Application Note

Power Amplifiers for Constant Voltage Audio Systems

ABSTRACT

Constant voltage audio systems are commonly used in installations where audio information needs to be distributed over long and varied distances to many different points of load with high total power delivery. These systems are widely used in commercial building installations for public announcement (PA) or for fire safety and building security notifications by specific zone. This application note describes the operation of constant voltage audio systems and derives the equations needed to determine overall system efficiency. Advantages of integrated power amplifiers, such as the TPA3255, compared to traditional discrete amplifier implementations are discussed. An example system was built using the TPA3255 and measurements were taken with different audio transformers to show the impact that different transformer parameters have on overall system efficiency.

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1 Introduction

1.1 Power Amplifiers

Constant voltage audio systems are used to distribute audio over large areas. Whether in an airport terminal PA system or fire safety notification systems, constant voltage audio systems ensure that the audio is effectively distributed to speakers around the facility. To achieve such widespread audio distribution, power amplifiers are needed within the system to drive the distributed speaker network. Each amplifier can then be controlled to send the same or different sounds, depending on the zone. An example of a sound that would be the same throughout a system is music in a shopping mall. An example of a sound that would be different, depending on the zone, is different evacuation messages for different floors in a multi-story building. Regardless of use, the power amplifier stage of the constant voltage audio system plays a crucial role. Though that has traditionally been achieved through discrete implementation, it can be done with integrated Class-D amplifiers, typically at lower cost and in a smaller area.

1.2 Discrete Power Amplifier Implementation

Figure 1-1 shows a traditional, discrete implementation for the power amplifier in a fire safety application.

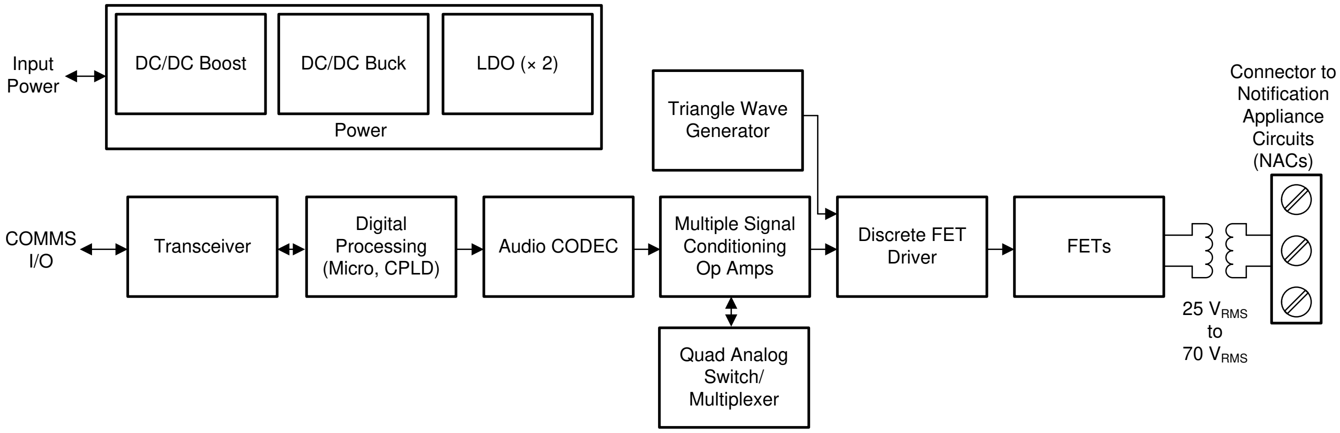

Figure 1-1. Power Amplifier Discrete Implementation

This implementation scheme requires many different components to achieve the waveform amplification. The transceiver at the beginning of the signal chain enables communication between the power amplifier board and a central control unit. The digital processing block then decides which audio signal to send through the system. Then, the audio CODEC, along with various operation amplifiers, switches, and a triangle-wave generator, condition the audio signal to be a usable input for the FET driver. The FET driver then drives the FETs, which creates the final audio signal. That signal is then sent through the transformer and to the notification appliance circuits (NACs).

This implementation scheme requires many different components to achieve the waveform amplification. The transceiver at the beginning of the signal chain enables communication between the power amplifier board and a central control unit. The digital processing block then uses the appropriate audio signal to send through the system. Then, the audio CODEC, along with various operation amplifiers, switches, and a triangle wave generator, condition the audio signal to be a usable input for the FET driver. The FET driver then drives the FETs, creating the final audio signal. That signal is then sent through the transformer and to the NACs.

1.3 Class-D Amplifier Implementation

Figure 1-2 shows a more simple and integrated implementation of the power amplifier.

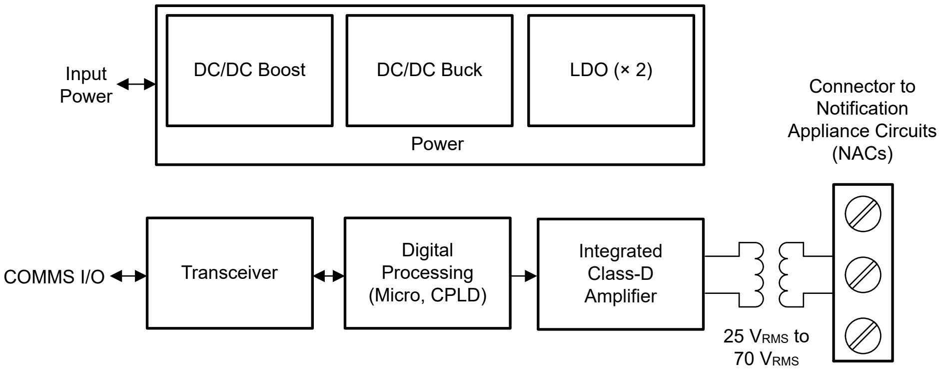

Figure 1-2. Power Amplifier Implementation With an Integrated Class-D Amplifier

In the integrated Class-D amplifier design, most of the discrete signal conditioning circuitry is removed and moved onto a single chip. This greatly simplifies the signal chain and overall circuit complexity. As with the discrete implementation, the transceiver at the beginning of the signal chain allows for communication between the power amplifier and central control unit. Then, the digital processing block determines which signal to send to the Class-D amplifier. Depending on the Class-D amplifier, the input can be either analog or digital, denoted by the TPA and TAS prefixes, respectively. The TPA3255 is an example of an analog input Class-D amplifier, and the TAS3251 device is an example of a digital input Class-D amplifier. The output of the Class-D amplifier then goes through the audio transformer and is distributed to the NACs.

The integrated Class-D amplifier implementation of the power amplifier still requires some of the same power blocks as the discrete implementation. The DC/DC boost, instead of being applied to the output driver FETS in the discrete circuit, is supplied directly to the Class-D amplifier. The Class-D amplifier then uses this voltage for the same purpose of providing the output amplitude of the power amplifier. The DC/DC buck is used for the main power supply of the Class-D amplifier. Finally, the LDOs serve two different functions: one is for the power supply of the microcontroller unit (MCU) and the other is for the internal digital circuitry of the Class-D amplifier.

1.4 Advantage of a Class-D Implementation

When comparing the integrated Class-D implementation to the discrete implementation, there are multiple advantages to consider. The first, and most evident advantage when observing Figure 1-1 and Figure 1-2, is the simplification of the circuit design. By using an integrated Class-D amplifier with digital input, it can receive the signal input directly from a microcontroller. Thus, the integrated Class-D amplifier, in this case, removes the need for signal conditioning circuitry. Second, because the integrated Class-D amplifier simplifies the circuit by replacing multiple components, it reduces the overall bill of material (BOM) cost. By choosing representative parts for each block replaced by the integrated Class-D amplifier, the estimated 1-kU cost of the replaced components is approximately double that of the integrated Class-D amplifier. This evaluation also includes the necessary external passive components for the implementation of the Class-D amplifier. Third, implementing a power amplifier using the integrated Class-D amplifier over the discrete implementation introduces board-size savings. Doing a layout analysis of the discrete components replaced by the integrated Class-D amplifier shows that they occupy approximately eight square inches (not including heat sinks) in total. The integrated Class-D amplifier, specifically the TAS3251 device for this analysis, requires only approximately three square inches. The size savings offered by the integrated Class-D amplifier can help greatly reduce system size. Finally, TI's Class-D amplifiers offer high performance, and further functionality improvements, over the typical discrete implementation. The TAS3251 device has integrated protection and error reporting on-chip that enables real-time monitoring for overvoltage, undervoltage, and clipping, while also protecting against events like short circuits. Additionally, the TAS3251 device has greater than 108 dB SNR, and less that 0.01% total harmonic distortion (THD), so it delivers strong audio performance at the output of the amplifier.

2 Background

2.1 Why Use Constant Voltage Audio Systems

For an audio system, sometimes a large amount of power is distributed to many small speakers. Audio systems, like those used for flight announcements at an airport or background music at a mall, often rely on a large number of speakers and only a few amplifiers to distribute audio. The constant voltage system is introduced based on these applications.

Suppose a ceiling speaker system with five or more speakers, each with a distance from the amplifier of 50 feet or more, needs to be installed. How would this system be designed? Running wire from the amplifier to each speaker would require a large amount of wire. If using a single wire to connect each speaker from the wire to ground in parallel, the resultant impedance of the paralleled speakers would be very low, and result in high current and large losses in the wire.

For example, five 4-Ω speakers results in 0.8-Ω equivalent resistance.

4 Ω || 4 Ω || 4 Ω || 4 Ω || 4 Ω= 0.8 Ω

This is too low for most amplifiers, and requires large amounts of current. The solution is called a “constant voltage”, or “distributed speaker”, system. Constant voltage systems were designed to reduce power losses across the wire in the same way electricity is distributed along power lines. In the system, a step-up transformer is used to increase the output voltage of the audio amplifier to 70 V_{RMS} or 100 V_{RMS}. The voltage is then converted back to a lower voltage using a small step-down transformer attached to each speaker. The high-voltage reduces the current on the wire, and results in less power losses on the wire.

In addition, constant voltage systems have the advantage of allowing different speaker impedance values to be attached to the same line. The system can be designed so that the primary and secondary transformers match the output impedance of the amplifier with the equivalent impedance of all the speakers. This is made possible by the two-stage transformer design.

2.2 Basic Principle of Constant Voltage Systems

Figure 2-1 shows a typical constant-voltage system. A step-up transformer is connected to the output of the amplifier and converts the output from voltage U_L to a higher voltage U (usually is 70 V_{RMS}, 100 V_{RMS}, or 140 V_{RMS}). R_L and R are equivalent loads of the primary and secondary side of the step-up transformer, respectively. Equation 1 shows the relationship of the voltage and resistances on each side of the transformer.

$$\frac{R_L}{R} = \left(\frac{U_L}{U}\right)^2 \tag{1}$$

On the speaker side, the high voltage is converted to a lower voltage to match the impedance of the speaker. R' and R are equivalent loads of the primary and secondary side of the step-down transformer, respectively. So,

$$P_0 = \frac{{U_0}^2}{R_0} \tag{2}$$

$$\frac{R'}{R_0} = \left(\frac{U'}{U_0}\right)^2 = \frac{U'^2}{P_0 R_0} \tag{3}$$

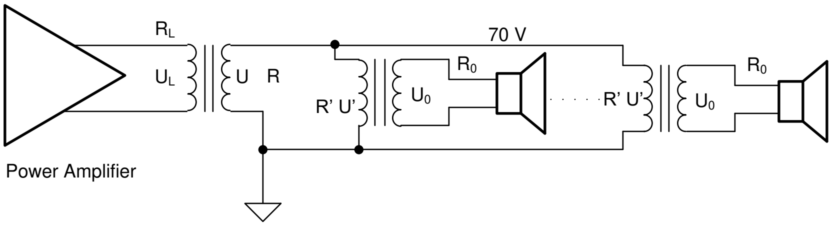

Figure 2-1. Typical Constant Voltage System

$$U' = U \tag{4}$$

$$R = \frac{R'}{N} \tag{5}$$

So for the whole system, if N number of the same speaker are used is:

$$R_L = \quad R\left(\frac{U_L}{U}\right)^2 = \frac{R'}{N}\left(\frac{U_L}{U}\right)^2 = \frac{1}{N}\left(\frac{U_L}{U}\right)^2\left(\frac{U'}{U_0}\right)^2 R_0 \tag{6}$$

U_L/U and U'/U_0 are used to calculate the turns ratio of the step-up and step-down transformer, respectively.

To make sure the amplifier works at certain loads, resistance must match well with the transformer. For instance, for an amplifier that can deliver 100 W with 4-Ω load, and the power goes to 10 4-Ω speakers. Then $R_L = 4\ \Omega$, $R_0 = 4\ \Omega$, $N = 10$, a turns ratio of step-up and step-down transformers should be chosen precisely according to Equation 6.

2.3 Power Loss in Transformer

Two side effects are introduced when adding a transformer in the audio amplifier system. First, the transformer has a frequency response limit. If the frequency is too high, the power losses in the iron core of the transformer increase and lead to lower efficiency in the transformer. If the audio frequency is too low (especially less than 50 Hz), the winding in transformer acts as a DC wire with a very low resistance, which also leads to higher power loss and potential system failure. The audio system with transformers has less bass response than normal. Also, the transformer can introduce extra noise, which leads to higher THD+N for in the audio output.

Second, the transformer in the up-conversion and down introduces additional power loss. For a typical transformer, there are two kinds of power loss: copper loss and iron (core) loss. Copper losses are dominant at low frequencies, and iron losses are dominant at high frequencies. For copper loss, the main parameter is DC resistance (DCR), and a higher DCR leads to higher copper loss.

$$P_{copper} = i^2 \times DCR \tag{7}$$

For core loss, when the frequency is higher, it induces eddy currents flowing in the core according to Faraday's law, which causes more power loss in the core (typically made of iron, so also called iron loss).

2.4 Auto-Transformer

Figure 2-2 shows a conventional double-wound transformer. An auto transformer has a similar magnetic core, but only one winding. This winding is shared between the primary and secondary side. Auto transformers can be designed as step-up or step-down transformers. To implement a step-up transformer, a small AC voltage is applied to a portion of the winding, representing the primary side. The output voltage is then taken across the entire winding, representing the secondary side. See Figure 2-3 for the step-up auto-transformer. The opposite is true for a step-down transformer. By applying a voltage across the entire winding and taking the output across a smaller portion, the auto-transformer converts into a step-down transformer.

The basic working principle between a conventional double-wound transformer and an auto transformer is similar. The main advantages of an auto-transformer are smaller size, and reduced copper winding and core material for the same VA rating. Since there is less material, both copper loss and iron loss can be less than a double-wound transformer. Auto-transformers can also be used in constant voltage systems to reduce the cost and power loss, as well as make it easier to install and transport.

The main disadvantage of an auto-transformer is the lack of electrical isolation, which might be a safety concern. For example, when using a step-down auto-transformer, if the secondary side is an open circuit, the primary voltage is all on the load, and causes much more power than intended. Or, if there is short-circuit on the secondary side, the resulting primary current is much higher than a conventional double-wound transformer.

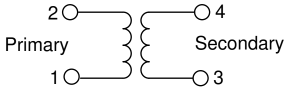

Figure 2-2. Conventional Double-Wound Transformer

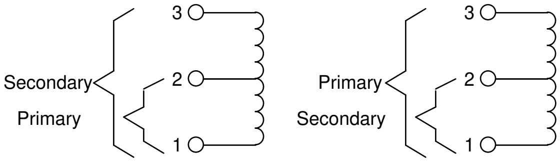

Figure 2-3. Step-Up and Step-Down Auto-Transformers

3 System Test (Based on TPA3255)

3.1 Transformer Characteristics

To better configure the transformer, characterization must be done first. For transformers used in constant voltage system, the turns ratio is the most fundamental parameter. It decides how the system is configured to get the best performance and efficiency.

3.1.1 Turns Ratio and Resistance Match

See the data sheet for turns ratio when using different configurations. For the transformer in Figure 3-1, the voltage on the primary and secondary sides has been marked. The turns ratio (abbreviated as TR) is proportional with the voltage ratio. Table 3-1 show the basic characteristics of the transformer.

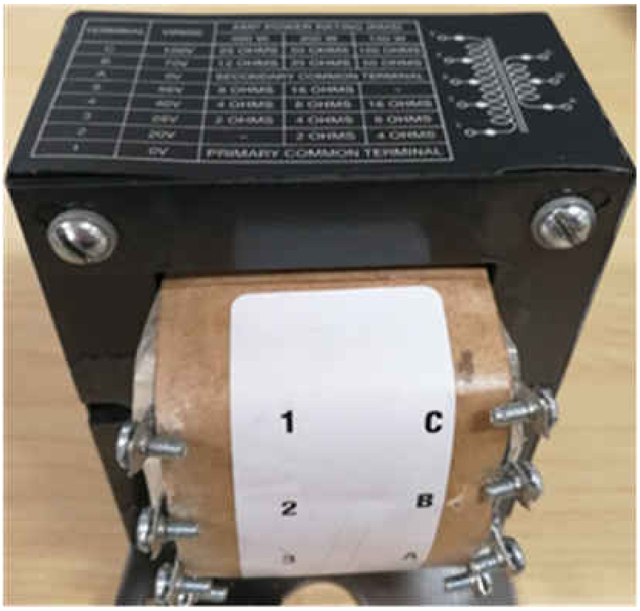

Figure 3-1. Step-Up Transformer From Peavey® (Auto Match II 400W 18737)

Table 3-1. Turns Ratio and Resistance Matching Under Different Configurations for Peavey® Step-Up Transformer (Tap 1 is Primary Ground and Tap A is Secondary Ground)

Configuration	Parameters	Secondary: Tap A, B (70.7 V)	Secondary: Tap A, C (100 V)
Primary: tap 1, 2 (20 V)	TR	1/3.535	1/5
	U1/U2	1/3.535	1/5
	R1/R2	1/12.496225	1/25
Primary: tap 1, 3 (28 V)	TR	1/2.525	1/3.571
	U1/U2	1/2.525	1/3.571
	R1/R2	1/6.375625	1/12.752041
Primary: tap 1, 4 (40 V)	TR	1/1.7675	1/2.5
	U1/U2	1/1.7675	1/2.5
	R1/R2	1/3.124056	1/6.25
Primary: tap 1, 5 (56 V)	TR	1/1.2625	1/1.786
	U1/U2	1/1.2625	1/1.786
	R1/R2	1/1.593906	1/3.189796

For the transformer in Figure 3-2, the voltage level is not marked on one side (4 Ω, 8 Ω side). Two methods can be applied to determine the turns ratio. First, a 300-W transformer. If 4 Ω is the primary configuration, and 300 W must be reached when the input is about 34.6 V (according to Equation 2), the turns ratio can be calculated as 34.6 / 70.7 = 1 / 2.04 under 4 Ω, 70 V configuration. If 8 Ω is the primary configuration, the corresponding voltage level is about 49 V, and the turns ratio for 8 Ω, 70 V is 49 / 70.7 = 1 / 1.44. The other option is to connect a certain resistor (say 40 Ω) to one side and test the equivalent resistance on the other side. If connecting 16 Ω to tap 70 V, and measuring the resistance between tap "4 Ω" and tap “Com” is measured as 3.84 Ω, the relevant turns ratio is 2.04 according to Equation 1.

Figure 3-2. Step-Up Transformer From EDCOR® (EA300)

Table 3-2. Turns Ratio and Resistance Match Under Different Configurations for EDCOR® Step-up Transformer

Configuration	Parameters	Secondary: 70.7 V	Secondary: 100 V
Primary 4 Ω	TR	1/2.04	1/2.89
	U1/U2	1/2.04	1/2.89
	R1/R2	1/4.1616	1/8.3521
Primary: 8 Ω	TR	1/1.45	1/2.05
	U1/U2	1/1.45	1/2.05
	R1/R2	1/2.1025	1/4.2025

For the step-down transformer in Figure 3-3, the turns ratio can be determined by measuring the equivalent resistance. In this case, a 70-V system was considered. For the primary side, the voltage and power is known. And for secondary side, the reference resistive load is known. Suppose input power P (10 W, 5 W, 2.5 W, 1.25 W or 0.62 W), primary voltage U_1 (70.7 V), equivalent resistance, R_1, and secondary side voltage is U_2 (unknown), or R_2 (4 Ω or 8 Ω). If power losses are ignored, the power on both sides should be the same.

$$P = \frac{U_1{}^2}{R_1} = \frac{U_2{}^2}{R_2} \tag{8}$$

$$U_2 = \sqrt{P \times R_2} \tag{9}$$

$$TR = \frac{U_1}{U_2} = \frac{U_1}{\sqrt{P \times R_2}} \tag{10}$$

The turns ratio was determined using Equation 10.

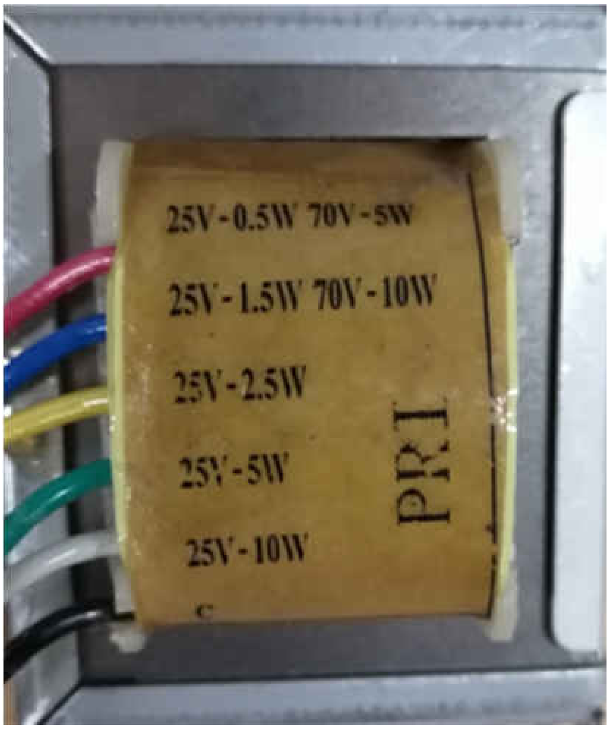

Figure 3-3. Step-Down Transformer From Peavey® (330-040) (a)

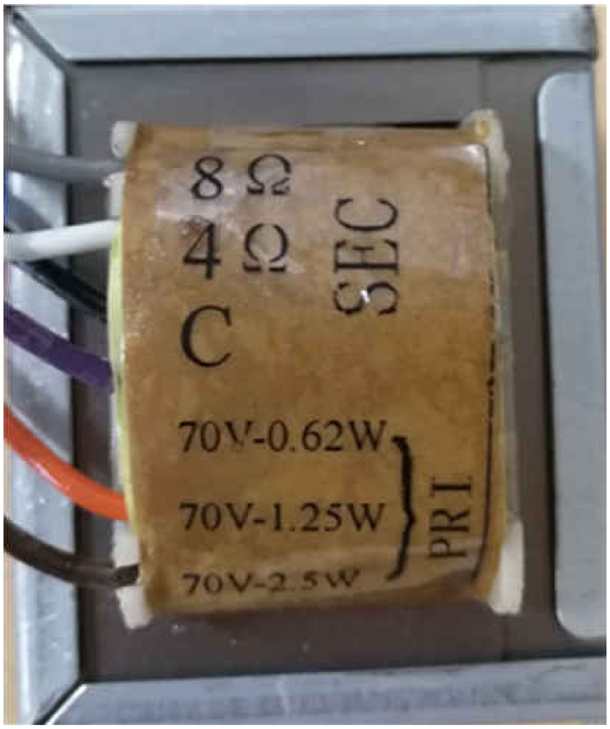

Figure 3-4. Step-Down Transformer From Peavey® (330-040) (b)

Table 3-3. Turns Ratio and Resistance Match Under Different Configurations for Peavey® Step-Down Transformer

Configuration	Parameters	Secondary: 4 Ω	Secondary: 8 Ω
Primary: 10 W	TR	11.179	7.905
	U1/U2	11.179	7.905
	R1/R2	124.9700	62.4890
Primary: 5 W	TR	15.809	11.179
	U1/U2	15.809	11.179
	R1/R2	249.9245	124.9700
Primary: 2.5 W	TR	22.357	15.809
	U1/U2	22.357	15.809
	R1/R2	499.8354	249.9245
Primary 1.25 W	TR	31.618	22.357
	U1/U2	31.618	22.357
	R1/R2	999.6979	499.8354
Primary 0.62 W	TR	44.895	31.745
	U1/U2	44.895	31.745
	R1/R2	2015.5610	1007.7450

3.1.2 DCR of the Transformer

Another important transformer parameter is the DC resistance of the primary and secondary sides. It can be used to estimate the copper loss in the winding. DCR is obtained by directly measuring two taps with the other side open (without any load).

For step-up transformer 1, the DCR is as listed in Table 3-4.

Table 3-4. DCR for Peavey® Step-Up Transformer

Side	Taps	DCR (Ω)
Primary (common tap: tap 1)	1,2	0.143
	1,3	0.154
	1,4	0.18
	1,5	0.26
Secondary (common tap: tap A)	A,B	0.42
	A,C	0.69

For step-up transformer 2, the DCR is as listed in Table 3-5.

Table 3-5. DCR for EDCOR® Step-Up Transformer

Side	Taps	DCR (Ω)
Primary (common tap: Wht)	Wht, 4 Ω	0.2
	Wht, 8 Ω	0.36
Primary (common tap: Blk)	Blk, 70 V	0.53
	Blk, 100 V	0.96

For step down transformer, DCR is as listed in Table 3-6.

Table 3-6. DCR for Peavey® Step-Down Transformer

Side	Taps	DCR (Ω)
Primary (common tap: PRI Blk)	PRI Blk, 10 W	27.7
	PRI Blk, 5 W	54.4
	PRI Blk, 2.5 W	87.7
	PRI Blk, 1.25 W	141.2
	PRI Blk, 0.62 W	221.2
Secondary (common tap: SEC Blk)	SEC Blk 4 Ω	0.54
	SEC Blk 8 Ω	0.72

3.2 System Build-Up

To use a 70-V constant voltage system to deliver power to different smaller speakers, the voltage must be converted to 70.7 V_{RMS} first through one step-up transformer, and then down to the proper voltage by the Peavey step-down transformers (see Figure 3-5; suppose N speakers are used, so N step-down transformers). The TPA3255 (along with a LC filter) is used as the amplifier (51 V, BTL mode, same condition in all of the following experiments). A Peavey step-up transformer (abbreviated as 18737) and a step-down transformer (abbreviated as 330-040) were used. In the first experiment, the configuration for the 18737 is 1,2 as primary and A,B as secondary, while the configuration for the 330-040 can vary between 10 W, 5 W, 2.5 W, 1.25 W, and 0.62 W in the primary side (secondary is fixed with a 4 Ω load).

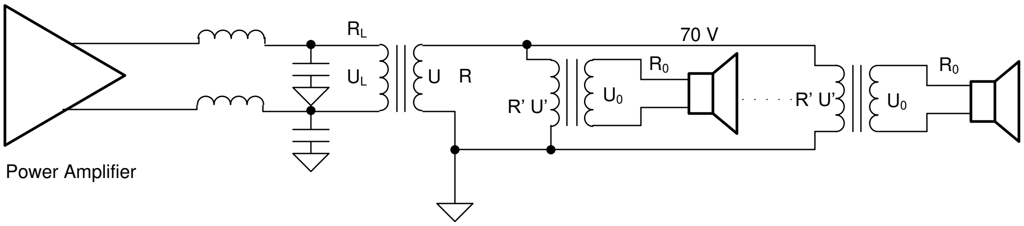

Figure 3-5. Full System for Constant Voltage System Based on TPA3255

$$\frac{R_L}{R} = \left(\frac{U_L}{U}\right)^2 \tag{11}$$

$$U' = U \tag{12}$$

$$P_0 = \frac{{U_0}^2}{R_0} \tag{13}$$

$$\frac{R'}{R_0} = \left(\frac{U'}{U_0}\right)^2 = \frac{U^2}{P_0 R_0} \tag{14}$$

$$R = \frac{R'}{N} \tag{15}$$

$$R_L = R\frac{{U_L}^2}{U^2} = \frac{R'}{N}\frac{{U_L}^2}{U^2} = \frac{1}{N}\frac{{U_L}^2}{U^2}\frac{{U'}^2}{{U_0}^2}R_0 \tag{16}$$

To best match the resistance, R_L should be more than 4 Ω. If the 18737 configuration is fixed as 20 V to 70 V and 330-040 is fixed as 10 W, 4 Ω:

$$N \leq \frac{{U_L}^2}{U^2}\frac{{U'}^2}{{U_0}^2}\frac{R_0}{R_L} = \frac{1}{12.496225} \times 124.97 \times \frac{4\ \ \Omega}{4\ \ \Omega} \approx 10 \tag{17}$$

Note that R_L is not always 4 Ω; it gets higher if using a lower power level for the 330-040. So N = 10, and ten 4-Ω resistors are used to simulate 4-Ω speakers.

3.3 System Test

1. Make sure the TPA3255 device is set up and working properly. Connect a 4-Ω resistor using amplifier configuration in BTL mode (without any transformers), and sweep frequency under different power levels.

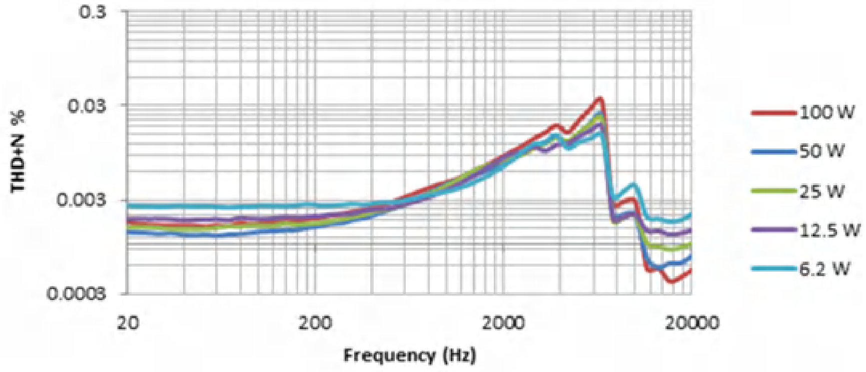

Figure 3-6. THD+N vs Frequency Results Based on TPA3255 Without Transformer

2. As Figure 3-7 shows, build the constant voltage system using one step-up and one step-down transformer (simplify the system by applying one load to start) with a 4-Ω resistor connected to 4-Ω tap of the secondary side of the 330-040. Apply a 1-kHz signal and modify the input amplitude until RMS (root mean square) of U reaches 70.7 V (peak to peak is about 200 V).

Note

Since the voltage is very high, necessary protection methods must be taken.

For the 330-040, set 10 W, 5 W, 2.5 W, 1.25 W, and 0.62 W (all 70 V) respectively, and use an Audio Precision (AP) analyzer to measure voltage and power across resistor R_0. Make sure the output voltage and power are as expected.

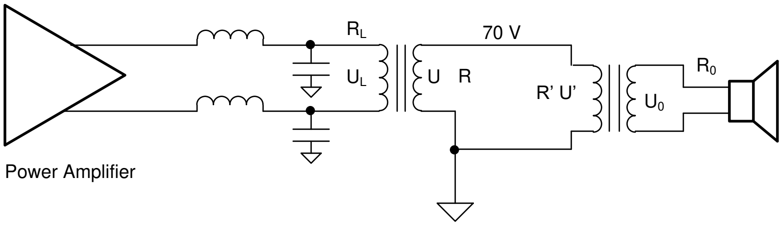

Figure 3-7. Simplified Constant Voltage System

3. Assemble the complete constant voltage system based on Figure 3-5 using 10 step-down transformers (N = 10) and 10 × 4-Ω resistors. Set the input to 70.7 V_{RMS}. Start by using the 0.62-W power level for each 330-040, and measure the THD+N vs frequency as shown in Figure 3-8. Multiply the power measured on one resistor by 10 to calculate the total efficient power. Do the same thing for the 1.25-, 2.5-, 5-, and 10-W settings.

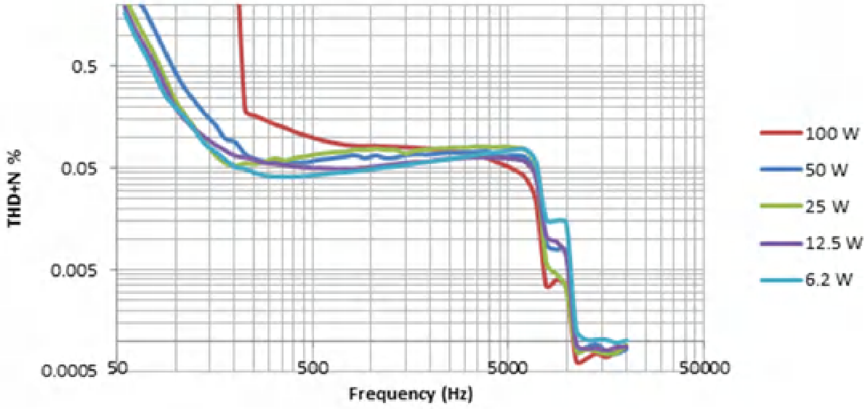

Figure 3-8. THD+N Versus Frequency Results Based on TPA3255 With 1 Step-Up and 10 Step-Down Transformers (1, 2 as Primary Side and A, B as Secondary Side)

Table 3-7 shows the power consumed and relevant efficiency when using the 330-040 with a 10-W configuration.

Table 3-7. System Efficiency for Ten 10-W Resistor Loads (Using One Peavey® 18737 and Ten 330-040 Transformers)

Power Level	Total Power (W)	Power for Each Resistor	Total Efficient Power (W)	Efficiency
10 W	186.66	9.737	97.37	0.522

4 Efficiency Analysis and Optimization

From the test result for the previously discussed experiment, the THD+N stays below 0.1% at most frequencies, which is slightly higher than when using the TPA3255 device to directly drive a 4-Ω load. This is due to the distortion of the two transformers. The efficiency is very low in this configuration. Even when driving large power (100 W in total across all the resistors), the efficiency is only a little more than 50%.

4.1 Efficiency of Three Parts

The system consists of three parts: the class D amplifier, the step-up transformer 18737, and step-down transformer 330-040. System efficiency is the product of the efficiency of each part.

4.1.1 Efficiency for TPA3255

For the power amplifier TPA3255, efficiency mainly depends on output load R and power P. For the same load R, efficiency increases as P goes higher. Likewise, for the same power, efficiency increases as R gets larger. Figure 3-1 shows the efficiency of the TPA3255 device when connected directly to a 4-Ω load in blue.

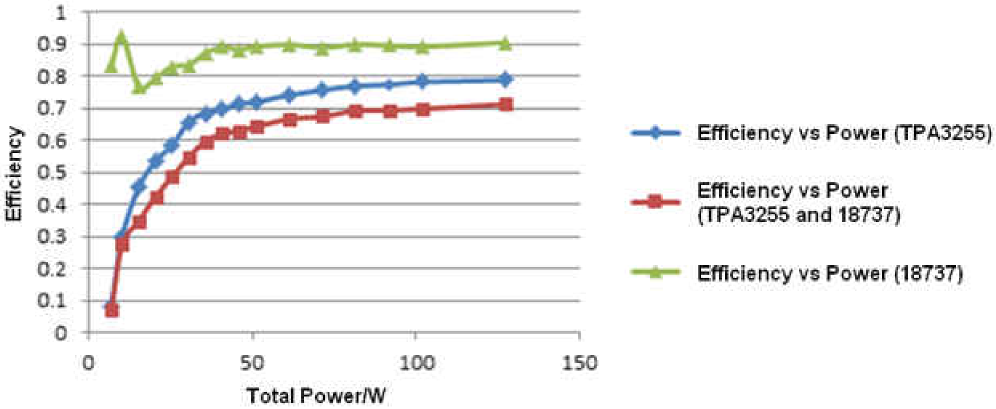

Figure 4-1. Efficiency Characterization for 18737

4.1.2 Efficiency for Step-Up Transformer

For a step-up transformer, it is hard to test the efficiency directly. By connecting the 1,2 (20 V) primary side with the TPA3255 device, and a 50-Ω resistor load with 70-V secondary side (based on Figure 3-7), an equivalent 4-Ω load is obtained according to Table 3-1. For this system, see the efficiency result from the red curve in Figure 4-1. Since system efficiency is a product of the TPA3255 device and the 18737, the transformer efficiency is represented by the red curve data over the blue curve data, resulting in the green curve.

4.1.3 Efficiency for Step-Down Transformer 330-040

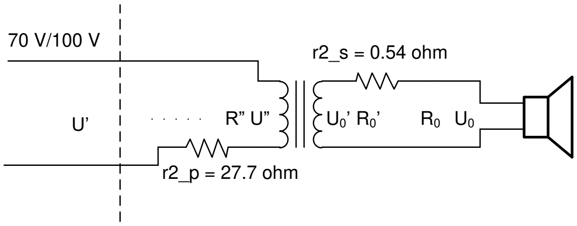

Figure 4-2. Equivalent System Circuit Including DCR for Peavey® 330-040

Since the amplifier cannot generate a 70-V_{RMS} signal to the 330-040, it is not easy to test the efficiency through experiment. According to Table 3-6, the DCR is relatively large for the step-down transformer. If only taking copper loss into consideration,

$$P_0 = \frac{U_0^2}{R_0} \tag{18}$$

$$U_0 = \frac{R_0}{R_0 + r2\_s} U_0' \tag{19}$$

$$R" = \left(\frac{U"}{U_0'}\right)^2 \left(R_0 + r2\_s\right) \tag{20}$$

$$U" = \frac{R"}{R" + r2\_p} U' \tag{21}$$

For the step down transformer:

$$\eta_{down} = \frac{R"}{(R" + r2\_p)} \frac{R_0}{(R_0 + r2\_s)} \tag{22}$$

According to Table 3-3 (configure 10 W as primary and 4 Ω as secondary):

$$R" = 124.97 \times (4 + 0.54) = 567.36 \quad \Omega \tag{23}$$

$$\eta_{down} = \frac{567.36}{(567.36 + 27.7)} \frac{4}{(4 + 0.54)} = 0.84 \tag{24}$$

As in the previous experiment, when using ten 4-Ω resistors configured as 10 W in Figure 3-5, the efficiency of the TPA3255 η_{amp} and step-up transformer η_{up} 18737 is 0.8 and 0.9 respectively (see Figure 4-1), so the system efficiency is about:

$$\eta = \eta_{amp}\eta_{up}\eta_{down} = 0.8 \times 0.9 \times 0.84 = 0.605 \tag{25}$$

This is 0.08 higher than the test result because, in one case, the iron loss in the step-down transformer is not considered here. Conversely, as power goes up, the current in the transformer gets higher and higher, which reduces the turns ratio and equivalent resistance as a result. This makes the amplifier load below 4 Ω, and thus reduces the efficiency of the TPA3255 device to below 0.8.

4.2 Improvements on System Efficiency

4.2.1 Improve Resistance Matching

One cause of the low system efficiency is the low equivalent resistance seen by the amplifier. The equivalent load can be increased by reconfiguring the 18737. From Table 3-1, R_L can be about 8 Ω if using tap 1, 3 as primary and tap A, B as secondary (or tap 4 as primary and tap C as secondary). With an 8-Ω load, η_{amp} increases from 0.8 to about 0.85. The theoretical system efficiency is:

$$\eta = \eta_{amp}\eta_{up}\eta_{down} = 0.85 \times 0.9 \times 0.84 = 0.64 \tag{26}$$

The final test result is about 0.61, which matches with the estimation. Figure 4-3 shows the THD+N test result with new configuration.

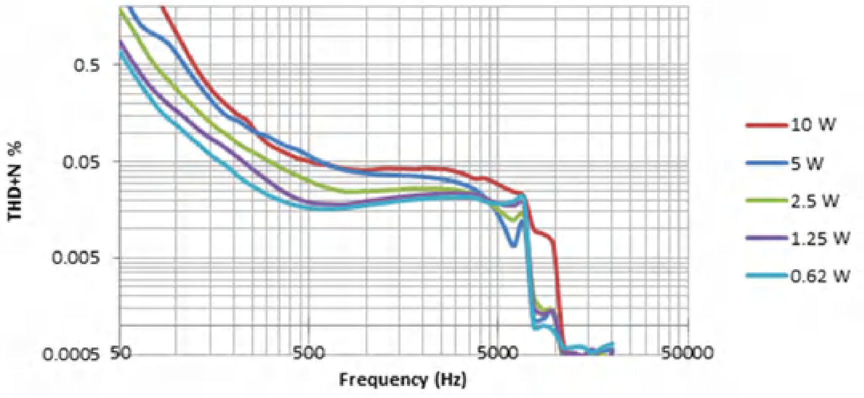

Figure 4-3. THD+N vs Frequency Results Based on TPA3255 With One Peavey® Step-up Transformer and 10 Step-Down Transformers (1, 3 as Primary Side and A, B as Secondary Side)

4.2.2 Apply a Transformer With Less Power Loss

Another efficiency limitation is the low efficiency of the transformer. This can be improved by applying a new step-up transformer from EDCOR® (EA300, see Figure 3-2, Table 3-2, and Table 3-5) to replace the 18737.

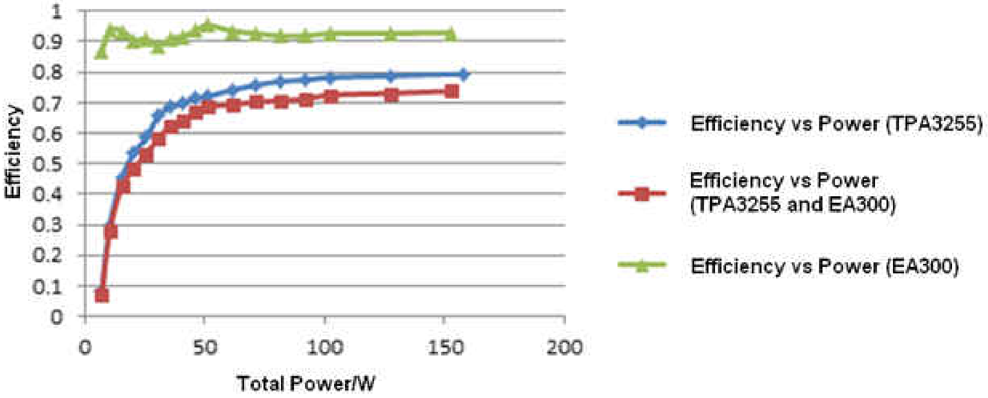

Figure 4-4. Efficiency Characterization for the EDCOR® Step-Up Transformer (EA300)

Configure EA300 as 4 Ω in the primary side, and 70 V in secondary side (a 16-Ω resistor load can make a 4-Ω equivalent load for the amplifier according to Table 3-2). See the characterization result from Figure 4-4. The efficiency of the EA300 can be 0.94.

Continue to use the EA300 with ten 10 W-configured 330-040s and 4-Ω resistors (N is set as 10 to simplify the system; actually more step-down transformers and resistors can be used in parallel), and test the performance and efficiency of the system. Since the resistance ratio of EA300 is much larger (from 1/12.5 to 1/4.16), the equivalent resistance of the amplifier is about 12 Ω, thus η_{amp} can be as high as 0.9. So in theory, the system efficiency is:

$$\eta = \eta_{amp}\eta_{up}\eta_{down} = 0.9 \times 0.94 \times 0.84 = 0.71 \quad (27)$$

The measured efficiency was 0.67, which is close to the calculated value of 0.71. Figure 4-5 shows the THD+N performance using the EA300. The performance is better than the previous transformer.

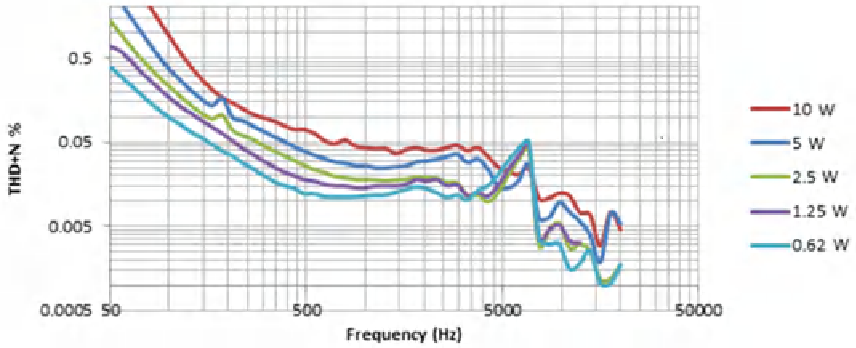

Figure 4-5. THD+N Versus Frequency Results Based on TPA3255 With One EA300 and 10 330-040s (4 Ω as Primary Side and 70 V as Secondary Side)

5 Considerations on Building a Constant Voltage System

To get good performance and system efficiency, it is important to properly pick and configure transformers for a constant voltage system.

5.1 Transformer Saturation

Unless choosing a transformer that covers a wide range of audio frequencies, pay attention to the power limit. For instance, if 100 W is to be delivered to different speakers, a greater than 100-W transformer should be applied. Also, it is best not to use the full power of the transformer, because at the power limit, the current in the transformer is high and near the saturation of the transformer. As a result, the turns ratio (from the primary to secondary side) can be much lower, and equivalent resistance on the primary side is much lower, which leads to lower efficiency for the Class-D amplifier.

5.2 Low DCR

DCR is an important parameter to measure the copper loss in a transformer. For a typical constant voltage system shown in Figure 3-5, Figure 5-1 is the redrawn figure taking DCR into the consideration. The efficiency of the step-down transformer η_{down} from Figure 4-5 is already known.

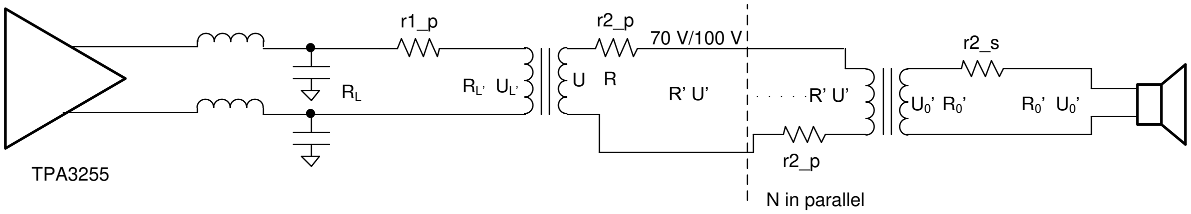

Figure 5-1. Equivalent System Circuit Including DCR for Step-Up and Step-Down Transformers

If the DCR of the step-up transformer is also taken into account, there is:

$$R' = R" + r2\_P = \left(\frac{U"}{U_0{}'}\right)^2 (R_0 + r2\_s\_ + r2\_p) \quad (28)$$

$$R = r1\_s + \frac{R'}{N} \quad (29)$$

$$U' = \frac{\frac{R'}{N}}{\frac{R'}{N} + r1\_s} U \quad (30)$$

$$R_L{}' = \left(\frac{U_L{}'}{U}\right)^2 R \quad (31)$$

$$R_L = r1\_p + R_L{}' \quad (32)$$

so

$$R = r1\_s + \frac{\left(\frac{U"}{U_0{}'}\right)^2 \left(R_0 + r2\_s\right) + r2\_p}{N} \quad (33)$$

$$R' = R" + r2\_p = \left(\frac{U"}{U_0{}'}\right)^2 \left(R_0 + r2\_s\right) + r2\_p \quad (34)$$

$$R_L{}' = \left(\frac{U_L{}'}{U}\right)^2 \left(r1\_s + \frac{\left(\frac{U"}{U_0{}'}\right)^2 \left(R_0 + r2\_s\right) + r2\_p}{N}\right) \quad (35)$$

$$R_L = r1\_p + \left(\frac{U_L'}{U}\right)^2 R = r1\_p + \left(\frac{U_L'}{U}\right)^2 \left(\frac{r1\_s + \left(\frac{U''}{U'}\right)^2 (R_0 + r2\_p}{N}\right) \tag{36}$$

For the step up transformer:

$$\eta_{up} = \frac{R_L'}{(R_L' + r1 + p)} \frac{R'}{(R' + r1\_s)} \tag{37}$$

If iron loss inside transformer is neglected, the efficiency for whole system is:

$$\eta = \eta_{amp}\eta_{up}\eta_{down} = \eta_{amp}\frac{R_L'}{(R_L' + r1\_p)} \frac{R'}{(R' + r1\_s)} \frac{R''}{(R'' + r2\_p)} \frac{R_0}{(R_0 + r2\_s)} \tag{38}$$

For the first experiment (18737, 1,2 as primary and A,B as secondary), r1_p = 0.143 Ω, r1_s = 0.42 Ω, r2_p = 27.7 Ω, r2_s = 0.54 Ω, and according the previous equations:

$$R_L' = \frac{1}{12.49}\left(0.42 + \frac{124.97 \times (4 + 0.54) + 27.7}{10}\right) = 4.8 \quad \Omega \tag{39}$$

$$R' = 124.97 \times (4 + 0.54) + 27.7 = 595.06 \tag{40}$$

$$\eta_{up} = \frac{4.8}{(4.8 + 0.143)} \frac{595.06}{(595.06 + 0.42)} = 0.97 \tag{41}$$

For the second experiment (18737, 1,3 as primary, and A,B as secondary), r1_p = 0.154 Ω and r1_s = 0.42 Ω, so η_{up} can be 0.98. It is a similar case for the third experiment with the EA300. The η_{up} can be 0.99 if only taking DCR into consideration. In the three experiments discussed, for both step-up transformers, the DCR is much smaller compared to the load in both sides, and copper loss can almost be neglected. Therefore, the main power loss lies in the iron loss, due to self-inductance inside the iron core of step-up transformer (generally, for a transformer with larger power, the current is higher, which requires smaller DCR to reduce copper power loss as much as possible).

5.3 Resistance Matching

Resistance must be delicately matched in the constant voltage system. In general, it is better to have a larger equivalent resistance for both sides of the transformer, as long as the power is large enough.

$$P = i^2 R \tag{42}$$

According to Equation 42, for a constant power P, the current goes lower as resistance R gets higher, which helps to make the transformer work far below the saturation limit. For the amplifier, a higher R also helps to increase the percentage of efficient power. The performance (THD+N) improvement with a higher R can also be achieved (shown in Figure 3-8 and Figure 4-3).

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