loop of claim 17 further comprising additional circuitry coupled to the feedback filter for compensating for an undesirable contribution to the second feedback path by the feedback filter.

20 19. The modulator loop of claim 18 wherein the additional circuitry cancels a pole associated with the high pass filter.

25 20. The modulator loop of claim 19 wherein the additional circuitry comprises a capacitor coupled between the switching stage output and the feedback filter.)

30 21. The modulator loop of claim 18 wherein the modulator stage comprises a plurality of stages, the feedback input being coupled to selected ones of the plurality of stages.

35 22. The modulator loop of claim 1 wherein the switching stage comprises an inverting switching stage, the modulator loop further comprising an inverter coupled between the output of the modulator stage and the feedback filter.

23. The modulator loop of claim 1 further comprising a gain control circuit coupled between the output of the modulator stage and the feedback filter,
5 the gain control circuit for controlling an amplitude of a modulator output signal at the output of the modulator stage.

24. The modulator loop of claim 23 wherein the
10 gain control circuit comprises a digital-to-analog converter with a variable output amplitude.