Hysteretic Multilevel NPC Converter Control for a Switch Mode Assisted Linear Amplifier

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ABSTRACT

A Switch-Mode Assisted Linear Amplifier (SMALA) combines the high quality of a linear amplifier required for audio applications with the high efficiency of a switch-mode amplifier. The careful choice of current sense point and switch placement allows a simple non-isolated hysteresis current controller for the switch-mode section. This paper explains the extension of the hysteresis current controller for the control of a three level Neutral Point Clamped (NPC) converter, with simulations as proof of concept. The NPC topology allows the use of lower voltage switches and lower switching frequencies to implement high power audio amplifiers using the SMALA topology.

1. INTRODUCTION

Switch-Mode Assisted Linear Amplifiers (SMALAs) as their name suggest combine a Switch-mode or Class D switching amplifier, and a linear (Class B) amplifier. Traditional audio amplifiers are linear amplifiers, because of their ability to deliver extremely low distortion and noise performance. However, linear amplifiers dissipate a lot of power which becomes significant in commercial applications. Using switch-mode techniques, class D amplifiers can achieve very high efficiency and thus low power dissipation, but have difficulty matching the noise and distortion performance of their linear counterparts. SMALAs synergistically combine the class B and D amplifiers to achieve high efficiency and excellent performance.

In a previous paper, the author outlined the concept and operation of a Switch-mode Assisted Linear Amplifier (SMALA) intended for Hi-Fidelity audio applications [1]. The chief novel contribution was an extremely simple implementation of hysteretic current control and direct MOSFET drive enabled by the choice of a new current sensing point. The amplifier was built and experimentally tested with excellent performance, but due to the low voltage ratings of the semiconductor devices (60V), the output power was limited to 20W.

A SMALA will more likely find practical application at higher power levels of 100W or more. This generally requires power semiconductor devices with ratings of greater than 100V. The topology as originally proposed requires a P channel MOSFET, which are unusual and expensive at these voltage levels.

Two solutions to this problem are presented in this paper. The first is to use a multilevel converter which allows the series stacking of the semiconductor switches. A three level Neutral Point Clamped (NPC) design is given and proven in simulation. One specific contribution of this paper is the demonstration of the switching control logic required to control the switches using the hysteretic current control to an arbitrary number of levels. Simulations showing the correct NPC SMALA control into a complex reactive load are presented.

2. PREVIOUS RELATED WORK

2.1. SWITCH MODE ASSISTED LINEAR AMPLIFIERS

The idea of cascading the linear amplifier and switch-mode amplifier was discussed in 1986 by Yundt [2]. He proposed four important properties that distinguish the different composite amplifier topologies. These properties related to the nature of the class B and class D amplifiers (voltage source or current source), their connection (series or parallel), and their interaction. Of the sixteen combinations, four are sensible, and one in particular is well suited to an audio SMALA application: the parallel voltage controlled topology.

This parallel voltage controlled topology has been further investigated in recent years [3–6]. An excellent mathematical examination of the tradeoffs between switching frequency, inductance value and ripple current, bandwidth and power dissipation is available [3]. It shows two key design considerations for the linear stage are obtaining a low output impedance and wide bandwidth. Finally, a number of alternative topological variations are suggested.

A number of independent research groups have presented experimental examples of the parallel voltage controlled topology with good results [1,4-6]. Reference [4] reports an excellent result of 0.01% THD at 1kHz from 0.5 to 50W, and an efficiency of 90% at 50W. A custom integrated circuit class D stage with a separate integrated circuit class B stage also achieves 0.02% THD up to 30W with 85% efficiency at 30W [5]. A full bridge configuration [6] achieves less than 0.1% THD at 25W. The authors own contribution [1] has been a 20W amplifier with a focus on low distortion (< 0.03%) using a non-switching deadband at low power (< 2W), and simplified hysteretic control.

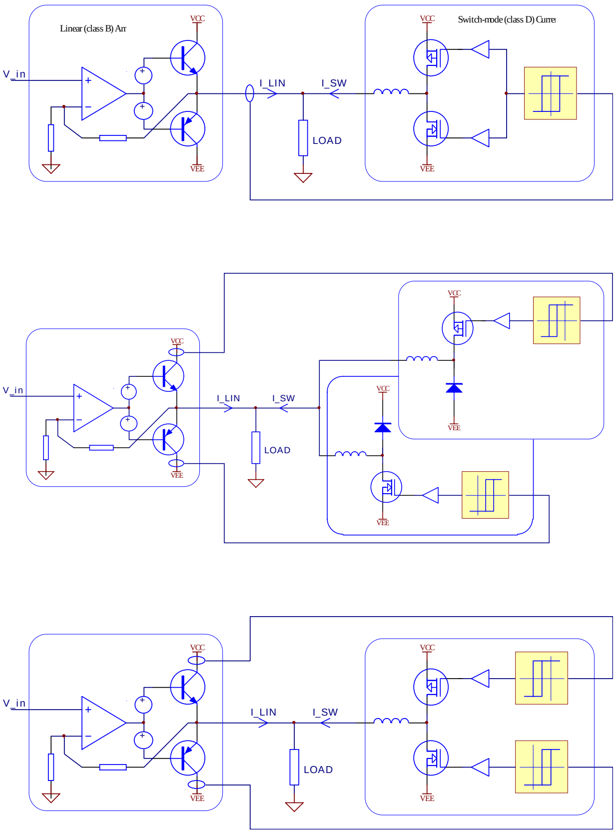

Fig.1 Parallel voltage controlled SMALA topologies for audio as proposed by Ertl, Kolar, Zach [3] (top) and then refined by Walker [1] (middle, bottom).

2.2. Device Ratings at Increased Power Levels

All of these experimental demonstrations have been at relatively low voltages and power levels. However, the SMALA concept will most benefit high power amplifiers. In the parallel voltage controlled topology, the linear class B amplifier provides the full load voltage, but only a fraction of the output current under normal circumstances. However, under transient conditions, this amplifier may be required to deliver a significant fraction of full load current to maintain signal fidelity. It defines the output voltage and the low output impedance. The Class B amplifier can be constructed easily to meet these demands by following current best practice [7]. The output stage can be reduced to a single pair of high voltage high current BJT audio devices given the typical lower current and power requirements. If necessary, current or power limiting circuitry can be included to protect these devices during transients.

The switch-mode or class D amplifier operates in parallel with the class B amplifier to supply the full output current, and is also rated to the full supply voltages. The topology proposed in [1] requires complimentary N and P channel MOSFETs which are rated to the full supply voltage ($V_{CC} - V_{EE}$) which will easily exceed 80V for a 100W amplifier.

Unfortunately, few manufacturers make P channel MOSFETs in ratings beyond 100V. Manufacturers have released MOSFETs optimised for class D audio applications, however most devices are N channel devices designed for drive by isolated boot-strapped gate drivers. A targeted search by application on International Rectifier's website for "Audio discrete HEXFETs" returned over 30 devices, but only 3 P channel devices, all 55V rated [8]. A similar search at Zetex Semiconductors returns a balanced selection of complementary N and P channel devices, but with a maximum rating of 70V [9]. Most class D applications operate as a full bridge, which simplifies power supplies and avoids power supply pumping [10]. Importantly, the full bridge topology also allows high power outputs from reduced supply voltages, especially if supplying low impedance loads.

2.3. Multilevel Topologies

A solution to limited switch voltage ratings is to use multiple series connected switches. Multilevel converters by their topology and control naturally ensure voltage sharing between these switches. Both the Neutral Point Clamped (NPC) and Full bridge converters considered here allow a doubling of output voltage swing for a given switch voltage rating, by sharing that voltage across a pair of switching devices. Both approaches will also avoid the possibility of power supply pumping which, although not observed, is certainly possible with a single ended SMALA.

The three level NPC along with a number of other multilevel topologies was suggested for further research by Ertl, Kolar and Zach [3]. Figure 2 shows the basic NPC topology shown in their paper.

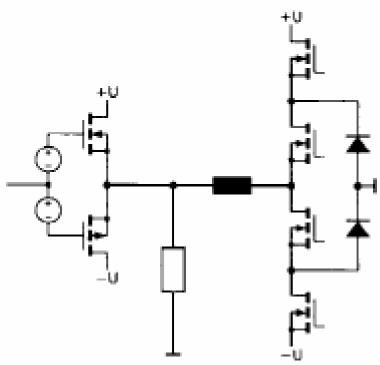

Fig.2 The NPC converter SMALA topology as proposed in [3].

The three level NPC converter is considered here as an alternative to a full bridge converter for two main reasons:

- A bridged (linear) amplifier generally requires a complete duplication of the amplifier signal and power components, and operates at double currents rather than double voltages.
- Conventional single ended amplifiers can be bridged to allow a further increase in power output; this option is generally not available if the amplifier is already bridged.

A NPC extension of the current SMALA topology would hopefully allow the simple structure of the single ended amplifier to be maintained. It would also allow a growth path for still higher rated power amplifiers.

3. Neutral Point Clamped (NPC) SMALA Topology and Control

The actual topology of the NPC converter as applied to a SMALA is shown in Figure 3. The numbering of the MOSFETs S1 – S4 and diodes D1 – D4 has been chosen to reflect the pairing of MOSFETs and diodes under the proposed control scheme. Diode D1 ensures MOSFET S1 never experiences a voltage exceeding V_{CC}, likewise D4 protects S4. Diodes D2 and D3 are not strictly necessary since the intrinsic MOSFET diodes can always conduct, however these diodes can be optimised for their switching function and will divert power dissipation away from the MOSFETs they parallel.

The topology as shown uses a single inductor, although this is not essential, and separate inductors is possible as is shown in the two level SMALA topologies in Fig.1. In this case S1, D1, S2, D2 operate with one inductor, and S3, D3, S4, D4 operate with a second inductor.

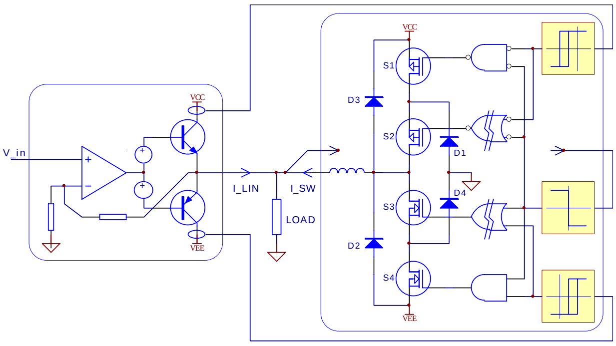

Fig.3 The three level NPC SMALA topology illustrating the first control strategy used.

The control strategy used is an extension of the original hysteretic control proposed for the two level SMALA [1]. A naïve approach which will work for resistive loads is simply to control the inner NPC MOSFETs using only the voltage level across the load, and control the outer MOSFETs only by the hysteretic current controllers as before. Consider the lower MOSFETs S3, S4 during the negative half cycle. When the load voltage is negative, S3 is turned on, and S2 is turned off. MOSFET diode pair S4 D4 now provide switch-mode assistance to the linear amplifier under hysteretic control, sinking current via MOSFET S3. The inductor is switched between V_{EE} and 0V, rather than V_{EE} and V_{CC}, which considerable reduces the switching frequency for a given current ripple tolerance band.

This naïve control strategy is seen to sub-optimal when the load has a complex impedance. A complex load will lead to an output current which lags or leads the voltage waveform, and so it is quite possible to have output voltages and currents of opposite sign. In fig.4, a Spice simulation into a complex load (8Ω + 1mH = 8 + j6.3Ω at 1000Hz) shows this occurring from 0.5 to 0.6ms, where the output voltage is positive but the output current is still negative. If S3 is switched purely based on the load voltage, S3 will be off, and S4-D4 are unable to sink the load current. The linear amplifier is forced to carry the full load current with greater than V_{EE} across the lower device – a high power dissipation condition.

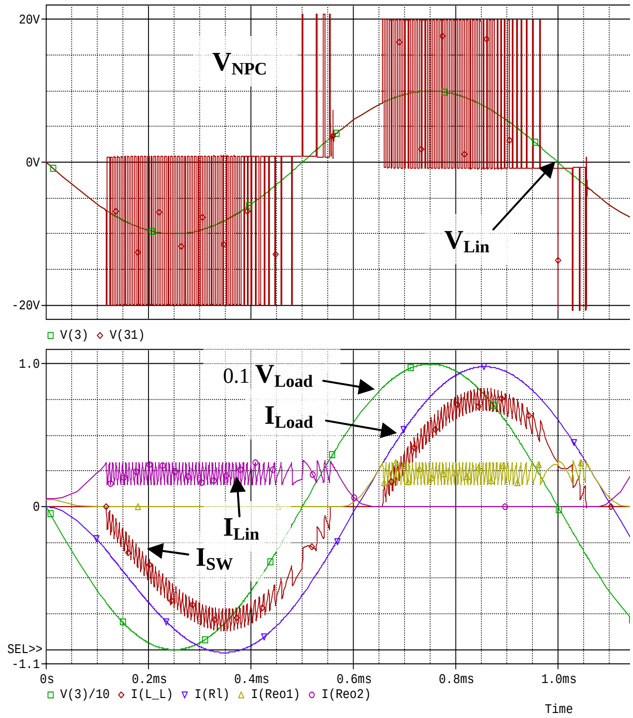

Fig.4 A Spice simulation of the three level NPC converter control strategy shown in Fig.3.

One solution is to allow S3 to switch on if the load current exceeds the negative hysteresis threshold. S3 will sink current via D4. When S3 turns off under hysteresis current control, D3 will conduct to ensure continuity of inductor current. To avoid any problems of cross conduction, S2 and S4 must be switched with mutually exclusive waveforms. In this implementation, S4 is locked out and S2 switched on when the load voltage is greater than 0V.

The simulation result presented in Fig.4 demonstrates the correct functioning of this control strategy. The simulation was conducted in Spice. The class B linear amplifier is component accurate with the exception of some biasing current sources. The class D three level NPC converter is simplified by using the SPICE switch device in place of real MOSFETs and simplified ideal comparator sub-circuits.

The second control solution to accommodate reactive loads is to set two separate thresholds for the hysteretic current control of the switches (see Fig.5). This concept along with many other multilevel hysteretic current control solutions is proposed by Marchesoni [11]. Considering first a purely resistive load, the initial rise in current in the class B stage switches on the inner switch, for example S3. However, since the voltage at the load is negative, D4 remains reverse biased and no current flows in the inductor. The class B stage current continues to rise to the second threshold, which then switches on S4. S4-D4 switch according to the higher hysteresis window.

If the load is reactive, such that the voltage is positive when the load current is negative, then the lower hysteresis window causes S3-D3 to supply the necessary switch-mode current assistance.

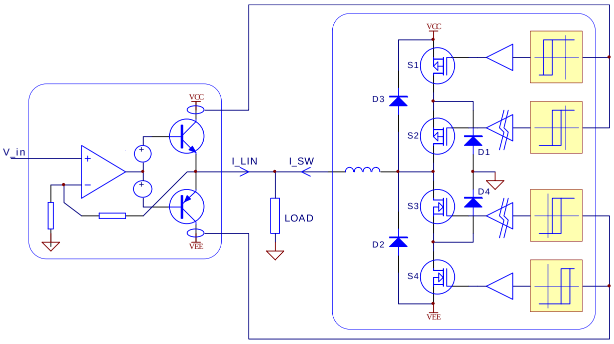

Fig.5 The three level NPC SMALA topology illustrating the second control strategy used.

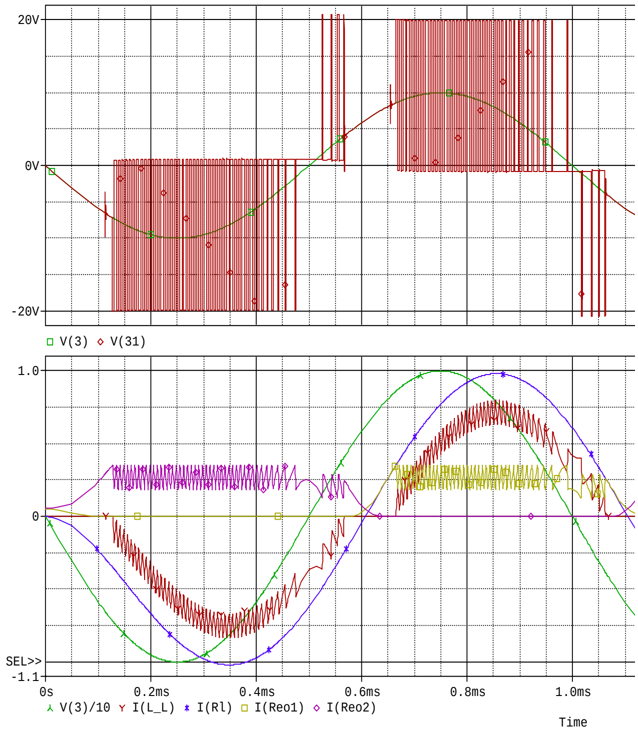

Fig.6 A Spice simulation of the three level NPC converter control strategy shown in Fig.5.

The simulation result presented in Fig.6 demonstrates the correct functioning of this control strategy. The slight difference in hysteresis windows as used to control each pair of switches is evident.

4. PRACTICAL IMPLEMENTATION ISSUES

4.1. ISOLATION OF SWITCH SIGNALS

The NPC topologies as shown would allow a SMALA to be built with equal power rating to a full bridge design using an equal number of equal voltage rated components. Can we retain the simplicity of the original two level implementation which made it so attractive?

The first control strategy does not appear to compete with the second on the basis of simplicity of control, so is not pursued further. The second hysteresis control strategy using a pair of controllers retains the very simple sensing structure of the original. The drive of the outer MOSFETS is also simple, requiring non-isolated drivers.

The inner NPC MOSFETs do require isolated gate drives. The low N channel device S3 can be isolated using a level shifting boot strap driver HVIC. Most logically, this would be a half bridge driver with independent channels, such as the IR21xx family of devices [12], driving S3 and S4.

However, no equivalent device is available for the P channel devices, capable of level shifting to a more *negative* voltage for device S2. Recent digital isolators using IC scale magnetic coupling techniques from Analog Devices [13] and NVE corporation [14] have low propagation delay, low power consumption, and excellent noise immunity. These devices would be suitable. For symmetry, they would probably be used on both upper and lower hysteretic controllers.

4.2. EXTENSION BEYOND THREE LEVELS

A class G amplifier has additional low voltage supply rails and output devices which supply the output waveform up to the limits of those low voltage supply rails. Beyond that voltage, the output is automatically supplied from the full voltage rails [7]. This approach leads to much reduced power dissipation in an audio amplifier application.

Due to the rapid rise in complexity and uneven switch utilisation, the NPC converter is generally limited to three levels in industrial applications, although five or more levels are possible. In a SMALA application, a five level NPC converter is a natural match to a class G linear amplifier with its main and auxiliary supply rails. The second control scheme using offset hysteresis windows would work with such a five level NPC converter. The auxiliary rails need not be an exact fraction of the main supply rails, and often they are not [7].

Although possible, creating a class G SMALA would be of questionable value. The main value of moving to a class G amplifier is to minimise power dissipation in the linear amplifier devices. This is also the goal of a SMALA. Never-the-less, some advantages would be the further reduction in power dissipation in the linear amplifier, and the use of lower voltage devices in the switching amplifier. Together this might mean for example the further minimisation or even elimination of heatsinks for some devices.

4.3. NPC SMALA ADVANTAGES

There are some key advantages of a three level NPC SMALA compared to a conventional two level SMALA which will assist with the overall implementation of the SMALA concept at higher power levels.

The switching voltage waveforms applied to the inductor have half the voltage swing of a conventional two level SMALA. This allows the halving of the maximum switching frequency for a given inductor value and given inductor ripple current specification. The switching frequency and current ripple at near 0V (an important case for audio) is also much reduced due to the diode freewheeling current from 0V rather than the opposite voltage rail to the MOSFET delivering current.

As mentioned, 100V rather than 200V MOSFETs will be able to be used at power levels of hundreds of Watts. This is particularly important given the limited availability of high voltage P channel MOSFETs.

Current experimental work is underway to build a two and then three level SMALA using 80V supply rails and capable of approximately 400W into 8Ω.

5. CONCLUSIONS

This paper has demonstrated that a simple extension of the hysteresis current control demonstrated in a previous two level SMALA implementation is suitable for controlling a three level Neutral Point Clamped (NPC) converter. The NPC topology allows the use of lower voltage switches and lower switching frequencies to implement high power audio amplifiers.

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