# Active Hybrid Filter Applied with a Multi-Cell Switch-Mode Power Amplifier

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Abstract-This paper discusses an active filtering method applied on a multi-cell switch-mode power amplifier. One main purpose of this system is to build high quality power sources up to the kW-region. The system is formed by a switch-mode and a linear amplifier. The power allocation of the two parts is approximately 10:1 depending on the operation mode of the system. The switch-mode power amplifier is realized by a multicell amplifier with a passive LC-filter, which is actively damped by feeding back the capacitor current. The workload of the linear amplifier is influenced by the factors input frequency and load current which are examined in this paper. The benefit of the presented system is the low rated voltage and current of the linear stage. The performance of the whole system's output voltage is demonstrated by measurements in the time domain and by high resolution spectra.

### I. INTRODUCTION

The main target of this paper is to demonstrate the functionality of a multi-cell switch-mode power amplifier (Fig. 1) operated with an active hybrid filter including a correction stage  $u_A$  (Fig. 2). To show the main points of this system, initially a basic multi-cell amplifier without hybrid filter is described shortly. The fundamental background is already published in [1-9]. Different active systems with various compensation concepts are presented in [10-14], whereas basic concepts are shown theoretically and by measurements. Each concept has different advantages and drawbacks, referring to the compensation system of the amplifiers. Some compensation stages have to deliver high



Fig. 1. Multi-cell amplifier with passive LC-Filter.

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current, some high voltages in relation to the total system parameters. One advantage of the here presented system is a simpler control concept with fewer measurement efforts. Another one is a more efficient damping method of the passive LC-filter. Passive damping of an LC-filter has, in contrast to active ones, the drawback of ohmic losses, reducing the efficiency of the total system. Series connected damping systems have the disadvantage of voltage drops and a high current flow over the relevant components.

## II. PASSIVE MULTI-CELL AMPLIFIER

## A. PWM-modulation and LC-Filter with active damping

Due to the fact, that a passive filter is theoretically not stable without a load resistor, an active damping concept, feeding back a proportional value of the capacitor current, is implemented and described. As shown in Fig. 1 the multi-cell amplifier consists of N series connected H-bridge converters operated with phase shifted signals. Each DC-link voltage, which is supplying one cell, has a value of U/N and the total



Fig. 3. Passive LC-Filter with active damping.



Fig. 4. Cell output voltages *u*<sub>ab,i</sub>, sum voltage, inductor current.

output voltage of the system is  $\pm U$ . The well-known multicell system [1, 10-11] is driven by phase shifted PWMsignals with a MOSFET switching frequency of the half bridge branch of  $f_{\rm S}=1/(2T)$ . The single bridge voltages  $u_{\rm ab,i}$ show a phase shift of T/N which is depicted in Fig. 4. The sum voltage  $u_{SW}$  of all cells shows a switching frequency of  $2Nf_{\rm S}$  and can be defined as  $\sum u_{\rm ab,i}$ . Depending on the number of cells, the maximum inductor ripple current  $\Delta I_{max}$ downscales by the factor  $N^2$  and the maximum capacitor voltage ripple  $\Delta U_{\text{max}}$  downscales by  $N^3$  [1]. It has to be mentioned that an increase of the number of cells N has a significantly higher influence on the maximum inductor current ripple and on the maximum capacitor voltage ripple as an increase of the switching frequency. One can see that for more than four cells the influence on the ripple is small. The ripple reduction is here only in the single-digit



Fig. 5. Maximum ripple current  $\Delta i_L$  (dark blue) and ripple voltage  $\Delta u_C$  (light blue) depending on *N*.

percentage range. These facts are illustrated in Fig. 5 for the maximum voltage and current ripple ( $\Delta U_{\text{max}}, \Delta I_{\text{max}}$ ) scaled in percents over the number of cells N.

## B. System description

The three main factors influencing the amplitude of the correction voltage of the linear amplifier are:

- the amplitude of the DC-link voltages of the cells U/N
- the difference of the single DC-link voltages
- the load current

To analyze and estimate the amplitude of the linear amplifier of the hybrid filter (Fig. 2), the model of the passive filter with active damping by the feedback of the capacitor current has to be considered. A simplified model of the system is shown in Fig. 3. The gain block with the factor k = 10 represents the multi-cell amplifier. In the frequency/Laplace domain the current through the filter capacitor  $I_{\rm C}$  can be calculated as

$$I_C = sCU \tag{1}$$

with U as output voltage. The current through the inductor is the sum of this current and the load current I

$$I_L = I + sCU \,. \tag{2}$$



Fig. 6. Bode-diagram of  $Z_{OUT}$  ( $L = 100 \ \mu\text{H}$ ,  $C = 4 \ \mu\text{F}$ ,  $R = 0,707 \ \Omega$ ).

Furthermore, the voltage across the inductor is determined as

$$U_L = (I + sCU) \cdot sL \,. \tag{3}$$

As a result of (1) to (3) the output voltage can be calculated according to

$$U = 10 \cdot U_I \frac{1}{1 + s10RC + s^2 LC} - I \frac{sL}{1 + s10RC + s^2 LC} \cdot (4)$$

Summarizing (4) the transfer function of the system without load  $G_{\text{RLC}}$  as well as the output impedance  $Z_{\text{OUT}}$  can be deduced

$$U = U_I \cdot G_{RLC} - I \cdot Z_{OUT} \,. \tag{5}$$

The diagram in Fig. 6 shows the frequency behavior of the output impedance  $Z_{OUT}$  which is responsible for voltage drops of the output voltage U. This load current I dependence of the output current can be found evidently in (4) and (5), respectively.

In no-load condition (I = 0) the system can be seen as  $2^{nd}$  order transfer function with a damping ratio adequate for sufficient stable poles.

The output impedance of the filter  $Z_{OUT}$  is a second order system with the cut off frequency of

$$f_C = 1/(2\pi\sqrt{LC}). \tag{6}$$

From (1) and (4) one gets

$$I_{C} = 10 \cdot U_{I} \frac{sC}{1 + s10RC + s^{2}LC} - I \frac{s^{2}LC}{1 + s10RC + s^{2}LC} .$$
 (7)

Applying the parameters from table I, it could be estimated, that up to the 10 kHz region the function of (7) can be approximated with (1) as shown in Fig. 7. As an example, the peak value of the capacitor current can be calculated for the maximum output voltage of 100 V and a frequency of 400 Hz to  $I_C = 1$  A. For the same output voltage and a frequency of 100 Hz the current now has only a value of  $I_C = 0.25$  A which is a fourth. With these examples it can be recognized that the linear amplifier must deliver/absorb currents of up to 1 A plus the ripple current  $\Delta I$  of the system in this realization. A higher frequency than the rated frequency could only be driven with a reduced amplitude of the output voltage  $u_0$ . Due to the physical characteristics of the filter capacitor *C*, a phase shift of 90° can be observed.



Fig. 7. Capacitor current  $i_{\rm C}$  over frequency for  $U_{\rm O} = 100$  V.

#### III. ACTIVE HYBRID FILTER

### A. Basic principle

The presented active hybrid filtering system (Fig. 8) consists of a switch-mode power amplifier, which is delivering a high percentage of the whole output power. In combination with this part of the system, based on a class D realization, a small linear amplifier is used only for a fractional part of the total system power. The linear amplifier has the purpose to compensate low frequency harmonics, which can not be suppressed sufficiently by the passive LC-filter. These unwanted spectral components are arranged in the pass-band region or rather in the region around the cut off frequency of the LC-filter. Another advantage of this hybrid filter concept is the fact that it also compensates the switching noise beside other noise components of the output signal. The linear amplifier operates as correction stage and delivers the correction voltage  $u_A$ . The output voltage  $u_0$  is formed by  $u_0 = u_C + u_A$ . (8)



Fig. 8. Control model of the active hybrid filtering system.

It has to be mentioned that the linear amplifier must also be able to deliver / absorb the capacitor current  $i_{\rm C}$ . Its dimension range and frequency-dependence are already examined in chapter II. The maximal amplitude of this current defines also the absolute maximum rating of the linear amplifier's output current, which is limited by the frequency value of the input voltage  $U_{\rm I}$ . The current flowing over the linear amplifier



Fig. 9. Output voltage for balanced (a) and non-balanced (b) cell voltages; blue traces: standard (i.e., open-loop) multi-cell switch-mode amplifier; red traces: multi-cell amplifier based on the proposed hybrid filtering technique. Cell voltages: 27.5 V - 27.5 V - 21 V - 27.5 V.

mainly consists of the frequency dependent current over the impedance formed by the filter capacitor C and the ripple of the current over the inductor L.

The presented system, which was also built up as a prototype set-up, acts as high quality voltage source up to the kW-region. To use the amplifier's full potential, it has to be fed by an also high quality signal source, like an oscillator or a high grade function generator with an output voltage range up to  $U_{\rm I} = \pm 10$  V. The gain of the whole amplifier system is defined as  $k_{\rm PWM} = U_{\rm O}/U_{\rm I} = 10$  resulting in a peak output voltage with a maximum value of  $U_{\rm O} = \pm 100$  V (limited by the control system).

The system realized in the prototype in Fig. 14 consists of N = 4 cells with a DC-link value of U/N = 25 V which allows a nominal output voltage of maximal U = 100 V. Due to the control concept, also if the cells are fully charged to 27.5 V, the output voltage is naturally 100 V. This is realized by adapting the duty cycle and voltage amplitude level  $u_A$  of the linear amplifier. If the cell voltages are the same for all cells (e.g. 25 V), the compensation power is low. If the cells are at the minimum cell voltage of 21 V, the voltage drop must be compensated by the linear amplifier to get an appropriate output voltage. That means for an extreme case of  $4 \times 21$  V, that the linear amplifier must deliver full amplitude  $u_A$  to reach the desired maximal voltage.

## B. Simulation model

In Fig. 9 simulation results of the hybrid filter system for different DC link voltages are shown. The used simulation model can be looked up in the simplified block diagram depicted in Fig. 8. This circuit diagram containing the series connection of H-bridge circuits with different DC-link voltages is summarized in the block MZ. The PWM-block connected before represents the phase shifted PWMgeneration unit for the multi-cell amplifier. For active damping of the LC-filter, the capacitor current is fed back over the value R<sub>FB</sub>. For an optimal operation of the whole system the positive feedback of the compensation voltage  $u_A$ is needed essentially [3]. Due to the fact that the multi-cell amplifier has a gain factor of the value k = 10, the feedback loops (including  $i_{\rm C}$ ,  $U_{\rm A}$  and  $U_{\rm O}$ ) must contain an adaption factor of 1/10. For the simple reason that the passive LC-filter with active damping produces a phase shift compared to the input signal  $U_{\rm I}$ , a filter block F(s) with the same phase behavior as the active damped LC-filter is needed [8]. This indispensably needed block has the purpose to minimize the difference of  $U_{\rm I}$  to  $U_{\rm O}/10$  and results in a reduction of the amplitude and power dissipation of the linear amplifier part. The voltage controlled source V and subsequent frequencydependent gain block represent the linear amplifier including the high performance operational amplifier. The relatively high transit frequency  $f_{\rm T}$  can be seen in the sketch of the bode-diagram block and subsequently the output resistance of the amplifier is represented by  $R_{\rm A}$ .

The simulation results of a multi-cell system with passive LC-filter are shown by the blue signal in Fig. 9. The low

frequency signal components of the multi-cell system are in the region of the switching frequency of a single cell  $f_{\text{CELL}} = 2f_{\text{S}} = 20 \text{ kHz}$  and can be noticed in the time domain signal for unequal DC link voltages (b) very obviously. Over this signal the ripple of the sum voltage  $u_{SW}$  with a frequency of  $f_{\text{SUM}} = 2Nf_{\text{S}} = 80 \text{ kHz}$  is overlaid. In the blue signal trace with the designator (a) for equal DC-link voltages only the frequency components of the sum voltage  $f_{SUM}$  can be seen. The red signals represent the output voltage  $U_0$  of the hybrid filter system for equal (a) and unequal (b) DC-link voltages. Both signals show very low amplitude harmonic components neither in the region of the switching frequency nor of the sum frequency. Only residual distortion signal components in the region of few mV can be noticed. Equal (balanced) cells means, that all cell voltages have the same value of U/N = 25 V. In contrast unequal (non-balanced) cells have different voltages (e.g. 27.5 V - 27.5 V - 25 V - 25 V) in the simulation.

## C. Compensation stage

In the presented system the maximum amplitude of the compensation voltage  $u_A$  has a value of less than 15 % of the highest possible output voltage of the total system  $u_0$ . The  $\pm$  15 V powered linear amplifier is designed for compensating the relative small ripple of the output voltage and the load current ( $I_0$ ) dependent voltage drop. Furthermore, reduced DC-link voltages of the batteries U/N, caused by increased load conditions, must be balanced. Further transients caused by e.g. gating time errors, errors of the driver and blanking time errors are also compensated.

The correction stage is realized by a high frequency operational amplifier delivering the input signal for a linear class AB current buffer with predefined quiescent current. This is achieved by a bias voltage on the base of the complementary transistors. The feedback loop of the linear amplifier contains the filter capacitor *C* forming a closed loop hybrid filter system. For designing the compensation amplifier, it has also to be mentioned that the ripple current of the multi-cell system  $i_{SW}$  has to be delivered / absorbed by the linear amplifier.



Fig. 10. Source: Signal generator Farnell LMF4 – 100 Hz (10 V corresponds with -10 dB).

## IV. MEASUREMENT RESULTS

To demonstrate the signal quality of the output voltage of the switch-mode power-amplifier with active hybrid filter system, spectral measurements with two typical frequencies were done. As signal source an oscillator based high quality signal generator was used. In Fig. 10 the output signal of this generator feeding the amplifier is shown with a frequency of f = 100 Hz.



Fig. 11. Hybrid filter fed by signal generator Farnell LMF4 – 100 Hz (10 V corresponds with -10 dB).

This signal has very low noise components, which are in the 1 mV region and below. A single prominent spectral line can be seen at the third harmonic, which is 70 dB below the fundamental component ( $U_1 = 7.5$  V,  $U_3 = 3$  mV – peak values). Beside that there are no relevant harmonics and distortion components in the spectrum. The hybrid filter, which is fed by the signal generator shows, operated with a 7.5 V / 100 Hz signal, components in the region of the switching frequency and multiples of it (10 kHz, 20 kHz, etc.). It has to be pointed out, that the third harmonic in the output signal of the amplifier is not generated by the hybrid filter system itself, but by the signal source.

Also the 400 Hz signal shows noise with a magnitude of 10 mV with some slightly increased components up to a



Fig. 12. Hybrid filter fed by signal generator Farnell LMF4 – 400 Hz (10 V corresponds with -10 dB).

dimension of 20 mV. The measurement results for a frequency of f = 100 Hz are shown in Fig. 11 and for f = 400 Hz in Fig. 12.

The measurements were done with a PC sound card via a 1:100 probe with following parameters: Sampling rate: 96 ksps, resolution: 24 bit, measure Window-Type: Blackman<sup>2</sup>. This extremely high resolution makes it possible to measure voltages at the input of the sound card in the  $\mu$ V-



Fig. 13. Hybrid filter fed by signal generator Farnell LMF4  $R = 9.4 \Omega$ , f = 100 Hz: Yellow:  $u_{out}$ , pink:  $i_{out} = 5$  A/div, magenta:  $i_{SW} = 5$  A/div, green:  $u_A$ .

region. The acceptable sampling rate is in that setting adequate to show the suppression of the low frequency harmonics in the region of the switching frequency.

The time domain signal for the 100 Hz spectrum is depicted in Fig. 13 and shows the output voltage of the amplifier system  $u_0$ , the compensation voltage  $u_A$ , the load current  $i_0$ and the inductor current  $i_L$  for an ohmic load of  $R = 9.6 \Omega$ . Due to the comprehensibly high amplitude, the low voltage amplitude harmonics are not visible here.

Besides, this hybrid filter technique is also able to drive inductive, capacitive and non-linear loads as a B2 bridge rectifier with capacitor smoothing [10].

### V. PROTOTYPE

The realized prototype shows eight 12V / 7Ah lead acid cells, where two are series connected respectively to reach 21-27 V depending on the state of charge (Fig. 14: region F). These four DC-voltage supplies are connected via cables to the amplifier PCB-board. Area A shows the linear amplifier realized by 15 parallel connected class AB stages and a high dynamic operational amplifier of the type THS4631 with a transit frequency of  $f_{\rm T} = 160$  MHz. Ten pieces of flat wire inductors with a value of 10 µH (and low series DC resistance each) are serial connected in region B and forming a sum inductance of  $L = 100 \,\mu\text{H}$ . The output capacitance is placed in sector C and has a total value of 4 µF. In the region D four series connected H-bridge inverters are located with isolated control signals. The power for the different H-bridge drivers is generated by small isolated DC/DC converters. These cells are equipped with low voltage / low R<sub>DS,on</sub> MOSFETs. To reduce voltage drops and to avoid a pulsed current through the batteries, bulk capacitors are connected in parallel to the

each cell. On the left side of the board a PWM-generator delivering the phase shifted signals for each converter is situated (region E). The measurement of the capacitor current for the active damping is done by a small transformer situated between A and C. The input signal is delivered over a shielded BNC-cable from an external high grade signal source. Under the transistors of area A a heat sink for cooling and thermal coupling of the components is mounted.



Fig. 14. Prototype of the hybrid filter system.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Output voltage (max.)	$\hat{u}_o = \pm 100 \mathrm{V}$
Frequency range	DC 400 Hz
Load region	up to $R = 5 \Omega$
(ohm-ind-cap)	$C_L = 100 \ \mu F$ , $L_L = 2 \ mH$
	@ max. 400 Hz
Cell voltage (nom.)	$U_{cell} = 25 \text{ V} (\pm 10 \%)$
Linear stage supply	$U' = \pm 15 \text{ V}$
Filter inductor	$L = 100 \ \mu H$
Filter capacitor	$C = 4 \ \mu F$
MOSFET sw. frequ.	$f_s = 10 \ kHz$
Total switching	$f_{SUM} = 80 \ kHz$
frequency	$(N \cdot f_{cell} = 4 \cdot 20 \ kHz)$
Number of cells	<i>N</i> = 4

## CONCLUSION

The active hybrid filtering concept described in this paper was demonstrated with a switch-mode multi-cell H-bridge power amplifier. As compensation stage for the voltage ripple a linear power amplifier including a high dynamic operational amplifier, followed by a current buffer was used. It could be shown by simulation and measurement results, that the voltage ripple of the output signal was reduced significantly compared to a passive filter concept. On the realized prototype, the residual output ripple was measured by spectral analysis. The remaining minor frequency components were located in the 10 mV region at the switching frequency  $f_S$  and multiples of it. Subharmonics due to different cell supplies are suppressed. The proposed active filter setup is appropriate for high quality voltage sources for an output power up to the kW-region.

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