A transformer Class E amplifier*

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Abstract: In a high-efficiency Class E ZVS resonant amplifier a matching and isolation transformer can replace some or even all inductive components of the amplifier thus simplifying the circuit and reducing its cost. In the paper a theoretical analysis, a design example and its experimental verification for a transformer Class E amplifier are presented. In the experimental amplifier with a transformer as the only inductive component in the circuit high efficiency $\eta_{\text{MAX}} = 0.95$ was achieved for supply voltage $V_i = 36$ V, maximum output power $P_{\text{OMAX}} = 100$ W and the switching frequency $f = 300$ kHz. Measured parameters and waveforms showed a good agreement with theoretical predictions. Moreover, the relative bandwidth of the switching frequency was only 19% to obtain output power control from 4.8 W to $P_{\text{OMAX}}$ with efficiency not less than 0.9 in the regulation range.

Key words: Class E amplifier, resonant inverter, dc/dc converter, transformer, leakage inductance

1. Introduction

High efficiency and a high degree of miniaturization achieved in switching resonant Class E amplifiers increase the scope of their applications including presently such areas as wireless energy transfer, induction and dielectric heating, dc/dc converters, plasma drivers, electro-surgical generators, electronic ballasts as well as r.f. transmitters. Among different types of Class E amplifiers much research effort is devoted to optimise a Class E ZVS (zero-voltage switching) amplifier with a power supply choke and a series resonant circuit [1-5]. One of possible improvements in this amplifier is the replacement of its supply choke with a finite dc-feed inductance. This also allows increasing load resistance and decreasing the amplitude of the current in the series resonant circuit for given output power and a supply voltage consequently reducing power losses in the circuit [2-5]. The improvement is useful e.g. in on-chip UHF Class E amplifiers, where small inductances of nH range are usually required and discrete

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coils are often replaced by inductances made of bond wires or copper tracks on silicon substrate [3].

In many applications of Class E amplifiers it is necessary to ensure galvanic isolation of the amplifier output from its input power supply source. This can be made by applying a transformer in the amplifier as proposed e.g. in [5]. The transformer also matches the amplifier load impedance to ensure nominal or off-nominal operation of the amplifier for its maximum output power. The primary winding inductance of the transformer can be utilized as a finite dc-feed inductance in the amplifier eliminating the need to use a separate dc-feed inductance (Fig. 1a). This reduces the number of separate inductive components in the circuit. However, the transformer also introduces leakage inductances, which modifies the operation of the amplifier (Fig. 1b). These leakage inductances have to be taken into account in the design of the amplifier. If a transformer with high leakage inductances is used then also the inductance of the series resonant circuit in the amplifier can be replaced by the leakage inductance $L_2$ of the transformer secondary winding ($L_{SR} = 0$ in Fig. 1b). Thus in the isolated Class E ZVS amplifier of Figure 1a the application of the transformer with high enough leakage inductances can reduce the number of used inductive components from three (a dc-feed inductance, a resonant inductance and a transformer) to only one – the transformer. Such a reduction of the inductive components simplifies the amplifier and lowers its cost. This is essential for the circuits operating in kilohertz and megahertz frequency range where discrete inductive components are usually with a magnetic core, and therefore are often bulky and costly.

However, the transformer Class E amplifier requires an analysis to find explicit relations between the parameters of the transformer, the amplifier nominal operation and obtained parameters of the amplifier. Published papers on Class E amplifiers with a transformer have not provided so far direct design rules or equations for computing parameters and component values for the lumped-component circuit of Figure 1a operating in kilohertz and megahertz frequency range [5-6]. The transformer Class E amplifier can find applications in low-cost isolated resonant dc/dc converters [7] and inverters. Some applications for the amplifier can be also predicted in emerging VHF power circuits with air core transformers, which are usually characterized by high leakage inductances [8-9].

The paper presents a theoretical analysis of the transformer Class E amplifier, a design example as well as experimental results for the designed and built circuit.

2. Principle of the circuit operation

Figure 1a shows a simplified diagram of the transformer Class E amplifier. The circuit comprises a bi-directional transistor switch T1D1 driven by a rectangular gate waveform $v_G(t)$ with the duty cycle $D = 0.5$ and the frequency $f$, a resonant circuit with the capacitors $C_1$, $C_{SR}$, the inductance $L_{SR}$ and the inductances of the transformer $Tr$ with the winding turn ratio $1:n$. The secondary leakage inductance $L_2$ of the transformer $Tr$ along with the external inductance $L_{SR}$, the capacitor $C_{SR}$ and load resistance $R_1$ form a series resonant circuit $L_2-L_{SR}-C_{SR}-R_1$ (Fig. 1b) with a high loaded quality factor to ensure a sinusoidal shape of the output current $i_O$. 
Fig. 1. The circuit diagram (a), equivalent circuits (b), (c) and theoretical waveforms (d) for the transformer Class E amplifier; $L_P, L_S$ – inductances of the transformer $Tr$ primary and secondary windings, respectively; $L_M, L_1, L_2$ – magnetizing inductance as well as primary and secondary leakage inductances of the transformer $Tr$, respectively; $V_I$ – supply voltage

The primary winding inductance $L_P$ acts as a finite dc-feed inductance and conducts the supply current $i_{LM}$ as well as the transformed output current $ni_O$. Both currents $i_{LM}$ and $ni_O$ compose the current $i_1$ which either is conducted by the transistor switch $T1D1$ as the current $i_S$ or flows through the capacitor $C_1$ as the current $i_{C1}$.
The analysis of the transformer Class E amplifier is based on the following assumptions:

a) The equivalent circuit of the amplifier is given in Figure 1c, where the transformer $Tr$ is modelled by its $T$–equivalent network with the winding turn ratio $n = (L_S/L_P)^{1/2}$,

b) the operation of the amplifier is nominal for the frequency $f = \omega/2\pi$, load resistance $R_L$ and the switch $S$ ON duty cycle $D = 0.5$,

c) the components of the amplifier are ideal,

d) the sinusoidal output current is given by $i_o(\omega t) = I_m \sin(\omega t + \phi)$, where $I_m$, $\phi$ – the amplitude and the phase shift of the $i_o$ waveform, respectively.

The loaded quality factor of the series resonant branch $L_R$-$C_R$-$R_L$/$n^2$ (Fig. 1c) is

$$Q_L = \frac{\omega L_R}{R_L} \cdot \frac{n}{n^2},$$

(1)

For the frequency $f$ the reactance $X$ of the $L_2$-$L_{SR}$-$C_{SR}$-$R_L$ circuit referred to the primary side is equal to

$$X = \frac{\omega (L_2 + L_{SR})}{n^2} - \frac{1}{\omega C_{SR}} \approx \frac{\omega L_R}{R_L} + \frac{X}{n^2},$$

(2)

where $\omega L_R - 1/(\omega C_{SR}) = 0$ – for the frequency $f$.

The following parameters are defined: $p, q [3, 5]$ and $k$ (the coupling coefficient of the transformer $Tr$)

$$p = \frac{\omega L_M n I_m}{V_L},$$

(3)

$$q = \frac{1}{\omega \sqrt{(L_1 + L_M)C_1}} = \frac{1}{\omega \sqrt{L_F C_1}},$$

(4)

$$k = \frac{L_M}{L_1 + L_M} = \frac{L_M}{L_F}.$$  

(5)

The current $i_{C1}(\omega t)$ flowing through the capacitor $C_1$ during the interval $\pi < \omega t \leq 2\pi$ is given by

$$i_{C1}(\omega t) = \omega C_1 \frac{dV(\omega t)}{d\omega t} = i_{LM}(\omega t) + nI_o(\omega t) =$$

$$= \frac{1}{\omega L_M} \int_{\pi}^{2\pi} (V_L - v_{L_1}(\omega t) - v(\omega t))d\omega t + i_{LM}(\pi) + nI_m \sin(\omega t + \phi).$$

(6)

For the same $\omega t$ interval the voltage $v_{L_1}(\omega t)$ across the leakage inductance $L_1$ is found as

$$v_{L1}(\omega t) = \omega L_1 \frac{di_{C1}(\omega t)}{d\omega t} = \omega^2 L_1 C_1 \frac{d^2 v(\omega t)}{d(\omega t)^2}$$

(7)
By differentiating both sides of Equation (6), then substituting Equation (7) to (6) and using the parameters given by Formulas (3), (4), (5), one arrives at the second order differential equation for the voltage waveform $v(\omega t)$ across the switch $S$ for the interval $\pi < \omega t \leq 2\pi$

$$\frac{d^2 v(\omega t)}{d(\omega t)^2} + q^2 (v(\omega t) - V_i (1 + p \cos(\omega t + \phi))) = 0.$$  

(8)

When the switch $S$ is on ($0 < \omega t \leq \pi$) the switch current $i_S(\omega t)$ is equal to the current $i_{L1}(\omega t)$ of the inductance $L_1$

$$i_s(\omega t) = i_{L1}(\omega t) = \frac{V_i \omega t}{\omega L_1 L_m} + \frac{\omega L_1}{\omega (L_1 + L_m)} (nI_m \sin(\omega t + \phi) + i_{Lm}(0)).$$

(9)

For $\omega t = 0$ there is

$$i_s(0) = i_{L1}(0) = i_{Lm}(0) + nI_m \sin \phi = 0 \Rightarrow i_{Lm}(0) = -nI_m \sin \phi.$$  

(10)

Hence substituting $i_{Lm}(0)$ found from Equation (10) to (9) and using (3) and (4) Equation (9) is now expressed as

$$i_s(\omega t) = i_{L1}(\omega t) = \frac{k n I_m}{p} \left( \omega t + p \sin(\omega t + \phi) - \sin \phi \right).$$

(11)

The dc value of the supply current $I_i$ flowing through the voltage source $V_i$ is found from Equation (11) as

$$I_i = \frac{1}{2\pi} \int_0^\pi i_s(\omega t) d\omega t = \frac{nI_m k B_1}{2 p \pi},$$

(12)

where

$$B_1 = 2 p \cos \phi + \pi (\pi/2 - p \sin \phi).$$

(13)

From Equations (11), (12) and (13) the normalized switch current $i_s(\omega t)/I_i$ equals

$$i_s(\omega t) = \begin{cases} \frac{2 \pi \omega t (\omega t + p \sin(\omega t + \phi) - \sin \phi)}{B_1} & \text{for } 0 < \omega t \leq \pi \\ 0 & \text{for } \pi < \omega t \leq 2\pi \end{cases}.$$  

(14)

For the nominal operation of the amplifier the switch is turned on in ZVS and ZDS (zero-derivative switching) conditions (15), and it is turned off in ZVS conditions (16)

$$V(\omega t) \bigg|_{\omega t = 2\pi} = 0 \wedge \frac{d v(\omega t)}{d\omega t} \bigg|_{\omega t = 2\pi} = 0.$$  

(15)

$$V(\pi) = 0 \wedge i_s(\pi) = i_{L1}(\pi) = \omega C_1 \frac{d v(\omega t = \pi)}{d\omega t} = \frac{V_i}{\omega L_p} (\pi - 2p \sin \phi).$$

(16)
By solving Equation (8) for the condition (16) the normalized $\frac{v(\omega t)}{V_I}$ voltage waveform across the switch $S$ is found

$$
\frac{v(\omega t)}{V_I} = \begin{cases}
0, & \text{for } 0 \leq \omega t < \pi \\
A_1 \cos q \omega t + A_2 \sin q \omega t + 1 - \frac{q^2 p}{1-q^2} \cos(\omega t + \phi), & \text{for } \pi \leq \omega t < 2\pi,
\end{cases}
$$

where

$$A_1 = -\frac{1}{q^2-1}(A_2 q \sin \pi q - A_4 \cos \pi q), \quad A_2 = \frac{1}{q^2-1}(A_1 q \cos \pi q - A_4 \sin \pi q),$$

$$A_3 = (q^2-1)(\pi - p \sin \phi) - pq^2 \sin \phi, \quad A_4 = 1 - q^2 + pq^2 \cos \phi.$$  \quad (17)

By substituting Equation (17) along with Equations (18) and (19) to the condition (15) a system of trigonometric equations is obtained that is used to compute $\phi$ and $p$ for a given $q < 0$; $2 > - \{1\}$

$$\begin{align*}
1 + & \frac{1}{q^2-1} \left( pq^2 \cos \phi + \sin 2\pi q (A_1 q \cos \pi q + A_4 \sin \pi q) \right) \\
- & pq \sin \phi + \cos 2\pi q (A_1 q \cos \pi q - A_4 \cos n \pi q) \right) + \sin 2\pi q (A_1 q \sin \pi q - A_4 \cos n \pi q) = 0.
\end{align*}$$  \quad (20)

The system (20) can be solved numerically e.g. by using the Newton-Raphson method. For $q = 1$ the system has no solutions, but it can be solved for $q$ close to 1 ($q$ can differ from 1 even less than $10^{-6}$, and (20) still can be solved), which is enough for practical circuits. For $q > 2$ the amplitudes of currents circulating in the amplifier components become increasingly high, and power losses increase making the circuit impractical [3-5].

If power losses in the amplifier are neglected then the output power $P_O$ equals the input power $P_I$

$$P_O = \frac{I_o^2 R_l}{2} = V_I I_I = P_I.$$  \quad (21)

Substituting Equation (12) to (21) the amplitude $I_o$ of the output current $i_O$ can be expressed as

$$I_o = \frac{k n V_I B_t}{R_l \pi}.$$  \quad (22)

Using (21) and (22) the output power $P_O$ is

$$P_O = \frac{I_o^2 R_l}{2} = \frac{1}{2R_l} \left( \frac{k n V_I B_t}{p \pi} \right)^2.$$  \quad (23)

From Equations (3) and (5) the normalized inductance $n^2 \omega L_p R_l$ of the primary winding of the transformer $Tr$ is given by
The normalized value $\omega C_1 R_L/n^2$ of the capacitance $C_1$ can be found from Equations (4) and (24) as

$$\frac{\omega C_1 R_L}{n^2} = \frac{1}{q^2} \frac{R_L}{\omega L_p n^2} = \frac{1}{q^2} \frac{k^2 B_1}{p^2 \pi}.$$  

(25)

From Equation (3) and (9) the voltage $v_{L1}(\omega t)$ across the leakage inductance $L_1$ for the interval $0 < \omega t \leq \pi$ is found as

$$v_{L1}(\omega t) = \omega L_1 \frac{d_i(\omega t)}{d\omega t} = (1-k)V_I(1+p \cos(\omega t + \phi)).$$  

(26)

For the interval $\pi < \omega t \leq 2\pi$ the voltage $v_{L1}(\omega t)$ is obtained from Equations (8) and (7) in the form

$$v_{L1}(\omega t) = (1-k)V_I(1+p \cos(\omega t + \phi) - v(\omega t)).$$  

(27)

The input voltage $v_1$ of the series resonant circuit $X/n^2 - L_R - C_R - R_L/n^2$ at the operating frequency $f$ is the fundamental component of the sum $v(\omega t) + v_{L1}(\omega t)$, and is given by

$$v_1 = v_R + v_X = v_R \sin(\omega t + \phi) + v_X \cos(\omega t + \phi),$$  

(28)

where $v_R$ and $v_X$ are found using the Fourier trigonometric series formula as follows

$$v_R = \frac{1}{\pi} \int_{0}^{2\pi} (v(\omega t) + v_{L1}(\omega t)) \sin(\omega t + \phi) d\omega t,$$  

(29)

$$v_X = \frac{1}{\pi} \int_{0}^{2\pi} (v(\omega t) + v_{L1}(\omega t)) \cos(\omega t + \phi) d\omega t.$$  

(30)

Hence the normalized series reactance $X/R_L$ of the series resonant circuit $X/n^2 - L_R - C_R - R_L/n^2$ at the operating frequency $f$ is equal to

$$\frac{X}{R_L} = \frac{V_X}{v_R}.$$  

(31)

The amplitudes $v_R$ and $v_X$ are found by substituting Equations (17-19, 26, 27) to Equations (29) and (30). Next, using $v_R$ and $v_X$ Equation (31) provides the normalized reactance $X/R_L$ as
By rearranging Equation (33) one can estimate the value of the coupling coefficient of the transformer. The dashed lines in the plots show the amplifier parameters for which the assumed value of the transformer Class E amplifier are plotted in Figures 2 and 3.

Even though a high value of the loaded quality factor $Q_R$ ($\geq 5$) that ensures a sinusoidal waveform of the output current $i_o$ [1] can be also achieved for $L_{SR} = 0$ if the value of the secondary leakage inductance $L_2$ is high enough. Because the inductance $L_2$ is related to $k$ and $L_p$ by $L_2 = (1 - k) L_s = (1 - k) n^2 L_p$ the value of $Q_R$ that can be obtained for given $k$ and $q$ ($X \leq 0$) is

$$Q_R = \frac{\omega L_2}{R_L} = \frac{(1 - k)p^2 \pi}{k^2 B_1}.$$ (33)

Even though $q$ does not explicitly occur in Equation (33) the value of $q$ is necessary to compute $B_1$ and $p$ as can be seen from (13) and (20).

By rearranging Equation (33) one can estimate the value of the coupling coefficient $k$ of the transformer $Tr$ for the given $q$ and the assumed value of $Q_R$ when $L_{SR} = 0$

$$k = \frac{p \sqrt{p^2 \pi^2 + 4 \pi B_1 Q_R} - p \pi}{2 B_1 Q_R}.$$ (34)

Normalized parameters of the transformer Class E amplifier are plotted in Figures 2 and 3. The dashed lines in the plots show the amplifier parameters for which the assumed value of $Q_R$ is constant (here $Q_R = 5, Q_R = 10$) and can be obtained by means of the secondary leakage inductance $L_2$ without the external inductor ($L_{SR} = 0$). The arrows in the plots point the direction where higher values of $Q_R$ are achieved with $L_{SR} = 0$. The diamond symbols in the plots mark the locations of the parameters of the circuit from the design example.
Fig. 2. Theoretical parameters of a transformer Class E amplifier versus \( q \) for various values of the coupling coefficient \( k \) of the transformer \( T_r \); a) \( \phi \) – phase shift of the output current \( i_o \), b) \( p \) parameter as defined by (3), c) normalized output power, d) normalized parallel capacitance \( C_1 \) of the switch \( S \).

Fig. 3. Theoretical parameters of a transformer Class E amplifier versus \( q \) for various values of the coupling coefficient \( k \) of the transformer \( T_r \); a) normalized series reactance for the frequency \( f \) of the resonant circuit \( X/n^2 – L_S – C_R – R_L/n^2 \), b) normalized reactance of the transformer primary winding inductance \( L_P \), c) normalized peak voltage and current of the switch \( S \), d) attainable values of \( Q_R \) versus \( q \) at constant \( k \) for \( L_{SR} = 0 \).
Figure 2c shows the plots of normalized output power \( P_O R_L / (n^2 V_I^2) \) versus \( q \) for various values of \( k \). The maximum value of \( P_O R_L / (n^2 V_I^2) \) for different \( k \) occurs at \( q = 1.412 \) [3-5]. From Figure 2c it can also be noticed that as the coupling coefficient \( k \) decreases the output power of the amplifier is reduced as well (see also Eq. (23)). Then to obtain a required level of output power it is necessary to increase the amplitude \( I_m \) of the output current \( i_O \), which in turn, can enlarge power losses. Thus, on the whole, a transformer Class E amplifier with \( k < 1 \) can experience higher power losses if compared to its transformerless version \((k = 1)\) for the same operating conditions. This issue is important for the special case of a transformer Class E amplifier when \( L_{SR} = 0 \) and it is expected then that \( k \) is rather low (typically there can be \( 0.7 \leq k \leq 0.9 \) for a transformer \( Tr \) with a ferrite core). The low value of \( k \) (when \( L_{SR} = 0 \)) is necessary to achieve a high enough value of the leakage inductance \( L_2 \) and to obtain a high \( Q_R \), and consequently the sinusoidal shape of the output current \( i_O \).

Figure 2d displays the plots of normalized capacitance \( C_1 \) of the switch \( S \) versus \( q \) for given \( k \). The maximum values of \( \omega C_1 R_L / n^2 \) for various \( k \) occur at \( q = 1.468 \). If \( q \) is increased from 0 to 1.468 the value of capacitance \( C_1 \) rises allowing the application in the amplifier transistor switches with higher output capacitance.

Figure 3a depicts normalized series reactance \( X/R_L \) of the series resonant circuit \( X/n^2 - L_R - C_R - R_L/n^2 \) against \( q \) for given \( k \). For \( L_{SR} = 0 \) to obtain a reasonable high value of \( Q_R \) (\( \geq 5 \)) the value of \( k \) is rather low and then \( X < 0 \) as shown by the dashed lines of \( X \) values for constant \( Q_R \).

Plots of normalized reactance of the transformer primary winding inductance \( n^2 \omega L_P / R_L \) versus \( q \) for various \( k \) are shown in Figure 3b. For \( q \) below 0.5 there is a fast increase in the value of \( n^2 \omega L_P / R_L \), which also means that then the value of the primary inductance \( L_P \) becomes high. A high-value primary inductance combined with a significant dc magnetizing component in the supply current conducted by the primary winding can cause that the size of the transformer \( Tr \) with a magnetic core can become large for low \( q \) and low \( k \).

In Figure 3c, the peak values of the switch voltage \( V_{S MAX} \) and the switch current \( I_{S MAX} \) normalized to the supply voltage \( V_I \) and the supply current \( I_I \) are shown, respectively. For the case of \( L_{SR} = 0 \) the attainable values of the loaded quality factor \( Q_R \) versus \( q \) for various \( k \) are plotted in Figure 3d. As it can be noticed the \( Q_R \) values can be even above 10 for low \( k \) and/or low \( q \).

3. Experimental circuit – design and measurements

To verify results of the theoretical analysis an experimental transformer Class E amplifier for \( L_{SR} = 0 \) was designed and built. Next, its basic parameters were measured. The given design example illustrates how the equations from the theoretical analysis can be used in the amplifier design. The experimental amplifier was designed for the nominal operation with the matching circuit \( C_O - R_O \) (Fig. 4a) and for the following assumptions: supply voltage \( V_I = 36 \) V, maximum output power \( P_{OMAX} = 100 \) W, the operating frequency \( f = 300 \) kHz, amplifier drain efficiency \( \eta_A = 0.94 \), supply power \( P_{MAX} = P_{OMAX}/\eta_A = 100/0.94 = 106.4 \) W, load
resistance $R_0 = 50 \, \Omega$, the duty cycle of the gate voltage waveform $D = 0.5$. The transformer $Tr$ was built with a gapped ETD39/20/13-3F3 ferrite core (gap – 1.32 mm) from Ferroxcube and a bi-sectional bobbin. Each of the two windings of the transformer was wound in the separate winding of the bobbin with a Litz wire $270 \times 0.071$. The primary winding was $N_p = 20$ turns, its inductance $L_p = 73.8 \, \mu H$ and the secondary winding was $N_s = 22$ turns, and its inductance $L_s = 91.3 \, \mu H$, which gave the winding turn ratio $n = (L_s/L_p)^{1/2} = (91.3/73.8)^{1/2} = 1.123$. The coupling coefficient $k$ of the transformer $Tr$ estimated from measurements was $k = 0.811$ [12]. From Equations (23) and (24) one computes the parameter $B_1 = 2\pi\alpha L_p P_{\text{MAX}}/ V_s^2 = 2\pi\times 2\pi \times 300 \times 10^3 \times 73.8 \times 10^{-6}/106.4/36^2 = 71.76$, which permits calculating from Equations (13) and (20) $q = 0.5121, p = 20.224$ and $\phi = -0.5244$ rad. From Equation (24) for the circuit of Figure 4a the load resistance $R_L$ for the nominal operation is equal to $R_L = (R_{\text{loss}} + R_s)$, where $R_s$ – series load resistance, $R_{\text{loss}}$ – series loss resistance modelling all power losses in the amplifier. The output current amplitude is $I_{\text{MAX}} = (2P_{\text{MAX}}/R_s)^{1/2} = (2 \times 106.4/6.309)^{1/2} = 5.808 \, A$, the series loss resistance $R_{\text{loss}} = (2P_{\text{MAX}} - P_{\text{OMAX}})/I_{\text{MAX}}^2 = 2(106.4 - 100)/5.808^2 = 0.38 \, \Omega$ and the series load resistance $R_s = R_L - R_{\text{loss}} = 6.309 - 0.38 = 5.93 \, \Omega$. From Equation (25) the capacitance $C_s = n^2 k^2 B_1/(q^2 p^2 \alpha \pi R_s) = 1.1123^2 \times 0.811^2 \times 71.76/(0.51212^2 \times 20.224^2 \times 2\pi \times 300 \times 10^3 \times \pi \times 6.309) = 14.57 \, \text{nF}$. The parallel capacitance $C_{\text{P}}$ is used to match resistance $R_0$ to $R_s$, and the value of $C_{\text{P}}$ is given by $C_{\text{P}} = (R_s/R_s - 1)^{1/2}/(2\pi \times 300 \times 10^3 \times 50) = 28.92 \, \text{nF}$. From (32) the normalized series reactance for the frequency $f$ is $X/R_L = -3.12$, which gives $X = -3.12 \times R_L = -3.12 \times 6.309 = -19.68 \, \Omega$. The series equivalent reactance $X_s$ in the circuit in Fig. 4a is found from $X_s = R_s/(R_s - R_L)^{1/2}/(R_s/R_L) = 50/(50 - 1)^{1/2}/(50/50 - 1) = -16.166 \, \Omega$. Taking into account $X_s$ the series capacitance $C_{\text{SR}}$ is given by $C_{\text{SR}} = 1/(\alpha \pi Q_{\text{SR}} R_s + X_s - X)) = 1/(2\pi \times 300 \times 10^3/(5.16 \times 6.309 - 16.166 - (- 19.68))) = 14.71 \, \text{nF}$. The secondary leakage inductance is $L_2 = (1 - k)L_s = (1 - 0.811) \times 91.3 \times 10^{-6} = 17.26 \, \mu H$. Hence the loaded quality factor $Q_{\text{SR}}$ is computed as $Q_{\text{SR}} = \omega L_2/R_0 = 2\pi \times 300 \times 10^6 \times 17.26 \times 10^{-6} / 6.309 = 5.16$. The theoretical peak values of of the switch voltage $v(t)$ and current $i(t)$ are found from the waveform Equations (14), (17) as $V_{\text{MAX}} = 3.572 \times V_s = 3.572 \times 36 = 128.6 \, V$ and $I_{\text{MAX}} = 2.843 \times I_s = 2.843 \times P_{\text{MAX}}/V_s = 8.404 \, A$. As the switch S an IR MOSFET transistor IRFB4115 was used. Polypropylene capacitors FKP1 from Wima were applied as $C_1$, $C_{\text{SR}}$ and $C_{\text{P}}$, and their measured values were $C_1 = 13.94 \, \text{nF}$, $C_{\text{SR}} = 14.35 \, \text{nF}$. $C_{\text{P}} = 28.83 \, \text{nF}$. The value of $C_1$ in the experimental circuit had to be lowered from its theoretical value to obtain nominal operation of the circuit because of the output capacitance of the applied MOSFET switch. The obtained maximum output power in the experimental amplifier was $P_{\text{OMAX}} = 99.79 \, W$ with the efficiency $\eta_{\text{OMAX}} = 0.95$. The measured peak values of the transistor switch voltage and current were $V_{\text{MAX}} = 136 \, V$, $I_{\text{MAX}} = 8.2 \, A$, respectively. The designed amplifier was also simulated using LTSpice with an ideal switch and component values as in the design example. The simulation results were $P_{\text{OMAX}} = 103.5 \, W$, $V_{\text{MAX}} = 134.5 \, V$, $I_{\text{MAX}} = 8.33 \, A$ for a steady state (after a hundred periods). For higher values of $Q_{\text{SR}} (>10)$ the output current $i(t)$ contains a lower level of harmonics and the differences between parameters of the simulated amplifier and the analytically designed circuit decrease.
The experimental amplifier was also tested with respect to FM control of its output power for $R_O = 50 \, \Omega = \text{const.}$ and $V_I = 36 \, \text{V}$. The operating frequency of the amplifier was varied from 300 kHz to 357.4 kHz and simultaneously the on-time of the switch was adjusted (from 1.67 $\mu$s to 0.46 $\mu$s) to assure its ZVS operation. The output power in the experimental circuit was regulated from its maximum value to 4.8 W with the efficiency decreasing from 0.95 to 0.9, respectively. Thus this wide range of output power control in the amplifier required only 19% change of the operating frequency.

4. Conclusions

The results of the presented detailed analysis of the Class E amplifier have shown how the amplifier parameters depend on some of the parameters of the applied transformer. A design procedure for a transformer Class E amplifier with only one inductive component has been proposed as well as verified both experimentally and by simulation. The theoretical and experimental results have agreed well enough to use the design procedure and the analysis results for engineering purposes. The analysis can be also used to design transformer Class E amplifiers both with an external inductor in the series resonant circuit and without the inductor ($L_{SR} = 0$). It is worth noticing that the analysis can be used to further optimise the transformer Class E amplifier by solving the presented equations for $D \neq 0.5$ and the nominal or off-nominal operation of the amplifier. Because the number of inductive components in the trans-
former Class E amplifier can be much reduced the circuit can find applications in low-cost, isolated miniaturised resonant dc/dc converters [7, 10, 11, 13, 14] and h.f. power generators [15, 16].

References