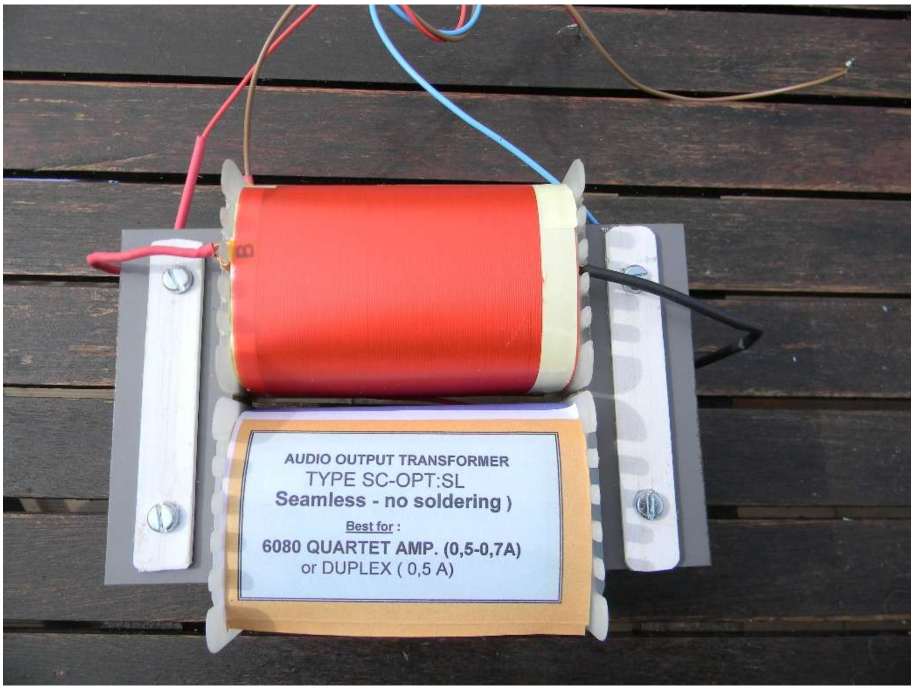
The Self Compensated Output Transformer

For Single Ended Valve Amplifiers

(An Aristide Polisois invention to be reconsidered and completed)



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Introduction

Aristide Polisois, more known as “Ari”, in the audio community, was a fan of SE valve amplifiers, for which he developed and experimented, a Self-Compensated OPT (SC-OPT), allowing to cancel, in the magnetic core, the annoying DC magnetic flux. The first achievements showed a remarkable musicality, but also the need, to meet HI-FI standards, for output power valves with low internal resistance. During his last years, he tried to find, without success, a solution allowing to overcome this restriction. Ari was my friend (1), and I had the privilege to follow and share his developing and experimenting period, that ended, when he left this world, in 2020. I believe that Ari's work should not be lost but rather benefit to SE valve amplifier enthusiasts. Therefore, it is the objective of this paper to make available, for interested audio designers, all the necessary information about their configuration, mathematical model, frequency response and possible evolutions to overcome SC-OPT actual restrictions.

SC-OPT configuration and notations

Configuration

The SC-OPT configuration is as shown in the figure: 1. It is usually composed of a C-cut or UI type magnetic core, made of laminated sheets of GOSS material, providing two legs. On one leg are wound the primary and secondary windings, the design of them being like those of a conventional OPT (CO-OPT), to provide a good high frequency response. On the other leg is wound the tertiary winding, which has the same number of turns than the primary, but in opposite phase with the primary, to cancel the DC magnetic flux. A large capacitor by-passes the tertiary winding terminals, to eliminate the AC voltage across it. This configuration provides a loose coupling between the primary/tertiary and the secondary/tertiary, as well as a tight coupling between the primary/secondary.

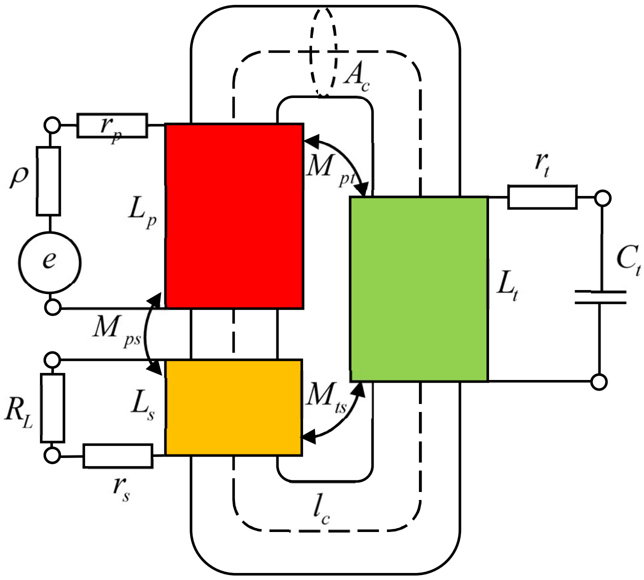


Figure: 1. Usual SC-OPT configuration

Notations

The notations we are using throughout this paper are:

L_p	Primary inductance
n_p	Number of primary turns
r_p	Primary resistance
L_s	Secondary inductance
n_s	Number of secondary turns

r_s	Secondary resistance
L_t	tertiary inductance
n_t	Number of tertiary turns
r_t	Tertiary resistance
e	Output power valve electromotive force
ρ	Output power valve internal resistance
R_L	Loading resistance
C_t	By-pass capacitor across the tertiary
M_{pt}	Mutual inductance between the primary/tertiary windings
M_{ps}	Mutual inductance between the primary/secondary windings
M_{st}	Mutual inductance between the secondary/tertiary windings
S_c	Cross section area of the magnetic core
l_c	Average magnetic path length of the magnetic core

SC-OPT schematic diagram and AC equations

Schematic diagram

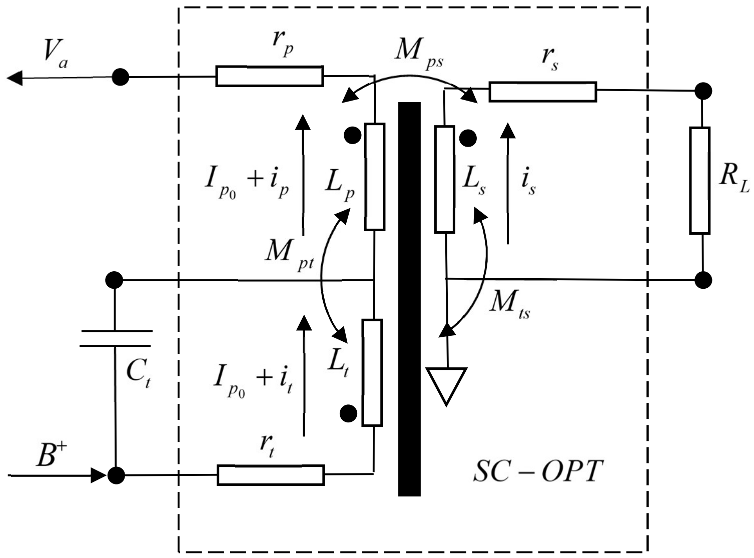


Figure:2 SC-OPT Schematic diagram

From the SC-OPT usual configuration, we derive the schematic diagram given in the figure: 2, where:

I_{p0}	Quiescent DC current of the output power valve
i_p	AC current flowing through the primary
i_t	AC current flowing through the tertiary

i_s AC current flowing through the secondary

AC equations

As the by-pass capacitor is large, it behaves like a short-circuit for AC current. Therefore, AC equations describing the SC-OPT behaviour can be simplified and become:

$$L_p \frac{di_p}{dt} + M_{sp} \frac{di_s}{dt} + M_{tp} \frac{di_t}{dt} + (\rho + r_p) i_p = e$$

$$L_s \frac{di_s}{dt} + M_{ps} \frac{di_p}{dt} + M_{ts} \frac{di_t}{dt} + (R_L + r_s) i_s = 0$$

$$L_p \frac{di_t}{dt} + M_{pt} \frac{di_p}{dt} + M_{st} \frac{di_s}{dt} + r_t i_t = 0$$

In addition, we use the following classical relationships:

$$n = \frac{n_p}{n_s}$$

$$L_p = n^2 L_s$$

$$L_p = L_t$$

$$M_{ps} = M_{sp} = \sqrt{L_p L_t} = \frac{L_p}{n}$$

$$M_{pt} = M_{tp} = -\lambda \sqrt{L_p L_t} = -\lambda L_p$$

$$M_{st} = M_{ts} = \lambda \sqrt{L_s L_t} = -\lambda \frac{L_p}{n}$$

Substituting these relationships into the AC equation gives finally:

$$L_p \frac{di_p}{dt} + \frac{L_p}{n} \frac{di_s}{dt} - \lambda L_p \frac{di_t}{dt} + (\rho + r_p) i_p = e$$

$$\frac{L_p}{n^2} \frac{di_s}{dt} + \frac{L_p}{n} \frac{di_p}{dt} - \lambda \frac{L_p}{n} \frac{di_t}{dt} + (R_L + r_s) i_s = 0$$

$$L_p \frac{di_t}{dt} - \lambda L_p \frac{di_p}{dt} - \lambda \frac{L_p}{n} \frac{di_s}{dt} + r_t i_t = 0$$

Where:

n OPT ratio

λ Coupling coefficient

Remarks

Because the problem to solve is the control of the low corner frequency, SC-OPT equations describe only the SC-OPT behaviour at low frequency. Hence, the coupling factor between the primary/secondary has been made equal to 1, simplifying greatly the equations, without any consequence at low frequency.

At high frequency, the SC-OPT behaves like a Conventional OPT (CO-OPT) and the high corner frequency is determined according to the leakage inductance and parasitic capacitances between the primary/secondary windings

To make SC-OPT working correctly, the coupling factor λ must be set close to one, for a good magnetic flux cancellation, but cannot be set equal to 1. The Ari's arrangement for SC-OPT provides a value, for the coupling coefficient in the range 0,985-0,994 which has been found optimal with the first achievements.

Solution of AC equations

Let be:

$$Z_a = n^2 (R_L + r_s)$$

$$Z_{eq} = \frac{(\rho + r_p) Z_a}{(\rho + r_p) + Z_a}$$

We apply the Laplace transform to the AC equations, in order to obtain a linear system of 3 equations with 3 unknows: i_p, i_s, i_t, the solution of which allows determining the normalized transfer function of the SC-OPT. We get:

$$y = \frac{p\left[p + \frac{r_t}{L_p\left(1-\lambda^2\right)}\right]}{p^2 + p\frac{\left(r_t + Z_{eq}\right)}{L_p\left(1-\lambda^2\right)} + \frac{r_t Z_{eq}}{L_p^2\left(1-\lambda^2\right)}}$$

Where p is a complex number

This normalized transfer function has:

2 zeros:

$$z_1 = 0$$

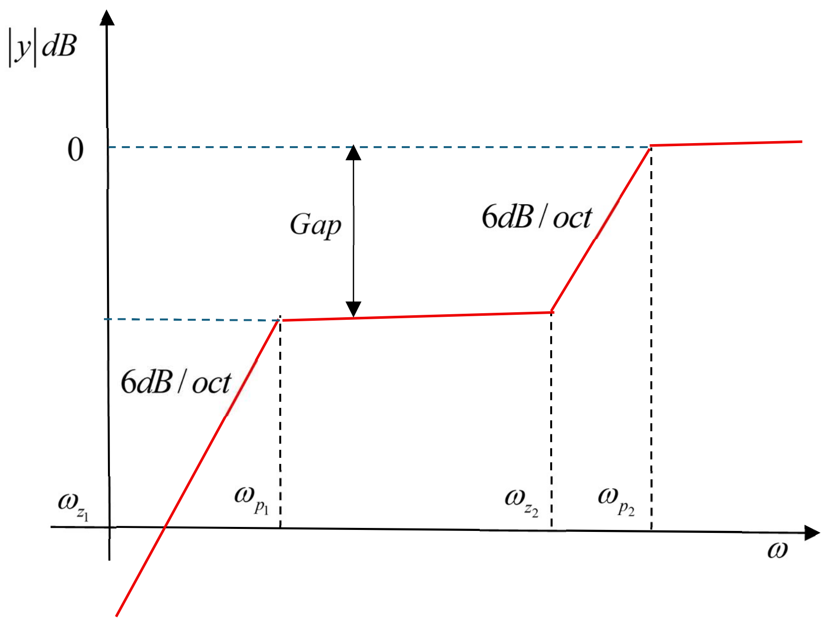
$$z_2 = -\frac{r_t}{L_p\left(1-\lambda^2\right)}$$

And 2 poles:

$$p_1 = -\frac{\left(r_t + Z_{eq}\right)}{2L_p\left(1-\lambda^2\right)} + \frac{\left(r_t + Z_{eq}\right)}{2L_p\left(1-\lambda^2\right)}\sqrt{1 - 4\frac{Z_{eq}\left(1-\lambda^2\right)}{r_t\left(1+\frac{Z_{eq}}{r_t}\right)}}$$

$$p_2 = -\frac{\left(r_t + Z_{eq}\right)}{2L_p\left(1-\lambda^2\right)} - \frac{\left(r_t + Z_{eq}\right)}{2L_p\left(1-\lambda^2\right)}\sqrt{1 - 4\frac{Z_{eq}\left(1-\lambda^2\right)}{r_t\left(1+\frac{Z_{eq}}{r_t}\right)}}$$

The frequency response is given, making $p = j\omega$. Its asymptotic representation (Module versus frequency) is given in the graph: 1.



Graph: 1 SC-OPT-Asymptotic frequency response with tertiary resistance of medium value

Comments

From the preceding results, we can deduce the following situations:

The pole p_2 is the dominant one and the SC-OPT design must be such that it reduces the gap between the high frequency and low frequency level.

If the tertiary resistance tends to zero, we get, for the transfer function:

$$\lim_{r_t \to 0} y = \frac{p}{p + \dfrac{Z_{eq}}{L_p\left(1-\lambda^2\right)}}$$

The SC-OPT in that case is equivalent to a first order high pass filter with a low corner frequency:

$$f_{Lf-3dB} = \frac{Z_{eq}}{2\pi L_p\left(1-\lambda^2\right)}$$

This is the actual situation of SC-OPT, because all of them have a low tertiary resistance.

As the coupling coefficient λ is in the range of (0,985-0,994), the effective primary inductance is strongly reduced and the only way to maintain the low corner frequency, to a low value, is to set Z_{eq} as low as possible, and consequently, the internal impedance of the output power valve, as low as possible. We now understand why actual SC-OPT are limited to output power valves exhibiting low internal resistance

On the contrary, if the tertiary resistance tends to infinity, we get for the transfer function:

$$\lim_{r_t \to +\infty} y = \frac{p}{p + \frac{Z_{eq}}{L_p}}$$

This situation is extremely interesting, because no more depending on the tertiary resistance and the coupling coefficient. The SC-OPT in that case is equivalent to a first order high pass filter with a low corner frequency

$$f_{Lf-3dB} = \frac{Z_{eq}}{2\pi L_p}$$

It is the corner frequency of a conventional OPT (CO-OPT). Therefore, extending the use of SC-OPT to any output power valves, whatever their internal resistance value, requires setting the tertiary resistance to a value as large as possible.

Remark

With a large tertiary resistance, the SC-OPT behaves like a conventional OPT (CO-OPT), but with the advantage of having any DC magnetic flux in its magnetic core. The Gral for SE valve amplifiers.

Proposed solutions for a large tertiary resistance

Passive resistance

If the tertiary resistance is a passive resistance, as the DC quiescent current of the output power valve flows through it, we get the following drawbacks:

Large heat production in the tertiary resistance, due to a large DC voltage drop across it.

Need for a higher DC voltage B^+ to compensate for the DC voltage drop across the tertiary resistance

Implementing this solution in the design of a SC-OPT should be made on the following reasonable basis:

Tertiary resistance higher than 1000 Ohm

DC voltage drop across the tertiary resistance, less than 100V

Nevertheless, if this solution is simple, it is not always possible to set the tertiary resistance as large as it should be.

When looking to the module of the frequency response, a gap level between the high and low frequency appears. The larger the tertiary resistance, the lower the gap level. A good design will be to maintain this gap level below 1,5 dB, for example.

Active resistance

A much better solution would be an active resistance that exhibits a low DC resistance and a large AC resistance. In that case, the drawbacks pointed out, with a conventional resistance, disappear and large AC resistance values can be set for the tertiary resistance. This is exactly the field where audio designers willing to experiment this elegant solution should go. A Constant Current Source (CCS), using modern MOSFET, will do. I tested it successfully, by simulations, using a network analysis software (ESACAP), but never tested it, in the real world, on a real SC-OPT.

Conclusion

In this paper, we have described the configuration of SC-OPT, specially designed for SE valve amplifiers and given all the AC equations necessary to determine its behaviour, at low frequency. From them, we have derived its transfer function and shown that actual SC-OPT's, that have a low tertiary resistance, are only compatible with output power valves exhibiting a low internal resistance, to meet HI-FI standards. Solutions, to extend to output power valves of any internal resistance value, have been proposed and justified, using a conventional tertiary resistance or an active one. I sincerely hope that the above information and analysis will convince interested designers to complete Ari's work, for the benefit of SE amplifier enthusiasts. Interested people requiring more information, or technical details, can reach me at: p.touzelet@orange.fr. I will do my best to answer properly to their questions.

Additional information

1 The three Musketeers

During the developing and experimenting period (1998-1920), "three Musketeers": Menno Van der Veen, Aristide Polisois, Pierre Touzelet, used to meet, each year, in summer, at Ari's house, in Lahoussaye France. During these meetings, free technical discussions, and long listening sessions have contributed helping Ari to finalize his SC-OPT invention.

2 Aristide Polisois brief life story

Aristide Polisois was born in Cairo in 1928, to a Greek father, Yannis Polyzoîs, and an Italian mother, Margherita della Chiesa. After obtaining a diploma, in 1943, as a commercial technician, from the Don Bosco Institute in Cairo, he started to work at the Egyptian Sugar and Distillery, in Cairo, from 1943 to 1960, then left Egypt, to take a position at PIRELLI's tyre division, in Milan Italy, as an export trader. He got a degree in Social, Political, and Economic Sciences from the Alfieri Institute in Milan, in 1963, followed by a degree in Economics and Commerce, from the Catholic University of Milan, in 1968. These new qualifications led to his appointment as Export Director of Pirelli's tire division, a position he held until 1972. He left then Pirelli to join the Bertolini company in Reggio Emolia and shifted rapidly to the Oleo-Mac company in Bagnolo a Piano, where he helped to transform this small, artisanal company, into a robust international enterprise producing and marketing chainsaws under the EIMAC brand. At the end of his professional career, he became a consultant for numerous companies involved in hydromechanical activities. He retired in 1992 at Lahoussaye, in France, a small town in Paris's surroundings. He dedicated his retirement to his passion for high-quality tube amplifiers, developing his own electronic circuits, such as the DCMB (Direct Coupling Modulated Bias). He started, in 1998, (1), designing and experimenting with the SC-OPT (Self-Compensated Output Power Transformer) for Single-Ended tube amplifiers and obtained patents for his invention (INPI patents n° 03 10898 and 01 02457). He also worked with Giovani Mariani, the founder of GRAAF, in Italy, on an evolution of the SC-OPT: the SC-SCC-SET (Split Core-Stereo Common Circuit-Single Ended Transformer). Until his death in 2020, he tried, without success, to free the SC-OPT from its limitations, aiming to make it the ideal output power transformer for single-ended tube amplifiers.

3 List of AES Papers

Aristide Polisois, Pierre Touzelet

"The Self-Compensated-Output Transformer (SC-OPT). Theory and properties".

Paper 6346-118th AES Convention, 2015-Barcelona Spain

Aristide Polisois, Giovanni Mariani

"The self-compensated audio transformers for tube and solid-state single ended amplifiers"

Paper 6831-120th AES Convention-2016-Paris France

Aristide Polisois, Pierre Touzelet

"Direct current offset and balance for audio transformers used with paralleled tubes or solid-state devices" Convention paper 7151-122nd AES Convention, 2017-Vienna Austra