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Universal Output Transformer for Guitar Amplifiers

The author proposes a new universal output transformer for use with various tube amp topologies.

By Menno van der Veen

Almost a century after their introduction, vacuum tube amplifiers are still appreciated for their special qualities. Even now, many companies design new valve amps which are highly rated by audiophiles. Musicians—especially guitarists—also 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 high impedance vacuum tubes and the low impedance loudspeaker. The major reasons are the inherent low nonlinear distortion and the very small leakage inductance, which allows for a precise tuning of the high-frequency rolloff 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. So mostly less expensive EI transformers are used.

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

BASIC QUESTIONS

There are many tube amplifiers in the world, with many different topologies, such as single-ended (SE), push-pull (PP), paralleled push-pull (PPP), and cathode follower (CF). All tube amps are of different design, concept, and quality. Do they have the same basic concept? If yes, 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 so, what is the general nature of those characteristics?

One final question: Is it possible to design a universal output transformer that will fit into all the valve amplifiers?

If so, then there exists a very good reason to design such an output transformer. But let's first start with the first question about the basic concept of tube amplifiers.

FIGURE 1: Where to connect an output transformer?

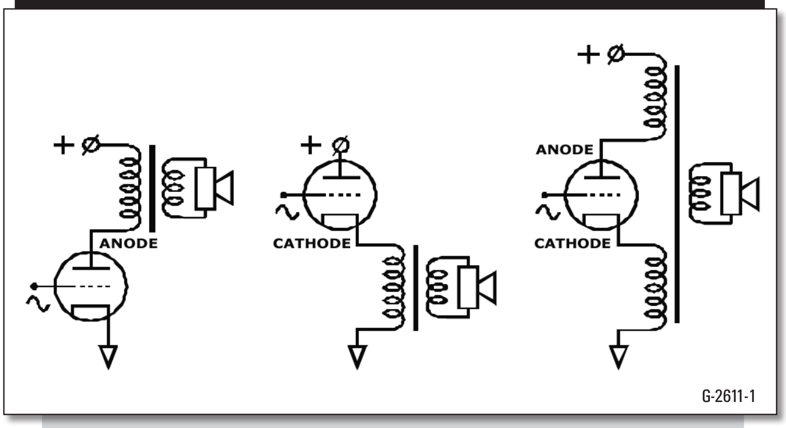
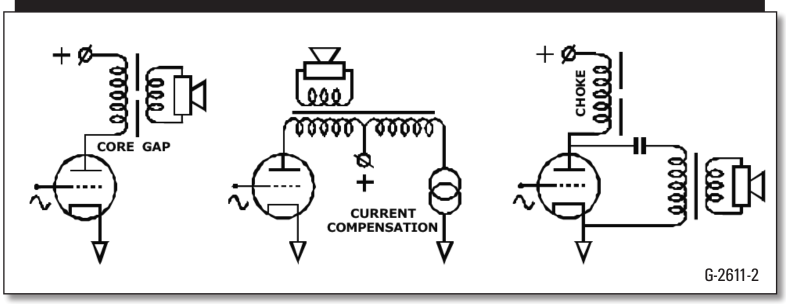


FIGURE 2: OPT connections for SE applications.



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 you wish to extract power from a tube, you should connect the output transformer (OPT) 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.

You 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 must be gapped, or a kind of balancing current compensation should be applied, or capacitor coupling. This again delivers for three possible single-ended choices (**Fig. 2**).

The next classification considers push-pull amplifiers, in which 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 such as the Circlotron with two separate power supplies).

For details, see **Fig. 3**. For push-pull, you now have two new choices.

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

FIGURE 3: Basic push-pull topologies.

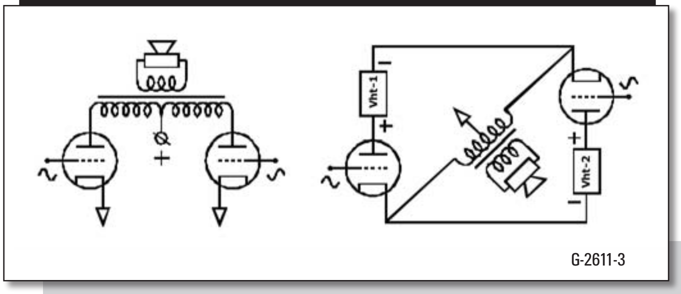


FIGURE 4: Local feedback with the screen grid.

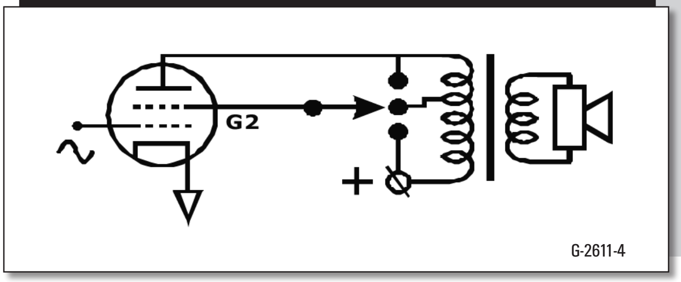
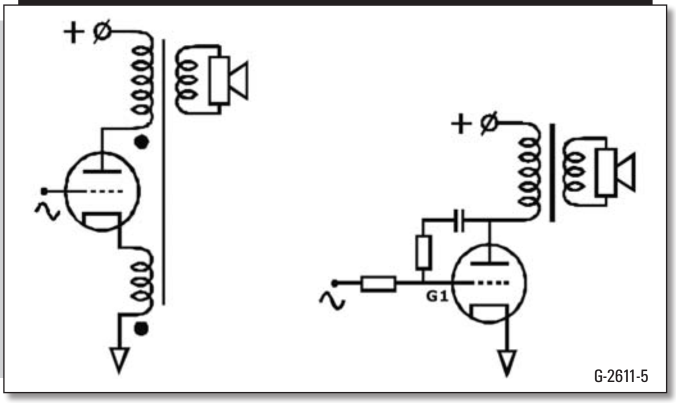


FIGURE 5: Local feedback with the control grid.



three new choices available.

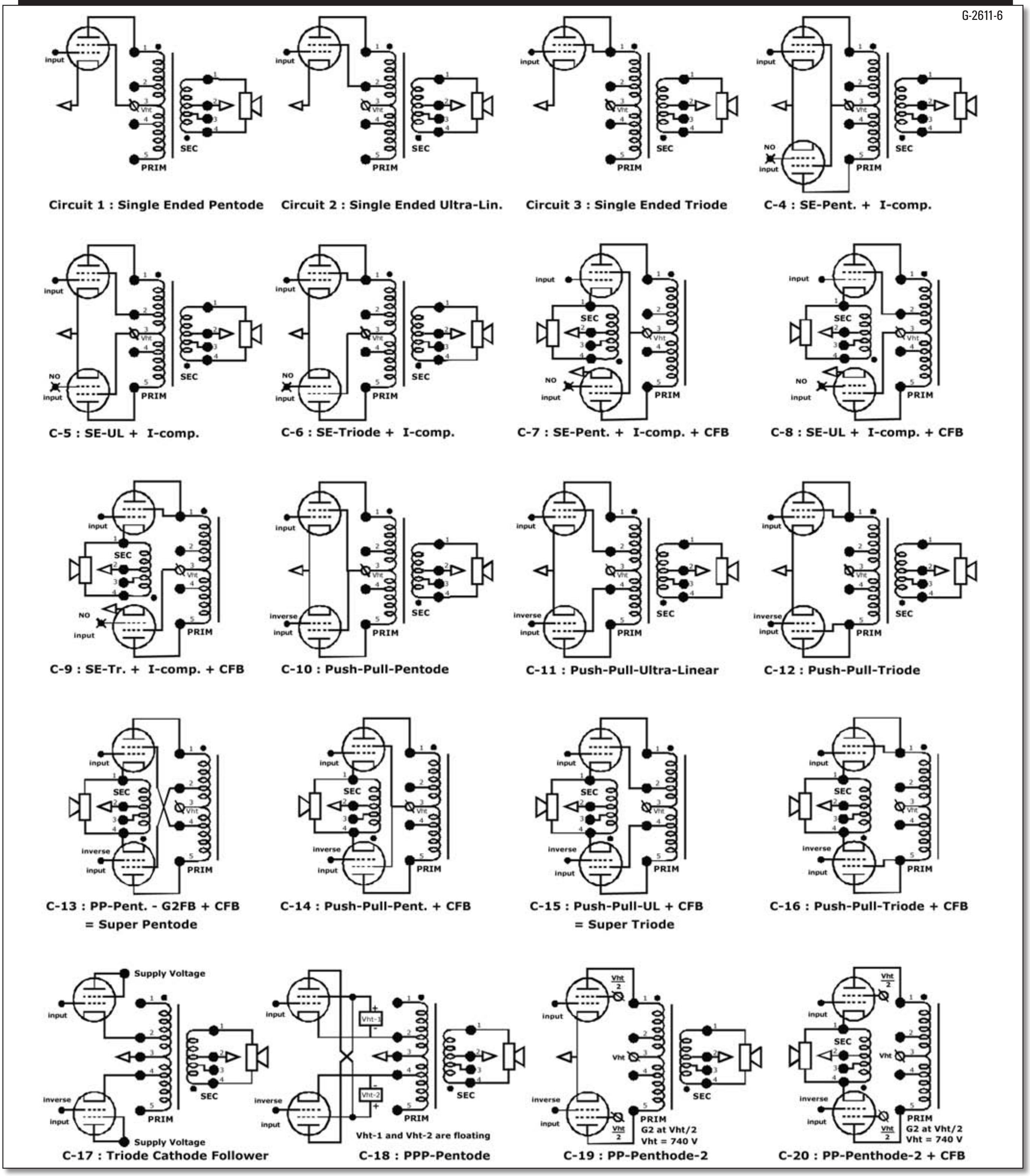
Or you can apply other sorts of local feedback: at the cathode through a separate winding at the output transformer, or at the control grid by means of local feedback with resistors. This delivers two new choices.

When you multiply the number of choices available, you get 54 for SE 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 I will tell more about the results of these tests.

SPECIFICATIONS OF THE NEW OPT

I have shown that a general approach delivers a universal system for all tube

FIGURE 6: Twenty amplifiers resulting from the general system.



amplifiers. The next question is: Is it possible to derive the specifications of a universal OPT from this system? I approach this question from the practical side by investigating common features of today's musical instrument amplifiers.

One of the most common tubes in the 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 such as the 6L6 and 6550 are also often seen in the guitar world. The high-end scene adds the KT66 and KT88 to these choices, but for now, let's just consider guitar applications.

In most amps the high voltage supply is somewhere between 300 and 500V, and the power to be delivered by two tubes in push-pull should be around 40W. Many guitar amplifiers are overspecified in regard to power. Very often the peak power is mentioned, which is a factor 1.5 times the continuous output power, depending on the regulation of the power supply transformer. So, 60W in guitar world can be equal to 40W continuous power. But who is able to hear on stage the difference between 40 and 60W (= 1.8dB)? All these conditions lead to a primary impedance (for push-pull) around 4kΩ with a power capability of 40W.

When you consider high voltage supplies around 700 to 900V, then a primary impedance of 8kΩ is optimal. For instance, with 2 × EL34 at 740V, you can expect a continuous output power around 70-80W.

The maximum output power of an OPT is directly related to its lowest full-power frequency. The lowest guitar tone is at 90Hz, and you can expect to hear some resonating of the guitar body. Then the OPT should be able to deliver *80W power at 8kΩ primary at 40Hz* to fulfill all these demands. In a 40W amp the same core can handle this power at a frequency 40/√2 = 28Hz. Then the –3dB power bandwidth starts at 20Hz, which opens the door for high-end applications.

If you choose cathode-follower configurations in push-pull topology, then *the primary impedance should range from 500 to 1000Ω*.

Suppose you wish to apply this push-pull transformer to single-ended applications. Then you should gap the core to compensate for the DC-magnetization of the core. Gapping the core means that the primary inductance Lp is much smaller than with a non-gapped core. Consequently, the exciting current is much larger in the gapped core (Iex = 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 semiconductor design, and it removes the huge disadvantage of large, 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 reasonably wide range of SE primary impedances between 1000 and 4000Ω in practical situations.

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

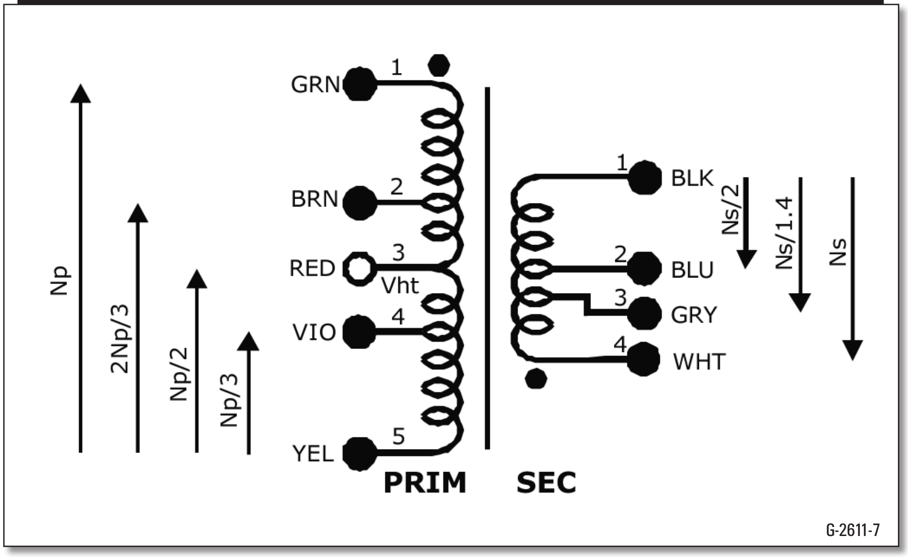
The last important demand is that the insertion losses in the magnet wire resistances should be less than 0.2dB, because in guitar amps the OPT is often used in overdrive, thus preventing the OPT to end its life in flames.

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

THE ACTUAL UNIVERSAL OPT

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

FIGURE 7: The universal output transformer.



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

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

When you consider push-pull applications of this transformer, refer to **Table 1** for 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 ultralinear taps

2 and 4). These tables are based on the fact that impedances from secondary to primary transform by $(Np/Ns)^2$ and vice versa.

Knowing that most loudspeakers have 4 or 8Ω impedances, you can select from these tables the secondary tapping to adapt the optimal value to the application. Because the impedance of a loudspeaker is frequency dependent, you should select a tap with an impedance closest to the nominal impedance of the loudspeaker and not worry whether or not the match is 100% perfect. 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.

TABLE 1 PUSH-PULL APPLICATION

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 2 SINGLE-ENDED 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 3 CATHODE-FOLLOWER 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]

EXPERIMENTAL SETUP

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

In circuits 19 and 20 the quiescent current was set to 25mA per power tube. The power supply is not shown, but this supply contains two fully separated 270V windings, rectified and buffered by 330µF, delivering 370V DC under quiescent conditions and 340V DC under full power operation. The supply also delivered Vn = –55V 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 **Fig. 8** for the "audio part" of the universal amp.

An example of the interconnections between the power tubes and the OPT is given in **Fig. 9**. It concerns circuit 20, which explains how amplifier and OPT can be systematically connected to each other.

To change the amplifier topology, you need to rearrange only some interconnections, and with **Figs. 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 4Ω 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 4Ω load between secondary taps 1-2 in order to produce a primary impedance Za = 2kΩ.

In circuits 10-16 I connected a 4Ω load between secondary taps 1-3 to produce a primary impedance Zaa = 4kΩ.

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

In circuits 19-20 I connected a 4Ω load between the secondary taps 1-2 in order to produce a primary impedance Zaa = 8kΩ.

Subjectively, I evaluated the amps in stereo, with a high-quality preamp plus CD-player and loudspeakers and interlinks. With a restricted number of tracks of some very good CDs, 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.

RESULTS AND DISCUSSION

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

Circuits 1-3: 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, with much 2nd harmonic distortion—too much to produce an open soundstage.

Circuits 4-6: now the Lp value is large again. There is no core saturation, and the bass is strong. The amount of power is not large yet because the lower current compensating EL34 eats power. Its plate impedance is not infinity. However, these amps sound loud and silky.

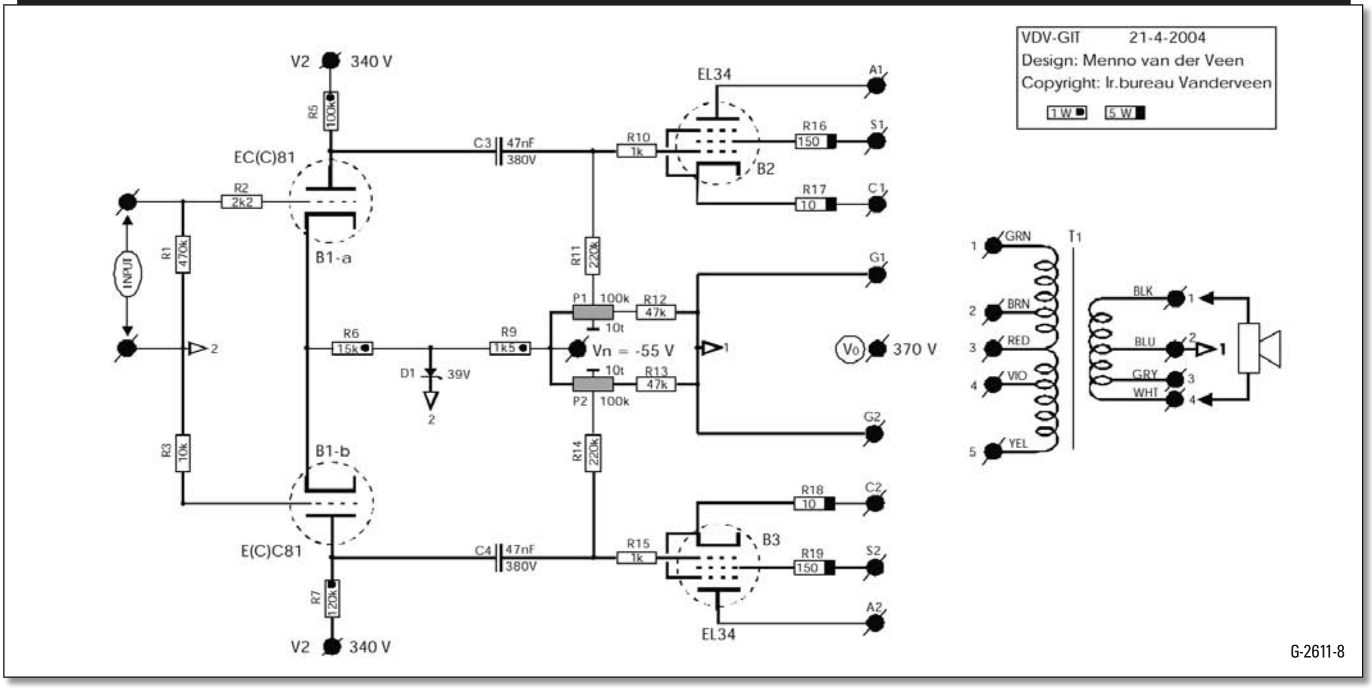
Circuits 7-9: with cathode feedback the output impedance is extra small, with good bass control, but the sound character becomes harsh because the clipping behavior is less soft.

Circuits 4-9: an EL34 in pentode mode is used as a current supply. This circuit is not ideal. Two things are needed for improvement. First, remove any ripple voltage at Vo; otherwise, 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.

Second, add a cathode resistor to raise the effective plate resistance of the current source (or any other clever trick). This will prevent the current source from eating power. Also a 50mA quiescent current is not the optimal choice, but was kept constant due to good comparison between the different amps. I leave it to the reader to improve this further.

Circuits 1-9: In all these amps the primary impedance was set at 2kΩ. 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 or detailed. However, each SE builder

FIGURE 8: The universal amplifier setup.

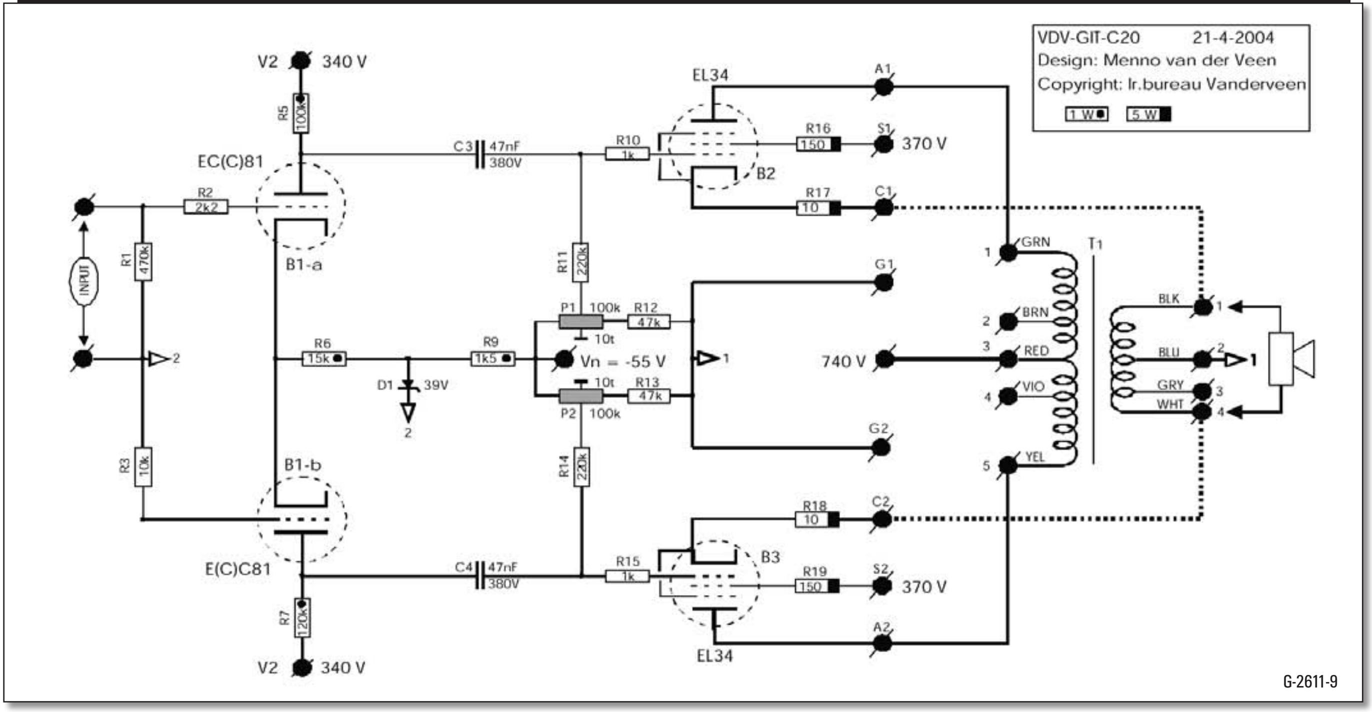


knows how to optimize these SE circuits, which was not the goal for this research.

Circuits 10-12: the sky opens, a curtain is removed, there is power and dynamics and little distortion. Triode circuit 12 is especially well-detailed.

Circuits 13-16: the cathode feedback improves the loudspeaker damping. However, in circuit 13 the subjective result has a little (not yet

FIGURE 9: Example of connections for circuit 20.



understood) harsh character. Circuit 15 sounds superior and identical to circuit 12, but has twice the power, which is an important feature.

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

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

TABLE 4 TEST RESULTS

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-Ultra-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]	[-]	

SUMMARY

This systematic approach to vacuum tube amplifiers shows 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. You can use this new universal output transformer for all the amplifiers of the system, especially for musical instrument (guitar) amplification with valve amplifiers.

Tests with this output transformer in 20 amplifiers of the system show the validity of this approach, making it extremely easy to change from one amplifier topology to another, simply by rearranging some wires. This approach is 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. aX

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