Part III

Chapter 8

Non-linear Control

The control methods investigated so far have all been based on linear feedback control. Recently, non-linear control techniques related to One Cycle Control [Sm95] have been investigated for PMAs in several publications [La96b], [Sm97], [Ta97], [Ni98a]. The results indicate that there are some complications in making non-linear control realize the desired control objectives. However, the basic principles have an indisputable appeal from a theoretic point of view. Subsequently, the topic for the following will be an analysis of non-linear control techniques, and it will be investigated if various improvements could make non-linear control a viable alternative to the linear control methods. After a short introduction to the principles of One Cycle Control and the perspectives and motivating factors for the application of non-linear control to PMAs, the investigations will focus on an extended non-linear control configuration - Three-level One Cycle Control (TOCC). The method [Ta97], [Ni98a] has certain advantages over previously proposed nonlinear methods in PMA applications.

There are many non-linear elements within the PMA as shown in Chapters 3 and 4. PWM is inherently a non-linear process, power supply perturbation multiply with the modulating signal, there are several non-linear saturation/limitation characteristics etc. Subsequently, all control systems for PMAs may all be considered as non-linear control systems, i.e. control systems that operate on a non-linear plant. The distinction between the previously investigated systems and true non-linear controlled system lies in the characteristics of controller itself. Non-linear control systems are characterized by non-linear elements within the actual controller. Non-linear control excels by several potential advantages over

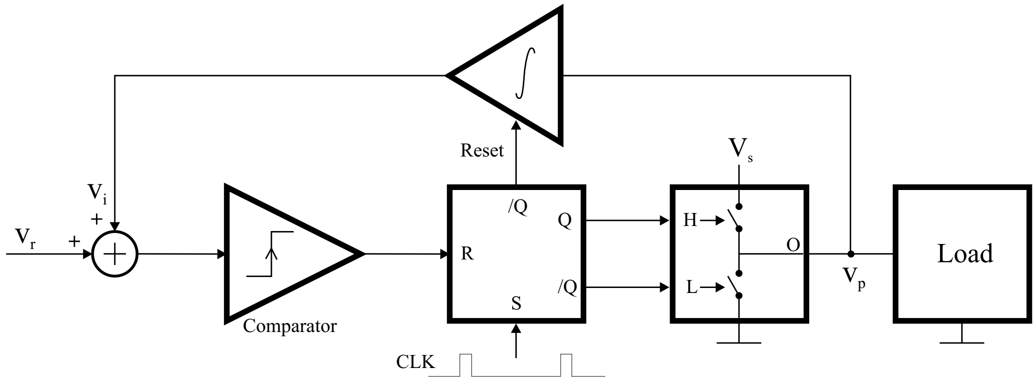

Fig. 8.1 Switching OCC power amplifier topology using single switching leg.

linear control, as unlimited correction corresponding to a sensitivity function of zero. Furthermore, the bandwidth constraints of linear control systems are not necessarily present with non-linear control. Clearly, non-linear control methods are only a viable alternative provided that there are practical implementation strategies. It will become apparent; that non-linear controller synthesis, analysis and verification are significantly different from the analysis methodology used for linear control systems.

8.1 Non-linear One Cycle Control

Fig. 8.1 shows a simple implementation of OCC in a fundamental DC-DC converter application. The controller is simple, consisting of an integrator with reset, a comparator, a flip-flop element and an oscillating clock that determines the carrier frequency. The control scheme involves four fundamental actions that are repeated in every cycle is illustrated in Fig. 8.2:

1. The switching power stage is turned ON by a constant frequency clock with period t_c. This forms the beginning of a switching period.
2. The switched variable v_p is integrated and compared with a reference voltage.
3. When the integrated output v_i reaches the reference voltage v_r at time t_{on}, the comparator output changes state.
4. The comparator state change resets the flip-flop which following turns the switch OFF.

This sequence of actions causes the average value of the switched variable v_p within each switching interval to be proportional to the reference input v_r. If the clock frequency (the carrier frequency) is considerably higher than the bandwidth of the reference v_r, the average of the switched variable, $\tilde{v}_p$, will be determined by the duty cycle $d = t_{on} / t_c$ as:

$$\tilde{v}_p = v_s d \tag{8.1}$$

The integrator output where $v_i = v_r$ is found by simple integration:

$$v_i = v_r = \int_o^{d \cdot t_c} \frac{1}{RC} v_s \, dt = \frac{t_c v_s d}{RC} = \tilde{v}_p \frac{t_c}{RC} \tag{8.2}$$

Consequently, the relation between the reference input v_r and the average of the switched output $\tilde{v}_p$ is a constant gain:

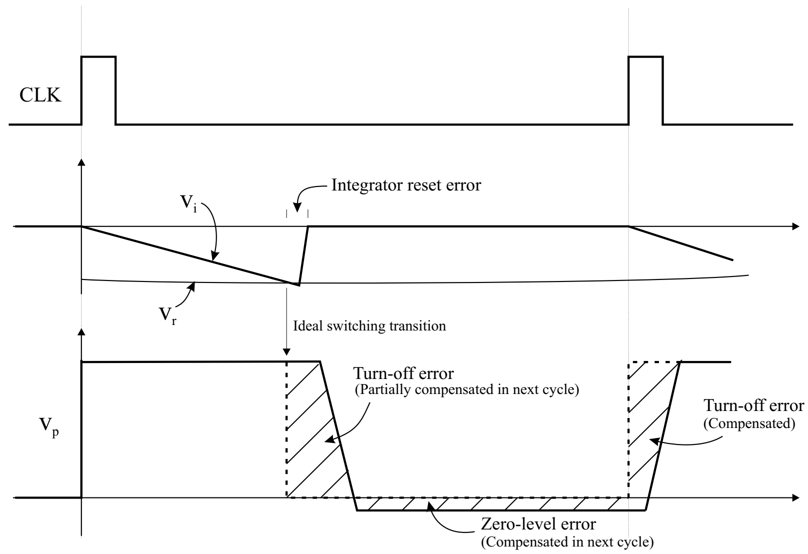

Fig. 8.2 OCC Non-linear control technique

$$K_{OCC} = \frac{\tilde{v}_p}{v_r} = \frac{RC}{t_c} \tag{8.3}$$

The closed loop gain is therefore determined alone by the switching frequency and the integrator time constant. In theory, this control method yields an infinitely fast transient response to steps on e.g. the power rail v_s or the reference input v_r. The equivalent bandwidth of the OCC based system may consequently be considered infinite. Furthermore, the integration does not stop until the output is a constant times the input, i.e. one should intuitively expect a complete elimination of all power stage error sources. This is in perfect harmony with the fundamental control objective, as specified in Chapter 6.

For PMAs (or DC-AC conversion) specifically, another interesting property is that the controller and modulator are in effect combined. The basic system does not involve a discrete modulator, although a clock signal is still required. The troubles of making a carrier generator (or multiples in the case of MICPWM) are saved. The basic topology synthesizes single sided PWM (LADS) in DC-AC applications. The system may as such be considered a modulator that is very robust towards errors, or a modulator with inherent control.

8.1.1 Fundamental limitations

Notwithstanding the appealing characteristics of OCC, there are a range of problems and inherent limitations connected with it practical realization the results presented in PMA applications have been of modest quality. The sources of these problems are discussed in the following, based on the simple two transistor converter in Fig. 8.1.

Propagation delays and finite switching times

An inaccuracy occurs as a consequence of the turn-off characteristic of the power switch, which is delayed and does not happen infinitely fast (see Chapter 4). The turn-off is constituted of the comparator propagation delay, flip-flop propagation delay and the delay from turn-off to the power switch turn-off transition actually happen. These inherent propagation delays combined with finite turn-off time of the switch causes suboptimal modulator/controller operation as indicated in Fig. 8.2. Fortunately, most of the turn-off "area" and zero-level "area" are compensated in the next cycle and OCC is in reality *two-cycle* control.

Reset complications

The implementation of a reset switch is impossible without a reset delay. The switch that performs the reset has to be implemented as a difficult trade-off between speed and switch impedance. A low reset switch impedance is required for a fast integrator reset. On the other hand, a high integrator switch speed is desirable. The finite reset-time leads to a small interval with no feedback in every cycle.

Limited PSRR

It can be shown that perturbations on v_s are only partially compensated by One Cycle Control [Ta97]. The general effects of a perturbation on the power rail are very difficult to analyze, as it is the case with many aspects of non-linear control. It has been shown that the power supply rejection ratio is both dependent on modulation method, frequency ratio and modulation depth. In general, the rejection is below what can be achieved by linear controllers, where the power supply rejection ratio is determined by the sensitivity function exclusively. But then again, OCC is in effect a combined modulator/control system, so a comparison with a linear feedback controlled system is not directly possible.

Stability problems

The extension of the topology in Fig. 8.1 to a PMA application requires a dual supply system for operation in all quadrants. Unfortunately, this extension is not trivial and leads to potential stability problems [La96b]. The only presented solution is a feed-forward of the power rail leading to an increase in controller complexity.

8.2 Enhanced non-linear control

An improved OCC topology is investigated in the following. The non-linear control topology, henceforth reference to as Three-level One Cycle Control (TOCC), is shown in Fig. 8.3. The method solves some of the above outlined problems and errors and furthermore has other pleasant characteristics. The apparent advantages are:

- The controller in effect synthesizes NBDS PWM (see Chapter 3 for NBDS characteristics). NBDS has superior spectral characteristics to two-level PWM waveform as NADS and NADD.
- An improved Power Supply Rejection Ratio.
- Improved stability. There is no need to feed-forward the supply voltage to stabilize the topology. The inherent stabilization reduces the complexity compared to a dual supply system.
- Relatively simple hardware implementation.

As seen on Fig. 8.3 the full bridge TOCC based PMA consists of to independent parallel sections that are synchronized by the same clock. Each of the controller legs needs an offset v_f added to the input in order to allow the output swing to have symmetric limitations. Perturbations on the power rail result in similar errors at the two outputs now only generating a common mode error. Consequently, the TOCC topology improves PSRR compared to normal OCC. Still, it is not possible to eliminate the dependency of power supply perturbations.

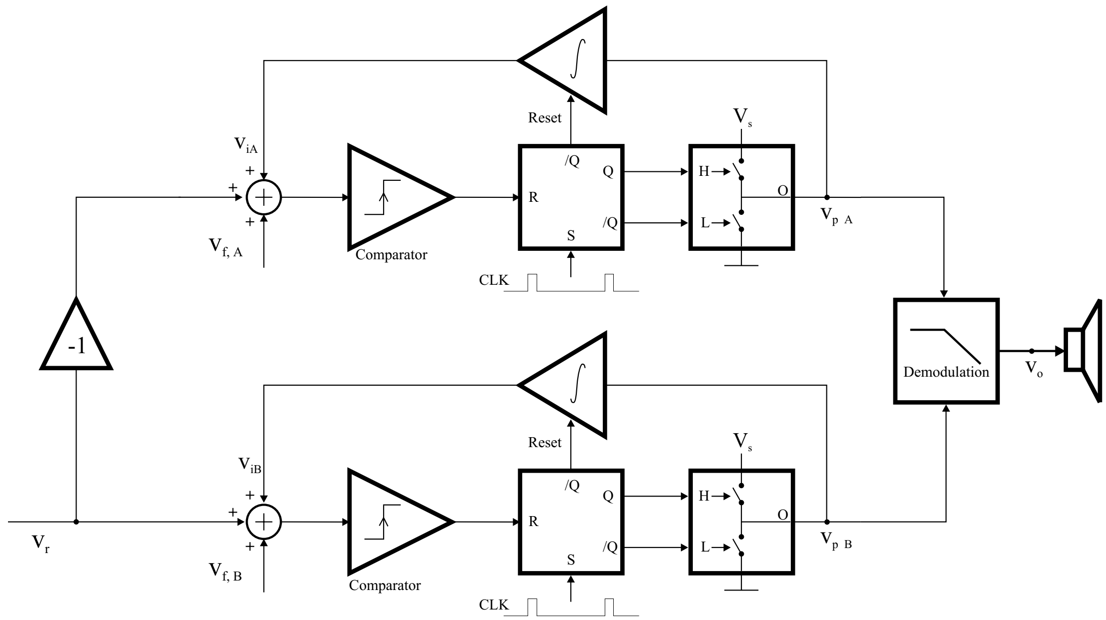

Fig. 8.3 Three-Level One Cycle Control (TOCC) effectively synthesizing NBDS PWM.

8.2.1 TOCC synthesis

The synthesis and optimization of a TOCC based PMAs requires the following fundamental steps:

- Design of power stage to meet power and bandwidth specifications.
- Design of the integrator w. reset to meet the gain specification.
- Verification of the system through non-linear simulation
- Implementation and verification in hardware.

Due to the nonlinear nature it is not possible to base the controller synthesis and optimization on a linear model of the system. The design has to be carried out a low circuit level.

8.2.2 TOCC non-linear modeling and simulation

A non-linear simulation model, shown in Fig. 8.4, has been developed using PSPICE to provide means for a detailed investigation of the behavior of the modulator/control system. The model is used throughout the following for both functional simulations with an ideal power stage and for parametric investigations where the correction effect towards non-linear behavior is investigated. The model is as ideal as possible with controllable perturbing parameters and allows analysis of one problem/effect at a time, without losing the connection between cause and result.

The integrator w. reset is modeled as shown in Fig. 8.5. It is impossible to implement the integrator fast enough using just one switch connected across the integrating capacitor. One way of achieving near instantaneous reset is by using two integrator capacitors and a more complex switch network. Only one of the two capacitors is active at a time and the other shorted, when a fast reset is needed the shorted capacitor is made active and the other is shorted. This configuration leaves one switch period to discharge a capacitor, and the swiftness of the reset is now determined only by the speed of the switches interchanging and discharging the capacitors. There are two serious drawbacks of this integrator

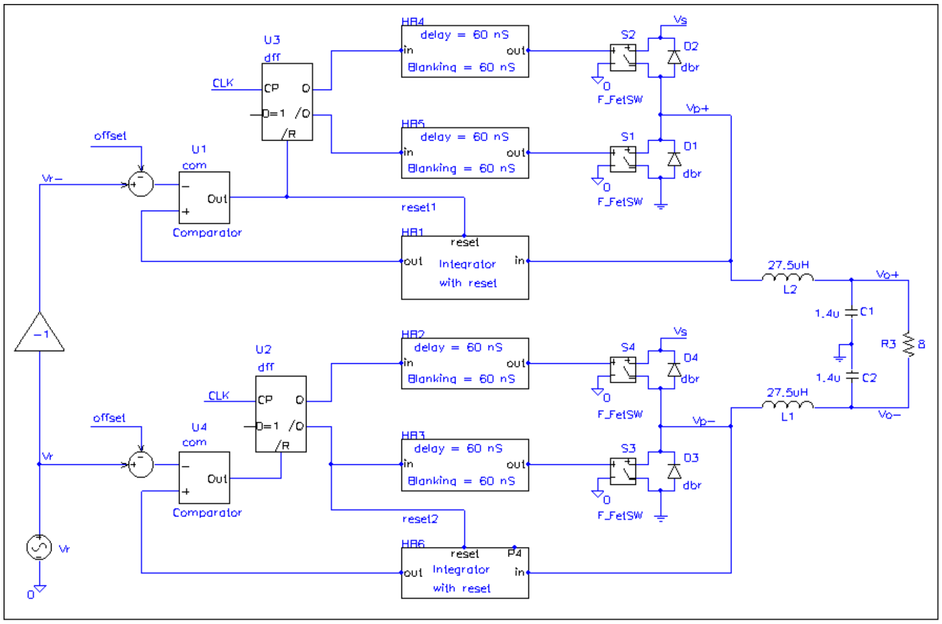

Fig. 8.4 PSPICE Model of TOCC system.

topology: The capacitors have to be matched to keep K_{OCC} constant, and the multi-switch topology is certainly not simple. The total reset capacitance is constituted of the parasitic capacitance of the switch and the integrator capacitance.

8.2.3 TOCC case example

A case example is subjected to a more detailed investigation in the following:

- The amplifier is designed for the full audio bandwidth, with a maximal power output of 350W in 8Ω. The desired power range requires a bus voltage V_S for the bridge of 80V.
- The carrier frequency is selected to be 300KHz.
- The maximal signal level at the integrator output is specified to 2.5V.

With these fundamental components now determined, the resulting system gain for each individual system on each side of the load is:

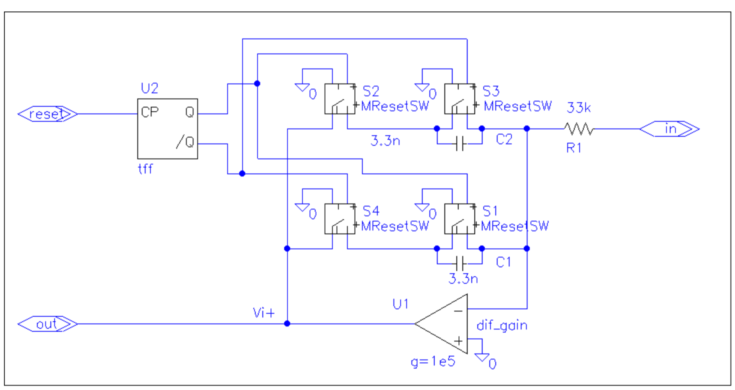

Fig. 8.5 Integrator w. reset (PSPICE model).

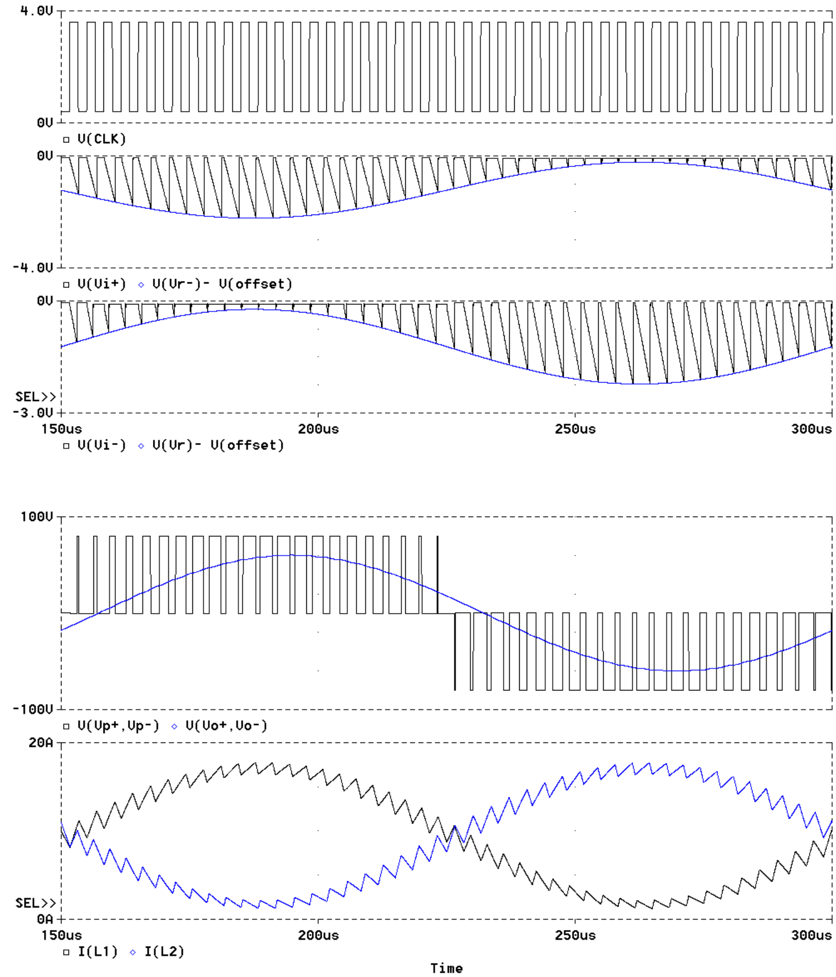

Fig. 8. 6 Functional simulation of case example with TOCC. From top to bottom: (1) Common clock, (2)-(3) control signals on both sides in terms of integrator output v_i and reference $v_r - v_f$, (4) Differential power stage output and demodulated output. (5) Inductor currents in the output stage illustrating the balanced drive of the load.

$$K_{OCC} = \frac{V_S}{\hat{v}_i} = 32 \tag{8.4}$$

The resulting system gain is doubled to 64 since the amplifier output is the difference between right and left side OCC systems. From (8.3) the time constant is determined:

$$RC = t_c K_{OCC} \tag{8.5}$$

With the specific integrator model the specification of R and C are not crucial, and R=33K and C=3.3nF are chosen arbitrarily to realize the time constant. Nevertheless, there are several factors to consider regarding the practical implementation. These implementation issues are addressed in Chapter 10.

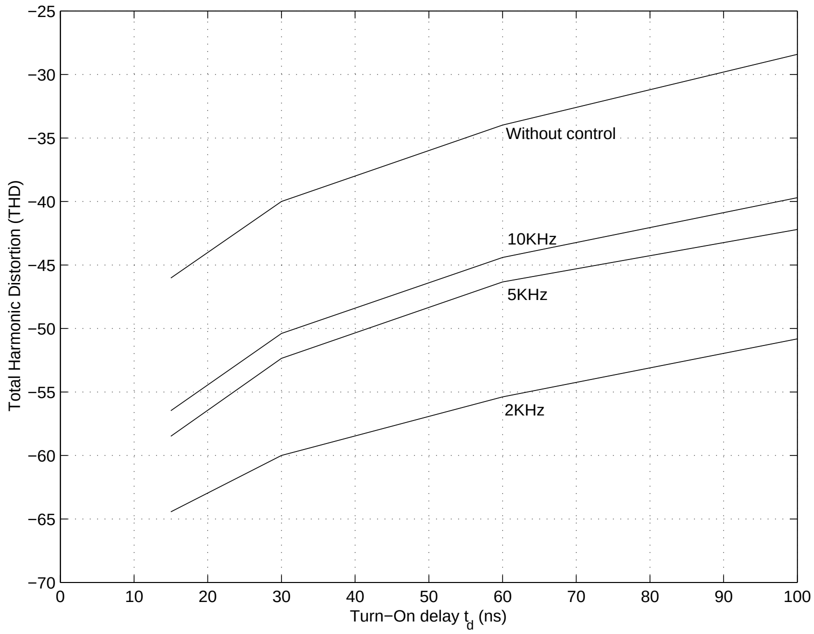

Fig. 8.7 Simulation of correction of PTE. THD vs. blanking delay t_d is investigated without control and with the TOCC controller.

Functional simulation

The functional verification of the TOCC based PMA is shown in Fig. 8. 6. The simulated system gain is 64 as expected. Observe the clear three-level nature of the differential output corresponding to NBDS modulation.

Correction of PTE

It is very interesting to investigate the correction of any kind of non-linearity that is introduced with the switching power stage, since this is very difficult to predict by theoretical investigations. Despite the non-linear nature of the controller, it is reasonable to expect a similar correction of all types of errors. However, it is difficult to predict the parametric dependency of the correction, i.e. the dependency on frequency and modulation depth. A complete investigation of various error sources within the complete frequency and power range would lead to an exhaustive set of simulations. Hence, a limited but accurately selected set of points within the parameter space has been selected for simulation. This comprises the following limited set of parameters:

- Frequencies 2KHz, 5KHz and 10KHz.
- Modulation index = 0.9.
- Blanking delays 0ns - 100ns.

Fig. 8.7 shows the simulated results. It is concluded that the controller does provide correction of errors from the PTE category, but the correction is strongly dependent of frequency. The suppression resembles what can be achieved by the linear VFC2 topology, both in terms of magnitude and frequency dependency. This is certainly somewhat disappointing, given that TOCC in theory should cancel PTE completely.

Correction of PAE

The effects of pulse amplitude errors are investigated by a simulation a perturbed system where a large 5KHz error signal of 40Vpp is superposed on the supply voltage. The signal frequency is 20KHz and the modulation index 0.75. Fig. 8.8 illustrates the control signals and resulting demodulated output. Clearly, the intermodulation is not visible in the time domain output. A frequency domain analysis reveals intermodulation components of 300mV at 15KHz and 25KHz corresponding to a power supply rejection ratio of about 30dB. Simulations at lower frequencies and lower modulation indices show improved power supply rejection than in this worst-case situation. This is to expect from previous investigations of OCC [Ta97].

Stability and Overload

One cycle control methods (TOCC included) have very distinctive characteristics regarding stability, robustness and overload. These are investigated in the following on the basis of the TOCC-model. One cycle control differs from linear control methods by exhibiting excellent stability characteristics. Fig. 8.9 shows the ideal response to a 20KHz square wave input with modulation index 0.5. The major benefit is that the control loop / modulator bandwidth can be considered infinite. The frequency response is exclusively determined by the demodulation filter. Furthermore, the controller is inherently stable and independent on any perturbation within the power stage. In terms of stability and robustness, the non-linear controller has indisputable advantages over the linear control methods that have been investigated throughout section III of this thesis.

It terms of overload, the TOCC based PMA also differs considerably from general linear control. The simulation model is used to investigate the effects of overload. Fig. 8.10 shows the essential control variables and output signals in with 5% over modulation. Clearly, even minor over modulation has dramatic effects on the output, since this immediately introduces completely *missing pulses* as opposed to the expected *full pulse* corresponding to a 100% duty cycle. The output distortion in this particular case is more that 10% or about an order of magnitude higher that would normally be expected at this level of overload. Needless to say, control circuitry is needed to limit both minimum and maximum duty-cycle. Such limiting circuitry adds complexity to the resulting system.

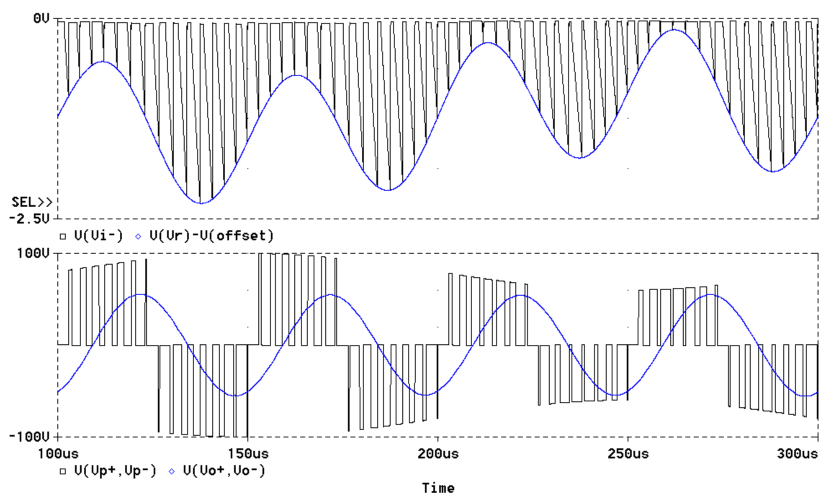

Fig. 8.8 Investigation of the effects of large 5KHz, 40Vpp perturbation on the power supply. Signal frequency and modulation index are 20KHz and 0.75, respectively. No intermodulation is visible from the time domain output. The non-linear controller provides a PSRR of 30dB in this worst-case situation.

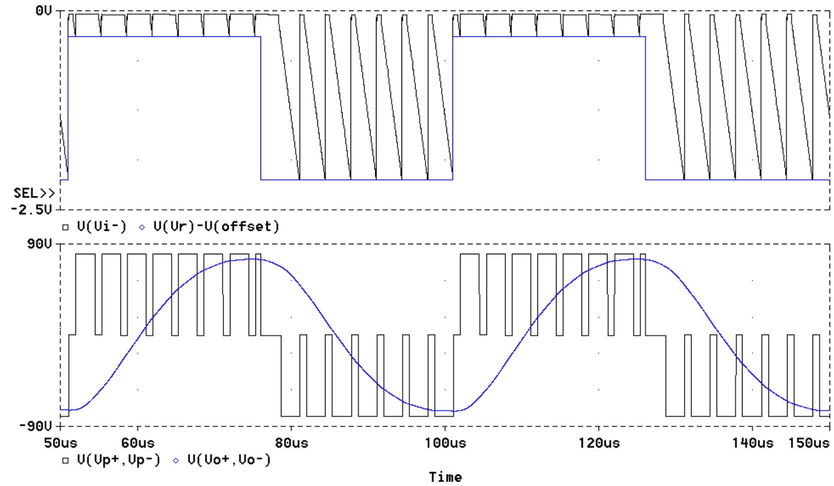

Fig. 8.9 Simulation of response to a 20KHz squarewave input. TOCC realizes ideal stability and transient response since the controller is inherently stable an the equivalent bandwidth is infinity.

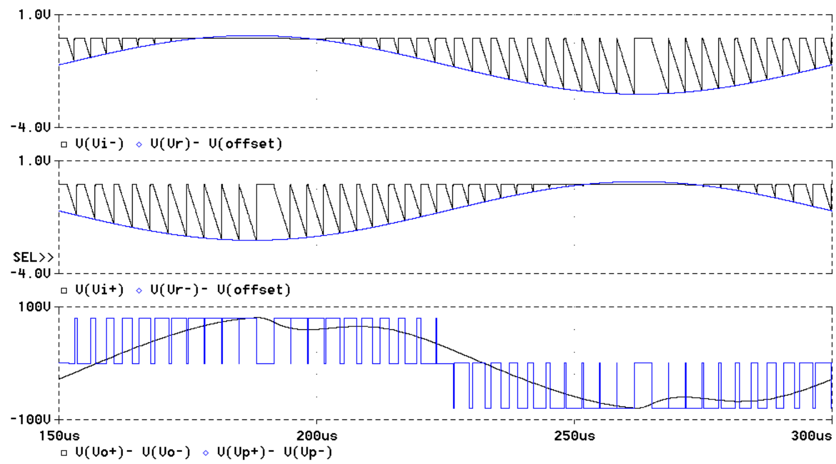

Fig. 8.10 Simulation of TOCC based system with 5% over modulation. The consequences of over-modulation are dramatic due to completely *missing* pulses as opposed to normal clipping with full (100% duty cycle) pulses.

8.2.4 TOCC extensions

An obvious extension includes the application of double-sided modulation to synthesize NBDD, which has further improved spectral characteristics compared to NBDS, as it was found in Chapter 3. However, implementation of double sided modulation significantly complicates the implementation [Ta97]. In addition, all error sources present within the single sided controller will also be present when using double-sided modulation. The improved characteristics come at a high cost, and will do nothing with the fundamental problems within the controller.

The application of a global feedback (VFC1) is possible to improve performance. For global feedback to be applied it is vital to limit the modulation index at the modulator section. However, a linear feedback loop is considered an irrational extension, since this leaves the system with all the design constraints of linear control systems, whereby the advantages of non-linear control vanish. The system might as well be realized by VFC1 or any of the more powerful linear control schemes as MECC in combination with conventional PWM.

8.3 Summary on non-linear control

The application of non-linear control methods for analog PMAs has been investigated in with focus on One Cycle Control. Non-linear control excels by potentially unlimited correction corresponding to a sensitivity function of zero. Furthermore, the bandwidth constraints of linear control systems are not necessarily present with non-linear control.

The basic OCC properties and failings were reviewed, and an enhanced three level non-linear controller (TOCC) that effectively synthesizes NBDS PWM has been devised. The topology offers improved modulation, robust realization without stability problems and relatively simple implementation. A PSPICE model was developed to evaluate the general correction capabilities of OCC and to enable a more detailed investigation of the TOCC circuit specifically. The non-linear controller proved indisputable advantages over any linear control method in terms of transient response, stability and robustness to uncertainties.

Unfortunately, the performance in terms of the correction towards PTE and PAE was limited. More fundamental and general constraints of OCC and similar non-linear control methods in general are concluded to be:

- Modeling and optimization is difficult. This complicates the formalization of general design methods.
- Performance improvements cannot be estimated and are difficult to control.
- Lack of flexibility. The system does operate on other feedback sources (as the global demodulated output). The are considerably difficulties in realizing double-sided modulation and other extension, etc.

The general conclusion is therefore that OCC and similar non-linear control schemes are inferior compared to the simple yet powerful control schemes that have been investigated throughout part III of this thesis. Even with significant technological advances, the considered non-linear topologies are not considered competitive with pure linear control.