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UNIVERSAL SYSTEM AND OUTPUT TRANSFORMER FOR VALVE AMPLIFIERS

Menno van der Veen

ir.bureau Vanderveen B.V., Zwolle, 8011 PA – 21A, The Netherlands
mennovdv@noord.bart.nl

Vacuum tube amplifiers have many different topologies like single ended (SE), or push pull (PP), or paralleled push pull (PPP) or cathode follower (CF). These topologies and all their variations are placed into one general system. This gives clear insight into the coupling between vacuum tubes and the output transformer, which functions as an impedance converter between the high impedance vacuum tubes and the low impedance loudspeaker. A new universal output transformer is proposed that can be used for all these topologies of tube amplifiers. This transformer is discussed and results are shown with twenty different amplifiers from the general system.

1. INTRODUCTION

Almost a century after their first introduction, vacuum tube amplifiers still are appreciated for their special qualities. Even now in 2005 many companies design new valve amps which are highly rated by audiophiles. The same is true for musical instrument amplifiers, where especially guitarists like the special musical character of vacuum tube amplifiers.

Earlier research (1-7) about toroidal output transformers has shown that the toroidal transformer is very well suited to function as the impedance converter between the high impedance vacuum tubes and the low impedance loudspeaker. The major reasons are the inherent low non linear distortion and the very small leakage inductance, which allows for a precise tuning of the high frequency roll-off and resonances inside the output transformer.

However, the toroidal transformer is expensive to manufacture and is not often used in musical instrument amplifiers, which are under high market pressure. There mostly less expensive EI transformers are applied.

This new research focuses on these EI transformers, leading to a new concept of an universal output transformer, especially intended for musical instrument amplification.

2. BASIC QUESTIONS

There are many tube amplifiers in the world. All are of different design and concept and quality. Do they have the same basic concept? If this is true, what is the nature of this concept?

Every tube amplifier has its own specific output transformer. Do these output transformers have the same characteristics? If true, what is the general nature of those characteristics?

Suppose, above questions can be answered with "yes", is it possible to design a universal output transformer that will fit into all the valve amplifiers?

If this last question would be true, then there exists a very good reason to design such an output transformer. But, lets first start with question one about the basic concept of tube amplifiers.

3. SYSTEMATICS IN DESIGN

In a tube the current runs from anode to cathode. The voltage on the control grid determines the amount of current and in most situations the control grid does not draw any current. When we wish to extract power from a tube, we should connect the output transformer to where the current runs, also to the anode or to the cathode or to a combination of both. Please note that this first systematic approach delivers three possible choices. Figure 1 shows the situation.

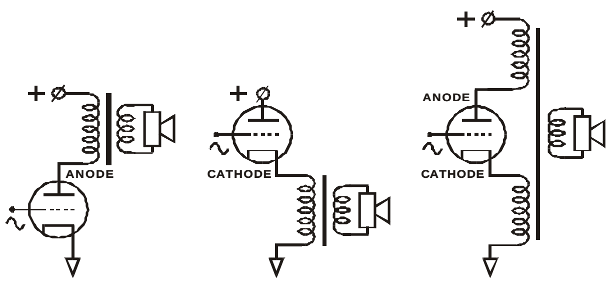

Fig.1. Where to connect an output transformer?

We can use one power tube and connect the output transformer to this tube. The quiescent current of the tube runs through the primary of the transformer. Consequently the core of the OPT has to be gapped, or a kind of balancing current compensation should be applied, or capacitor coupling. This again delivers for single ended three possible choices. See figure 2.

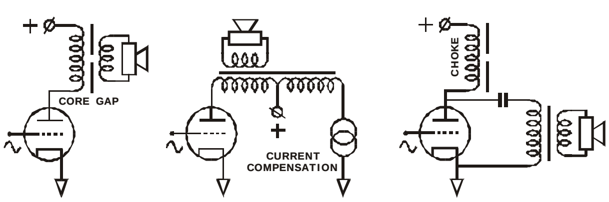

Fig.2. OPT connections for SE applications

The next classification considers push pull amplifiers, where two power tubes are driven with inverted signal phase at their control grids, while their DC quiescent currents cancel out in the center tapped primary. These circuits with all their variations can be divided into basic push pull and paralleled push pull (or configurations like the Circlotron with two separate power supplies).

See for details figure 3. For push pull we know have two new choices.

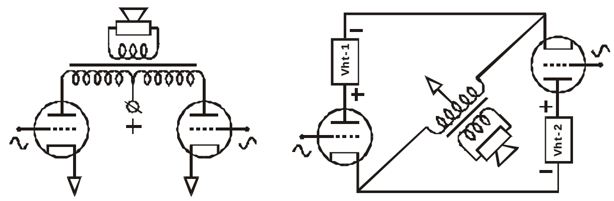

Fig.3. Basic push pull topologies

When using a pentode as power tube, three kinds of local feedback can be constructed with the screen grid. When the screen grid is connected to the anode, we have a triode. When the screen grid is connected to a tap on the primary winding, we have the ultra linear configuration. When we connect the screen grid to a voltage supply (which might be equal to the anode voltage supply) we have a pure pentode configuration. Again we have three new choices available.

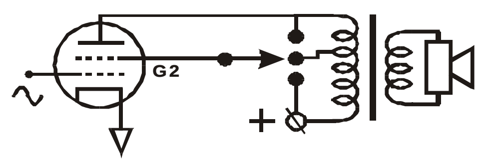

Fig.4. Local feedback with the screen grid

Or we can apply other sorts of local feedback: at the cathode through a separate winding at the output transformer, or at the control grid by means of local feedback with resistors. This delivers two new choices.

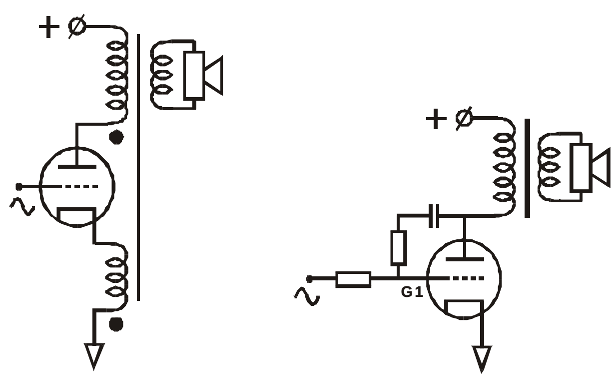

Fig.5. Local feedback with the control grid

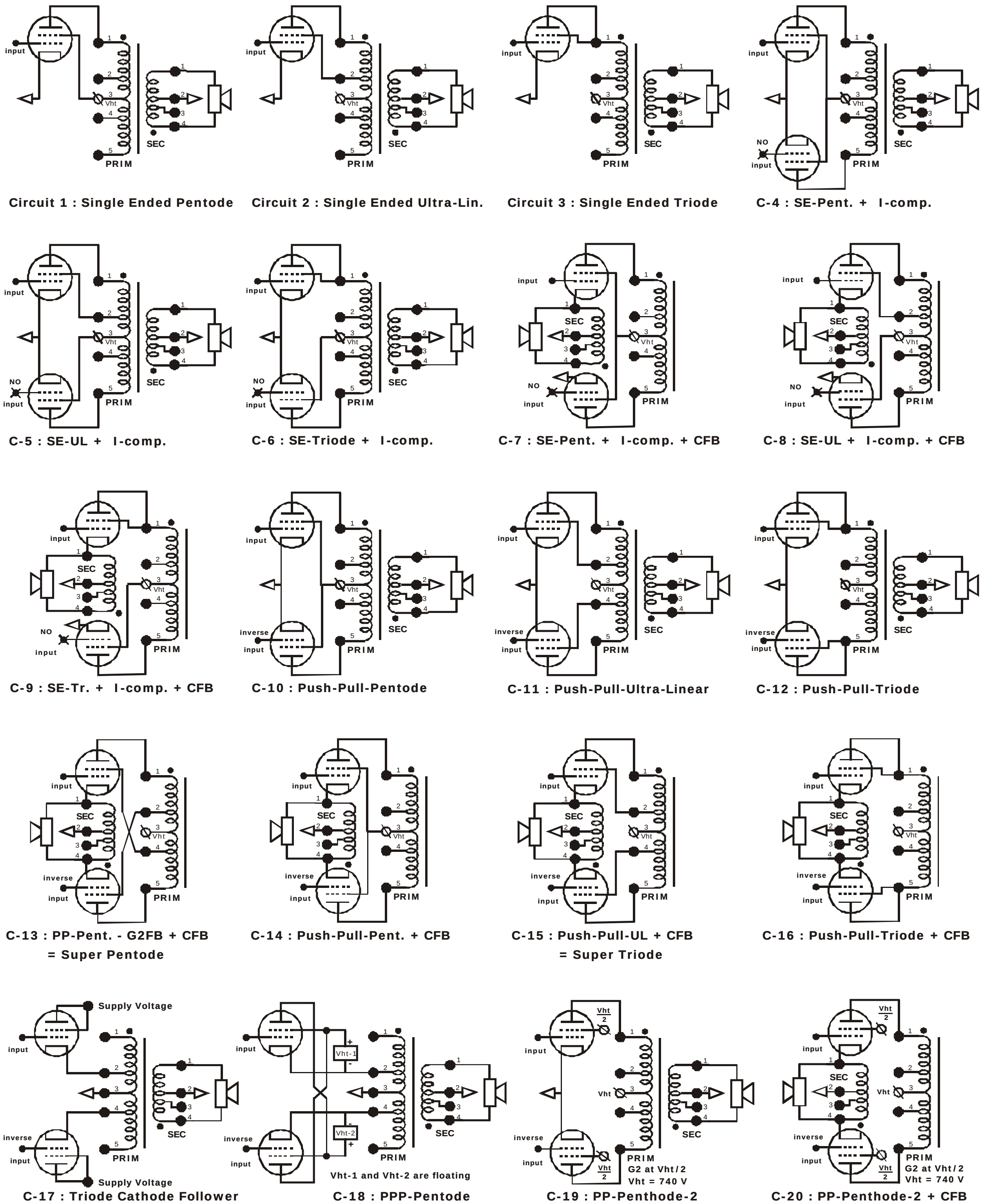

Fig.6. Twenty amplifiers resulting from the general system

When we multiply the number of choices available for SE we get 54 and 36 for PP. In summary, this approach delivers 90 different amplifier concepts, which all are based on one systematic approach of the possibilities offered by tubes. Figure 6 shows 20 of these 90 amplifiers. I built these 20 amps to check the validity of the system, and in the next chapters I will tell more about the results of these tests.

4. SPECIFICATIONS OF THE NEW OPT

Chapter 3 has shown that a general approach delivers an universal system for all tube amplifiers. The next question was: is it possible to derive the specifications of an universal OPT from this system? I approach this question from the practical side, by investigating common features of nowadays musical instrument amplifiers.

One of the most common tubes in guitar world is the EL34 with its American equivalent 6CA7 (which in fact differs from the EL34 because it is a beam power tetrode while the EL34 is a real pentode). Valves like 6L6 and 6550 are also often seen in guitar world. The high-end scene adds the KT66 and KT88 to these choices, but lets stay in guitar world for now. In most amps the high voltage supply is somewhere between 300 and 500 Volt and the power to be delivered by two tubes in push pull should be around 40 Watt. Many guitar amplifiers are over specified in regard to power. Very often the peak power is mentioned, which is a factor 1.5 times the continues output power, depending on the regulation of the power supply transformer. So, 60 Watt in guitar world can be equal to 40 Watt continues power. But, who is able to hear on stage the difference between 40 and 60 Watt (= 1.8 dB)? All these conditions lead to *a primary impedance (for push pull) around 4000 Ohm with a power capability of 40 Watt*.

When one considers high voltage supplies around 700 to 900 V, then *a primary impedance of 8000 Ohm* is optimal. For instance with 2 x EL34 at 740 V, *a continues output power around 70-80 Watt* can be expected.

The maximum output power of an OPT is directly related to its lowest full power frequency. The lowest guitar tone is at 90 Hz and we do wish to hear some resonating of the guitar body. Then the OPT should be able to deliver *80 Watt power at 8 kOhm primary at 40 Hz* to fulfill all these demands. In a 40 Watt amp the same core can handle this power at a frequency 40/sqrt2 = 28 Hz.

Then the –3dB power bandwidth starts at 20 Hz, which opens the door for high end applications.

Suppose we wish cathode follower configurations in push pull topology, then *the primary impedance should range from 500 to 1000 Ohms*.

Suppose we wish to apply this push pull transformer for single ended applications. Then we should gap the core to compensate for the DC-magnetization of the core. Now I am making a clear choice. Gapping the core means that the primary inductance Lp gets much smaller than with a non gapped core. Consequently the exciting current gets much larger in the gapped core (I_{ex} = V / (2.pi.f.Lp). This explains why SE amplifiers often have difficulties in reproducing low frequencies. *I decided to use a gapless core*, and to employ the possibilities of DC current compensation by means of a current source. Such a source is not so difficult to construct with modern semi conductor design, and it removes the huge disadvantage of large and useless exciting currents (which in fact exhaust the single ended tube at low frequencies). Consequently I can apply the standard push pull output transformer for SE applications. I only need to offer a reasonable wide range of *SE primary impedances between 1000 and 4000 Ohm* in practical situations.

When we add to this list of demands a *–3dB frequency range of at least up to 20kHz*, we should model leakage inductance and internal primary capacitance in a careful manner, which puts a demand on the way the windings are placed on the core.

The last important demand is that the *insertion losses in the magnet wire resistances should be less than 0.2 dB*, because in guitar amps the OPT is often used in overdrive, thus preventing the OPT to end its life in flames.

Is it possible to meet all these demands in one transformer? Yes, else I would not have written this paper.

5. THE ACTUAL UNIVERSAL OPT

Figure 7 shows the actual universal output transformer. The total number of primary turns equals Np.

The primary is tapped in the center (power supply connection) and there are two ultra linear taps (at 1/3 and 2/3 times Np). These taps can be used for 33 % ultra linear feedback or for cathode follower applications. The total number of secondary turns equals Ns and the secondary is tapped at 1/2 and 1/sqrt2 times Ns.

The final specs of the universal transformer are: Np/Ns = 22.4; Lp,max = 900 H; Rip = 210 Ohm (total primary winding); Ris = 0.13 Ohm (1-2 = Ns/2); Ris = 0.23 Ohm (1-3 = Ns/1.4) and Ris = 0.47 Ohm (1-4 = Ns); primary leakage inductance Lsp = 20 mH; primary effective capacitance Cip = 800 pF; power capability of the core is 80 Watt at 40 Hz at the onset of core saturation.

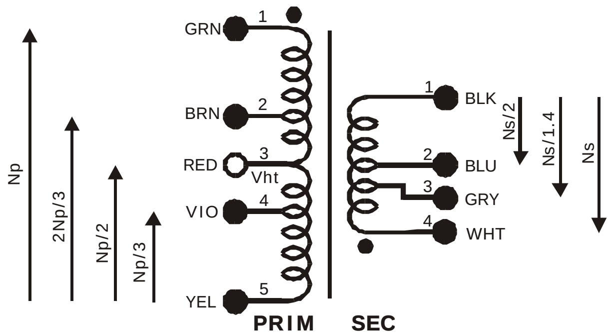

Fig.7. The universal output transformer

When we consider push pull applications of this transformer, table 1 gives the range of impedances that can be handled. Table 2 shows the single ended application between taps 1 and 3 (with the current compensation on tap 5), while table 3 shows the impedances for cathode follower application (cathodes connected to the ultra linear taps 2 and 4). These tables are based on the fact that impedances from secondary to primary transform by $(Np/Ns)^2$ and vise verse.

Zaa 1->5	**Zs 1->2**	**Zs 1->3**	**Zs 1->4**
2000	1	2	4
3000	1.5	3	6
4000	2	4	8
5000	2.5	5	10
6000	3	6	12
7000	3.5	7	14
8000	4	8	16
[Ohm]	[Ohm]	[Ohm]	[Ohm]

table 1: push pull application

Za 1->3	**Zs 1->2**	**Zs 1->3**	**Zs 1->4**
1000	2	4	8
1500	3	6	12
2000	4	8	16
2500	5	10	20
3000	6	12	24
3500	7	14	28
4000	8	16	32
[Ohm]	[Ohm]	[Ohm]	[Ohm]

table 2: single ended application

Zcc 2->4	**Zs 1->2**	**Zs 1->3**	**Zs 1->4**
500	2.3	4.5	9
600	2.7	5.4	10.8
700	3.2	6.3	12.6
800	3.6	7.2	14.4
900	4.1	8.1	16.2
1000	4.5	9	18
1100	5	10	20
[Ohm]	[Ohm]	[Ohm]	[Ohm]

table 3: cathode follower application

Knowing that loudspeakers mostly have 4 or 8 Ohm impedances, one can select with these tables the secondary tapping to adapt optimal to the application. Because the impedance of a loudspeaker is frequency dependant, a tap should be selected with an impedance closest to the nominal impedance of the loudspeaker and not to worry too much when there is not a 100 % perfect match. A match between 70 to 130 % is fine in real applications. Personally I always select the secondary tap impedance to be somewhat smaller than the nominal speaker impedance for lowest harmonic distortion.

6. EXPERIMENTAL SETUP

As said, I tested the twenty amplifier topologies as shown in figure 6. In the circuits 1-17 I used EL34 power tubes at 370 V high voltage supply with a quiescent current of 50mA per tube. In circuit 18 I used two separate supplies of 370 V. In circuits 19 and 20 I added the two supplies to 370 + 370 = 740 V while the screen grids got 370 V.

In circuits 19 and 20 the quiescent current was set to 25 mA per power tube. The power supply is not shown, only is told that this supply contains two fully separated 270V windings, rectified and buffered by 330uF, delivering 370 VDC under quiescent conditions and 340 VDC under full power operation. The supply also delivered Vn = -55 V for the trimming of the quiescent current of the power tubes and for the "current source" R6 of the ECC81 driver and phase splitter tube. See figure 8 for the "audio part" of the universal amp. An example of the interconnections between the power tubes and the OPT is given in figure 9. It concerns circuit 20, which explains how amplifier and OPT can be systematically connected to each other.

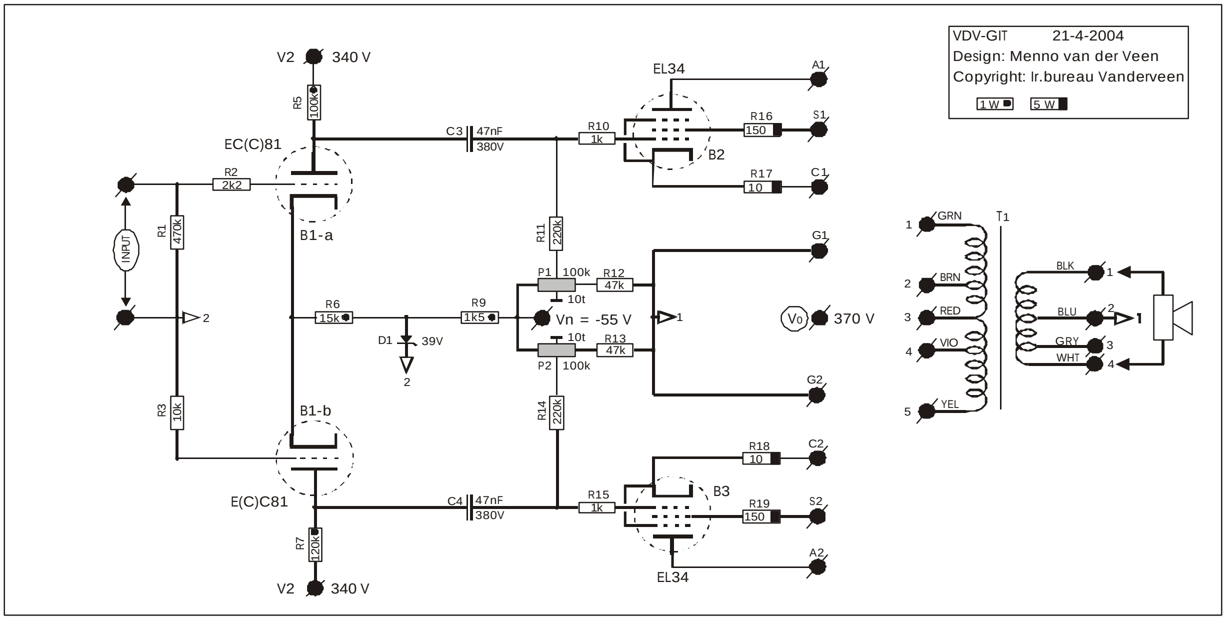

Fig.8. The universal amplifier setup

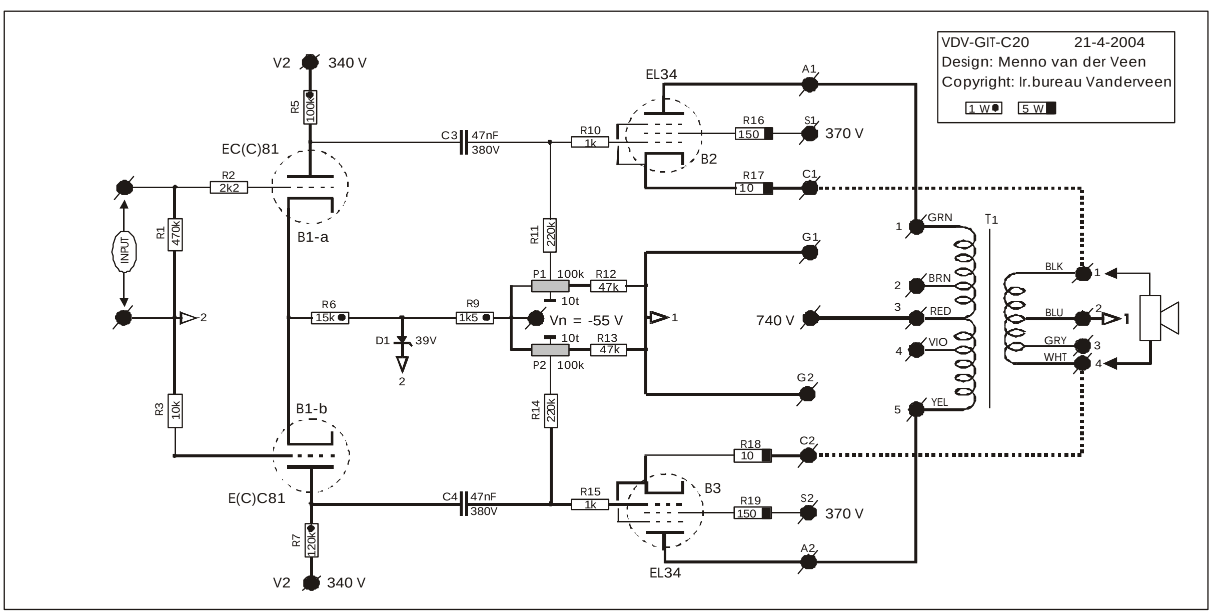

Fig.9. Example of connections for circuit 20

To change the amplifier topology, only some interconnections have to be rearranged, and with figure 6 and 8 combined it will be clear how to do so.

I tested all these amps on the following issues: maximum power (Pmax) at 1kHz at the onset of clipping (to check the primary load line), the lowest -3dB frequency (f-3L) at the loaded output at 8V peak to peak level (to check the primary inductance Lp), the same for the highest -3dB frequency (f-3H) (to check Lsp and Cip), the output impedance (Zout) at the speaker terminals using a 4 Ohm dummy load, and the gain from input to loaded output. With Zout and Gain I was able to determine the amount of local feedback in each circuit.

In circuits 1-9 I connected a 4 Ohm load between secondary taps 1-2, in order to create a primary impedance Za = 2000 Ohm.

In circuits 10-16 I connected a 4 Ohm load between secondary taps 1-3 in order to create a primary impedance Zaa = 4000 Ohm.

In circuits 17-18 I connected a 4 Ohm load between secondary taps 1-2 and loaded the primary between the UL-taps 2-4 in order to create a primary impedance of Zcc = 900 Ohm.

In circuits 19-20 I connected a 4 Ohm load between the secondary taps 1-2 in order to create a primary impedance Zaa = 8000 Ohm.

Subjectively I evaluated the amps in stereo condition, with a high quality pre-amp plus CD-player and loudspeakers and interlinks. With a restricted number of tracks of some very good CD's I was able to get impressions about total harmonic distortion, speaker damping (Zout), dynamics (Pmax), bass response (f-3L), high frequency range (f-3H) and preference of each amp for high end applications. After these stereo tests I evaluated the amplifiers with intensive guitar sounds. Some of the subjective findings are mentioned in remarks in table 4 and in the evaluation following.

7. RESULTS AND DISCUSSION

Table 4 shows the results of my many experiments. Changing from one amp to another was very easy in this concept. It just was a matter of soldering new wires to the different taps and a new amplifier was born.

<u>Circuit 1-3</u>: there is no DC-compensation. The core is saturated, resulting in a small Lp value and consequently f-3L is high, also depending on the effective plate resistance of the driving power tube. The sound character is soft and not loud, much 2-nd harmonic distortion, too much to create an open sound stage.

<u>Circuit 4-6</u>: now Lp is large again, no core saturation, subjective the bass is strong. The power is not large yet because the lower current compensating EL34 eats power. Its plate impedance is not infinitive. However, these amps sound loud and silky.

amp	P@1kHz	f-3L	f-3H	Zout	Gain	Remarks
1	3.1	57	31	45	20	SE-pentode, small Lp, little bass, silky
2	4.5	35	23	20.6	13.8	SE-Utra-Linear, small Lp, little bass, silky
3	4.5	23	18.6	3.8	8.9	SE-triode, small Lp, some bass, silky
4	5.3	8	15.7	45.2	6.7	SE-pent with current compensation, loud
5	5.3	8	15.7	18.9	5.9	SE-UL with current compensation, good bass, silky
6	5.3	7	19.8	3.3	3.9	SE-triode with current comp, deep bass and silky
7	9	8	26	4.9	4.9	SE, as 4, with CFB, hard clipping, not open
8	9	8	24	3.4	4.0	SE, as 5, with CFB, hard clipping, not open
9	6.1	8	23	2.0	3.0	SE, as 6, with CFB, hard clipping, not open
10	29	8	47	53	13.3	PP-pentode, clean, loud, dynamic
11	28	8	26.4	9.3	9.5	PP-UL, clean, loud, dynamic
12	14	8	24	3.4	6.2	PP-triode, very clean, superior
13	26	8	56	12.8	11.1	PP-Super Pent, powerful, somewhat harsh character
14	30	8	50.8	6	8	PP-Pent., CFB, powerful, not harsh
15	29	8	42	3.8	6.8	PP-Super Triode, powerful, extreme clean and open
16	13.4	8	28	2.4	4.9	PP-Triode with CFB, less power but cleanest of all
17	8	8	59	1.93	1.5	Triode Cathode follower, driver stage is limiting
18	11	7	68	1.33	0.2	PPP-pentode Cathode follower, driver stage is limiting
19	78 (91-peak)	8	20	45	12	PP-Pentode V0 = 737V, loud, not very open
20	72 (91-peak)	8	38	4.2	7.1	PP-Pentode V0 = 737V, with CFB, dynamic loud, open
[-]	[Watt]	[Hz]	[kHz]	[Ohm]	[-]	

Table 4. Test results

Circuit 7-9: with cathode feedback the output impedance is extra small, good bass control, but the sound character gets harsh because the clipping behavior is less soft.

Circuit 4-9: an EL34 in pentode mode is used as current supply. This circuit is not ideal. Two things are needed for improvement. Firstly, remove any ripple voltage at Vo, else there is too much hum at the speaker because the current source and amplifying tube have different plate resistances. Consequently the ripple voltage does not cancel out at the balanced primary winding. Secondly, add a cathode resistor to raise the effective plate resistance of the current source (or any other clever trick). This will prevent that the current source eats power. Also a 50mA quiescent current is not the optimal choice, but was kept constant for reason of good comparison between the different amps. All is left to the reader to improve further.

Circuit 1-9: In all these amps the primary impedance was set for 2000 Ohm. There was no research for the optimal load line or quiescent current setting. Consequently there is too much total harmonic distortion. This makes the sound character friendly and silky and soft but not open and not detailed. However, each SE-builder knows how to optimize these SE circuits, which was not the goal for this research.

Circuit 10-12: the sky opens, a curtain is removed, there is power and dynamics and little distortion. Especially the triode circuit 12 is excellent detailed.

Circuit 13-16: the cathode feedback improves the loudspeaker damping. However, in circuit 13 the subjective result has a little (not yet understood) harsh character. Circuit 15 sounds superior and identical to circuit 12, but has twice the power, which is an important feature.

Circuit 17-18: In these two circuits the driver stage did not have enough headroom to get to the clipping level, see the very small gain. However, these two circuits measure excellent and very clean. Because of the driver stage limitation there was no subjective evaluation.

Circuit 19-20: these circuits show how to get as much power as possible from 2 x EL34. Circuit 19 shows a very clear transition from class A to class B. This improves largely in circuit 20 through the cathode feedback. Especially circuit 20 is very dynamic.

For high-end applications the two circuits 12 and 15 are the real winners. For guitar I prefer circuit 10 and 19 for bluesy and Jazzy styles, while 20 is excellent clean and loud and open and even friendly in overdrive, making it the loudest amp for heavy on stage applications.

8. SUMMARY

A systematic approach to vacuum tube amplifiers has shown that a system can be defined which includes all possible variations in topologies. The system contains 90 variations (at least) and some of them have never been constructed until now.

Especially for musical instrument (guitar) amplification with valve amplifiers, a new universal output transformer has been defined which can be used for all the amplifiers of the system.

Tests with this output transformer in twenty amplifiers of the system has shown the validity of this approach, making it extremely easy to change from one amplifier topology to another, only by rearranging some wires.

I consider the approach of this research with the universal output transformer and system as a very valuable tool, which enables me to quickly and clearly gain insight in the character of different amplifier topologies, without having to deal with tremendous costs of a new output transformer for every new amplifier.

9. REFERENCES

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