Pulse Generation for TESLA Considerations on SMES-Variants

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March 1996

1 Introduction

As an alternative of voltage source modulators for the supply of pulse power to the TESLA RF-transmitters i.e. now installed and operated for the TESLA TEST FACILITY current source modulators using SMES - superconducting magnet energy storage - have been proposed. In addition to its basic configuration [1], which corresponds to the simple capacitor discharge in the case of the voltage source, SMES variants have been mentioned [2], [3] mainly in order to reduce the installed energy and with that the size of the modulators. Further reduction of the modulator expense may be achieved by the use of a new variant proposed here. The application of thyristors as magnet short circuit device with or without the influence of long distance cable connections for 2 variants have been analysed.

All diagrams of the electric quantities versus time come from SPICE simulations.

2 Load and Pulse Transformer Parameters

All data are those of the primary of the transformer having the turns ratio 1:13

voltage, top	$U_l = 10$ kV $\pm$ 1 % during 1.7 ms
load resistance, linear	$R_l = 8.93\ \Omega$
current, linear	$I_l = 1120$ A
(repetition rate	0.1 s)
pulse energy	ca 20 kWs
pulse transformer, resistance	$R_{tr} = 0.155\ \Omega$
dto leakage inductance	$L_s = 0.3$ (0.25) mH
dto main inductance	$L_h = 8$ H (2 H)
dto capacitance sec to ground	$C_{tr} = 0.22\ \mu$F
(dto input capacitance	$C_e = 0.1$ nF)

For the simulations we used the above parameters and regarded - only - the linear case. The series resistance R_{tr} represents all transformer losses (1.74 % of the effective power).

3 SMES–Restrictions and Variants

The SMES conception shown in Ref. [1] consists of a mainly short–circuited inductor conducting an impressed current. The short is only raised during the pulse period when the current passes the load and generates the power pulse. If the load is represented by a simple – linear or nonlinear – resistor this principle works in a similar manner as the pulse generation by switching a capacitor on a load resistor. But in reality one has to take into consideration series inductance – mainly the stray inductance of the pulse transformer – and parallel inductance of this transformer. This was already described in Ref. [2], where a parallel capacitor was proposed as commutating device thus setting up a temporary voltage source in order to deal with the influence of the series inductance.

The first SMES variant had been proposed in Ref. [2] and was based on the bouncer principle for voltage source modulators [4]. For this B(ouncer) SMES the SMES inductor is paralleled by a preloaded series resonant circuit which is shorted and opened simultaneously to the magnet. With this design, the stored energy and with that the size of the modulator will be reduced drastically and to a similar value compared to the voltage source bouncer modulator. Apart from this the influence of the main inductance on the slope of the pulse top is decisively reduced. A commutation capacitor is necessary here too. A strong disadvantage of the B–SMES is its enlarged di/dt value of the inductor due to its decreased inductance and the same

position in the circuit which exposes it to the same voltage as in the case of the simple SMES.

The DSM – double storage modulator – proposed in Ref. [3] and shown in fig. 1 needs 2 energy stores and 2 switches. With that a series resonant circuit is ringing at a suitable resonance frequency i.e. 25 Hz during the pulse duration and at the top of the current cosine wave shape and with central peak value. By these means the inductor voltage is reduced and likewise the size of the energy stores. A further reduction in both of these values will be got by the application of the B(ouncer) DSM shown in fig. 2. This modulator is equipped with a bouncer circuit put in series to the capacitor of the DSM. This bouncer consists of a parallel resonant circuit as in Ref. [4]. In contrary to that a half wave during the 1.7 ms top is generated.

4 DSM and BDSM-Basic Operation with Thyristor

In both figures #1 and #2 the parallel path with which the inductor L_1 is shorted during the pauses between the pulses is equipped with the thyristor Th. The pulse is started by switching on the - semiconductor - switch S. The Capacitor C_1 begins to discharge and a current is flowing via Th and the load. Within the parallel path its direction is opposite to the inductor current. The sum of both currents, the commutation current i_k is dropping during the commutation interval from its initial value – the inductor current – to zero. Then the thyristor turns off and the series resonant circuit C_1, L_1, load is in operation. With that a smooth transition of the current source is obtained without any additional commutation capacitor.
Simulations have been done using the following parameters of the modulators:

DSM, see figure 1

L_1	0.1 H; 1113 A
C_1	0.4 mF; 13.0 kV
R_2	10 mΩ
L_2	5 μH; 1113 A
L_4	20 μH
R_4	1 Ω
C_e	0
L_h	8 H

BDSM; see figure 2

L_1	0.05 H; 1120 A
C_1	0.4 mF; 12.95 kV
R_2	10 mΩ
L_2	5 μ H; 1120 A
L_3	0.284 mH
C_3	1 mF; -1.95 kV
L_4	10 μH
R_4	1 Ω
C_e	0
L_h	8 H; 2 H

The simulations yield the following diagrams:

Fig. 3	DSM Output voltage
Fig. 4	DSM Commutation process
	y_1 Inductor L_1 (=SMES) voltage
	y_2 Current i_k
Fig. 5	BDSM Output voltage; $L_h = 8$ H
Fig. 6	BDSM Commutation process; $L_h = 8$ H
	y_1 Inductor L_1 (=SMES) voltage
	y_2 Current i_k
Fig. 7	BDSM Output voltage; $L_h = 2$ H

From these diagrams is it obvious, that the BDSM-system results in these advantages:

- half-sized SMES
  With that the stored energies of the BDSM-elements as measure of their sizes are:

L_1	:	31.4 kWs	
C_1	:	33.5 kWs	
C_1	:	1.9 kWs	
C_3	:	3.3 kWs	(peak current: 4.85 kA)

  Total: 70.1 kWs or 3.5 $\times$ pulse energy.
  That is 73 % of the DSM–value.

- closer top tolerances

- lower SMES peak voltage and lower peak di/dt - value compared to DSM

$$di/dtBDSM/DSM = 2 \times 580/2900 = 0.40 \quad (1)$$

The influence of the pulse transformer main inductance L_h on the pulse shape of the BDSM may be cancelled be changing the initial values of L_1 and C_1 slightly. After current i_k having been zero there is sufficient reverse off–state voltage and turn–off time.

5 DSM and BDSM Transmission Line Operation

Due to the intended central housing of modulators for a larger number of RF- transmitters transmission lines between the pulse generator and the RF- transmitters belonging to it have to be installed. With that there are two possibilities:

a) Pulse transformer located near the modulator(s)

b) Pulse transformer housed close to the transmitter.

on a)
This could offer the chance to terminate the transmission line by its characteristic impedance Z_o because the RF klystron represents a nearly resistive load. For that $Z_o = 13^2 \times 8.93\Omega = 1,5k\Omega$ on the high voltage side is necessary. But this condition cannot be fulfilled by the use of high voltage coaxial cables for which $Z_o \approx 60\ \Omega$ may be expected. Higher values of Z_o could be got with soft iron central conductors but in this case the delay time increases.

The longest cable distance is assumed to be 1 km. For that the cable acts like a capacity. We may expect 0.1 μF as capacitance for this distance and PE- insulation and the time constant T = 0.1 μF $\times$ 1.5 kΩ = 0.15 ms. The load current i_l is

$$i_l = I(1 - exp\frac{t}{T}), \quad (2)$$

as response on the input current step I, series inductance neglected. With that no reasonable rise time may be obtained.

Another argument against a cable connection on the high voltage level is this: the stored energy of the cable capacitance during the pulse time is

$0.5 \times 0.1\ \mu$F (130 kV)^2 Ws = 845 Ws. When a klystron arc occurs only 20 Ws may pass the klystron. Therefore an expensive high voltage crowbar system located near the transmitter and/or a matched resistor connected via a clipper diode to the cable input are necessary.

on b)

In this case the coaxial cable connects the modulator output to the input of the pulse transformer. It has parallel and series reactances, see fig. 8 and the transmission line cannot be operated under matched conditions.

We looked to the influence of a loss–free cable of 1 km length and varied Z_o and the suppression network (see fig. 8), whilst the delay time T_d was constant. In most cases we used $T_d = 8\ \mu$s; that corresponds to cable parameters of C = 0,2 μF/km; L = 320 μH/km and $Z_o = 40\ \Omega$. For other simulations we applied $T_d = 6\ \mu$s. That value could belong to a cable with $Z_o = 40\ \Omega$; C = 0.1 μF/km and L = 240 μH/km.

The BDSM modulator yields reasonable waveshapes only by transmission with a $Z_o = 3O\ \Omega$ cable. $Z_o = 40\ \Omega$ would in this case require impedance matching of the whole modulator system and changing the transformer turns ratio from 13 to 13 .$(30/40)^{0..5} = 11.26$. Then the nominal rated modulator output voltage is 11.55 kV instead of 10 kV. – The delay time is not influenced by this measure.

The following diagrams depict the transmission line influence on the pulse form of thyristor operated modulators:

Fig. 9	DSM Output Voltage L_1: 1120 A; C_1:13.2 kV, $Z_o = 40\ \Omega$, $T_d = 8\ \mu$s
Fig. 10	DSM Commutation process of fig. 9 y_1 Current i_k y_2 Inductor L_1 (= SMES) voltage
Fig.11	BDSM Output voltage Ls = 0.25 mH, $Z_o = 30\ \Omega$, $T_d = 8\ \mu$s
Fig.12	BDSM Commutation process of fig. 11 y_1 = Current i_k y_2 = Inductor L_1 (= SMES) voltage
Fig.13	BDSM Output voltage $Z_o = 30\ \Omega$, $T_d = 6\ \mu$s
Fig.14	BDSM Commutation process of fig. 13 y_1 = Current i_k y_2 = Inductor L_1 (= SMES) voltage

All circuits have $C_e = 0.1$ nF as transformer input capacitance. Only parameters not mentioned in the above data lists and parameters in brackets there are listed here.

To draw a comparison with this thyristor operated modulator we looked to the behaviour of a BDSM device with fast current interruption i.e. by the use of IGBT s instead of thyristors. In this case (positive) forward off–state voltage after current interruption is required and therefore both paths of the suppression network have to be equipped with capacitors (not shown in fig. 8). The capacitor to be added acts as commutation device too and has to be large–sized. Its capacitance destines the magnitude of the voltage across the SMES as shown below:

Fig.15 BDSM Output voltage
$Z_o = 30\ \Omega$, $T_d = 8\ \mu$s; add. SN capacitor 50 μF
Fig.16 BDSM Inductor (= SMES) voltage
after current interruption. Circuit as for fig. 15.
Fig.17 BDSM Output voltage
$Z_o = 30\ \Omega$, $T_d = 8\ \mu$s, add. SN capacitor 30 μF
Fig.18 BDSM Inductor (= SMES) voltage
after current interruption. Circuit as for fig. 17.

6 Results

This study proves

- the advantageous properties of the proposed bouncer DSM modulator for the basic operation: smaller size, closer top tolerances and lower SMES-di/dt value, compared to the DSM without bouncer
- that for both investigated SMES modulator types and for both operational modes – natural commutation and fast current interruption – the rise time of the pulse caused by a 1 km coaxial cable between modulator and pulse transformer is increased by 2/3, compared to the basic operation
- that in the case of thyristor operated modulators the distortion of the pulse top by the influence of the 1 km cable remains within tolerable limits if a properly designed suppression network is used. With that the maximum di/dt–value of the SMES is even lower than this of the normally operated BDSM. In the case of the DSM, this value is enlarged

- that fast current interruption when operating over a long distance yields no improvement of the pulse shape compared to thyristor operation, but needs commutation capacitance
- that the BDSM with cable connection gives the best pulse shape if the cable time delay is reduced from 8 μs to 6 μs. That allows to increase the transformer leakage inductance from 0.25 mH to the "normal" value 0.3 mH.

References

[1] H. Salbert and K.P. Juengst: "Generation of High Power Pulses Using a SMES", 1994 21st International Power Modulator Symposium, pp 52-55, Costa Mesa, USA, June 1994

[2] W. Bothe: "Pulse Genration for TESLA, a Comparison of Various Methods", TESLA 94-21, July 1994

[3] K.P. Juengst and H. Salbert: "Fast SMES for Generation of High Power Pulses",14th International Conference on Magnet Technology, 1995 Tampere, Finland

[4] H. Pfeffer, C. Jensen, S. Hays, L. Bartelson: "The TESLA Modulator", TESLA 93-30, July 1993

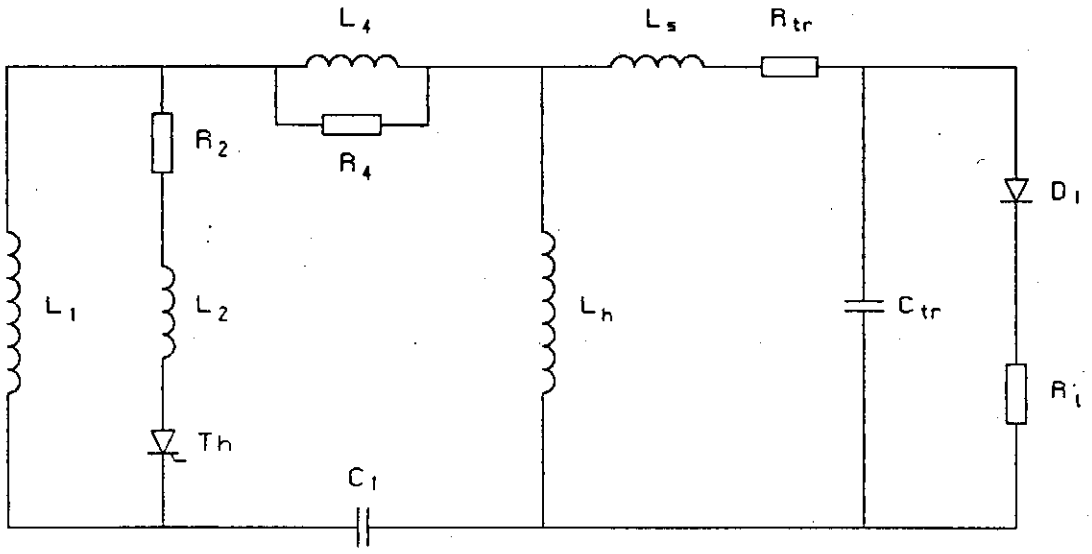


Figure 1 DSM–Basic Circuit Diagram

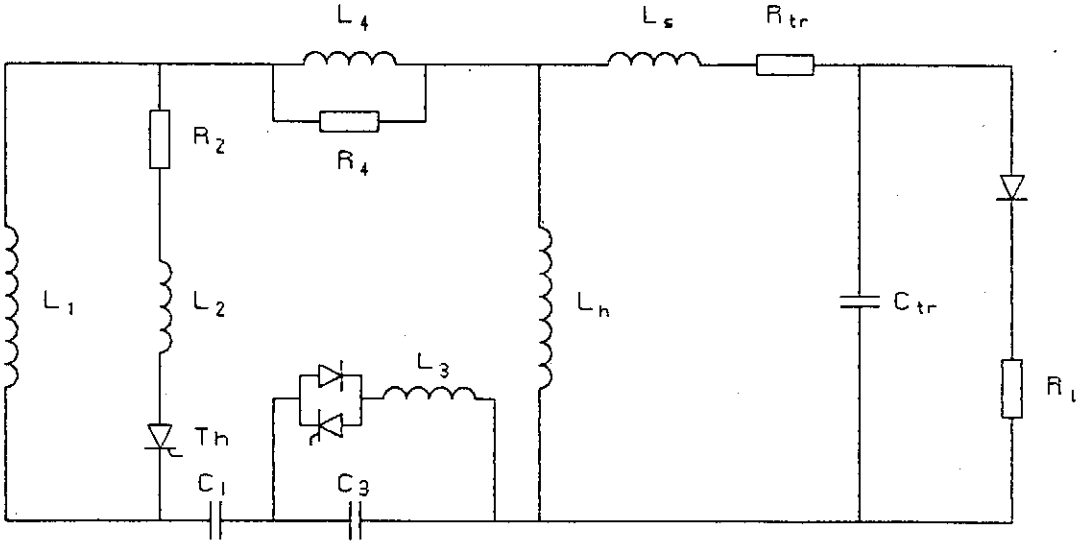


Figure 2 BDSM–Basic Circuit Diagram

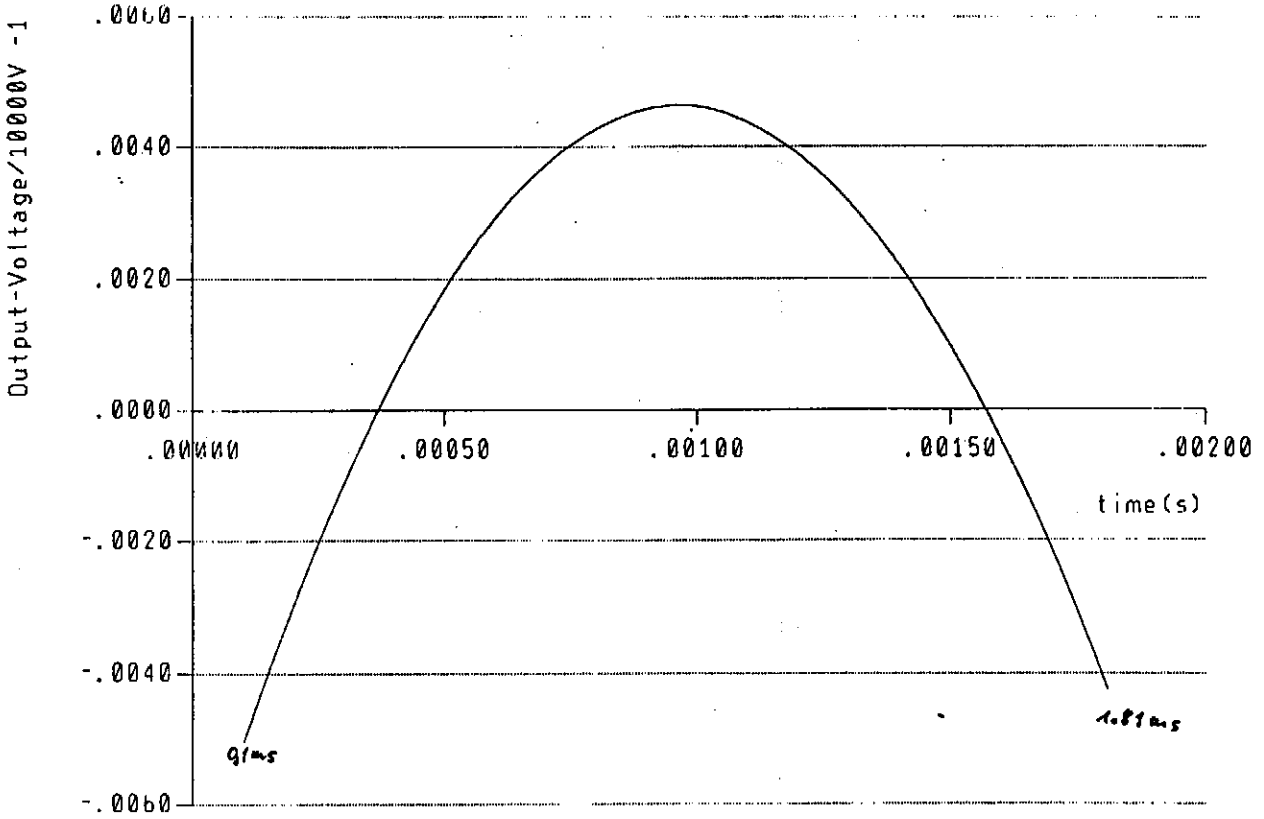
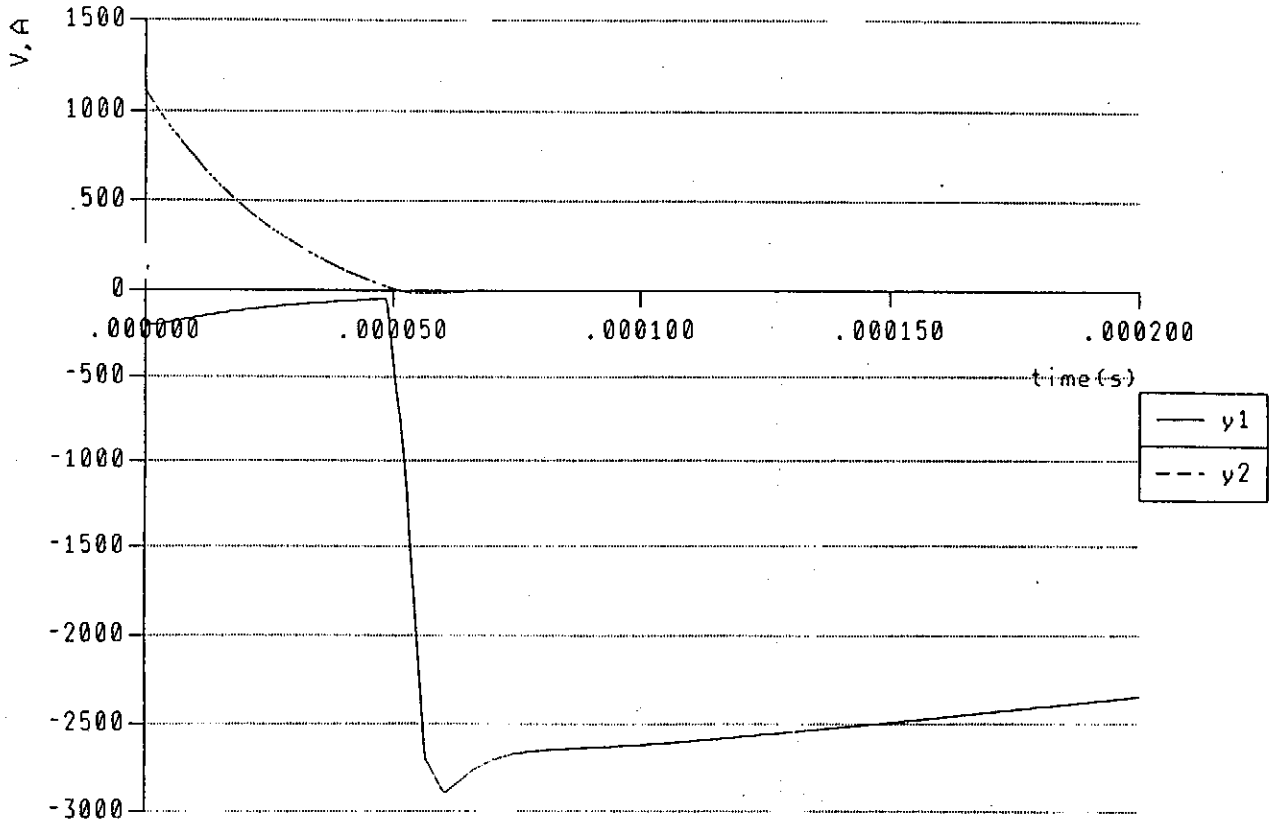


Figure 3



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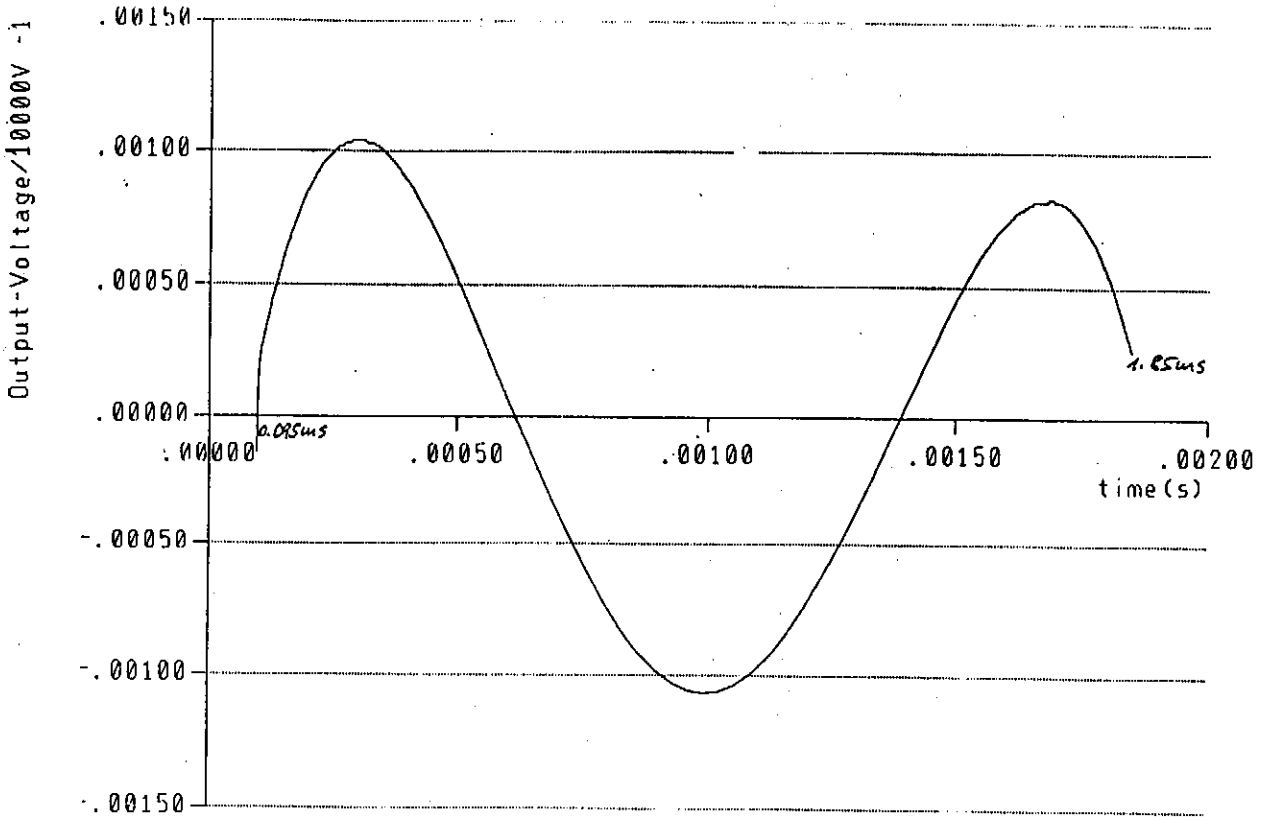
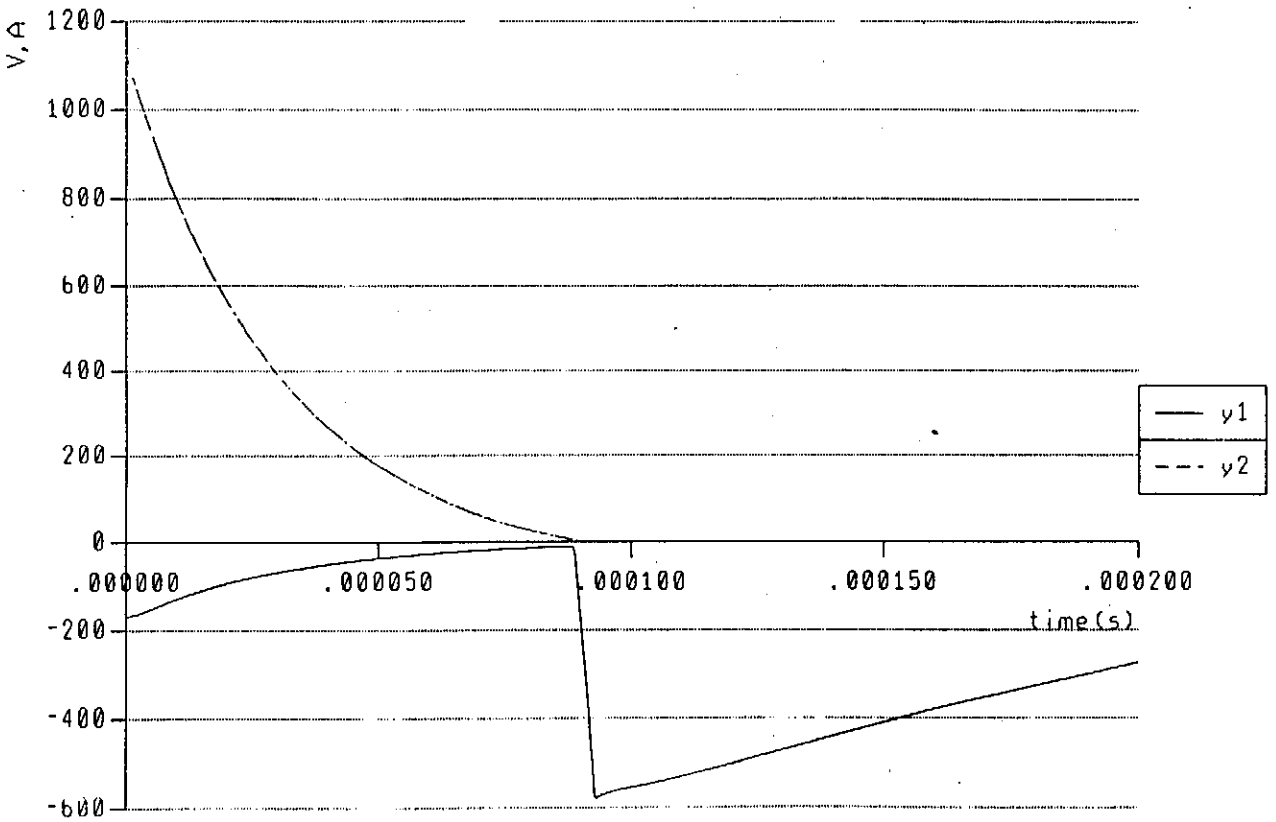


Figure 5



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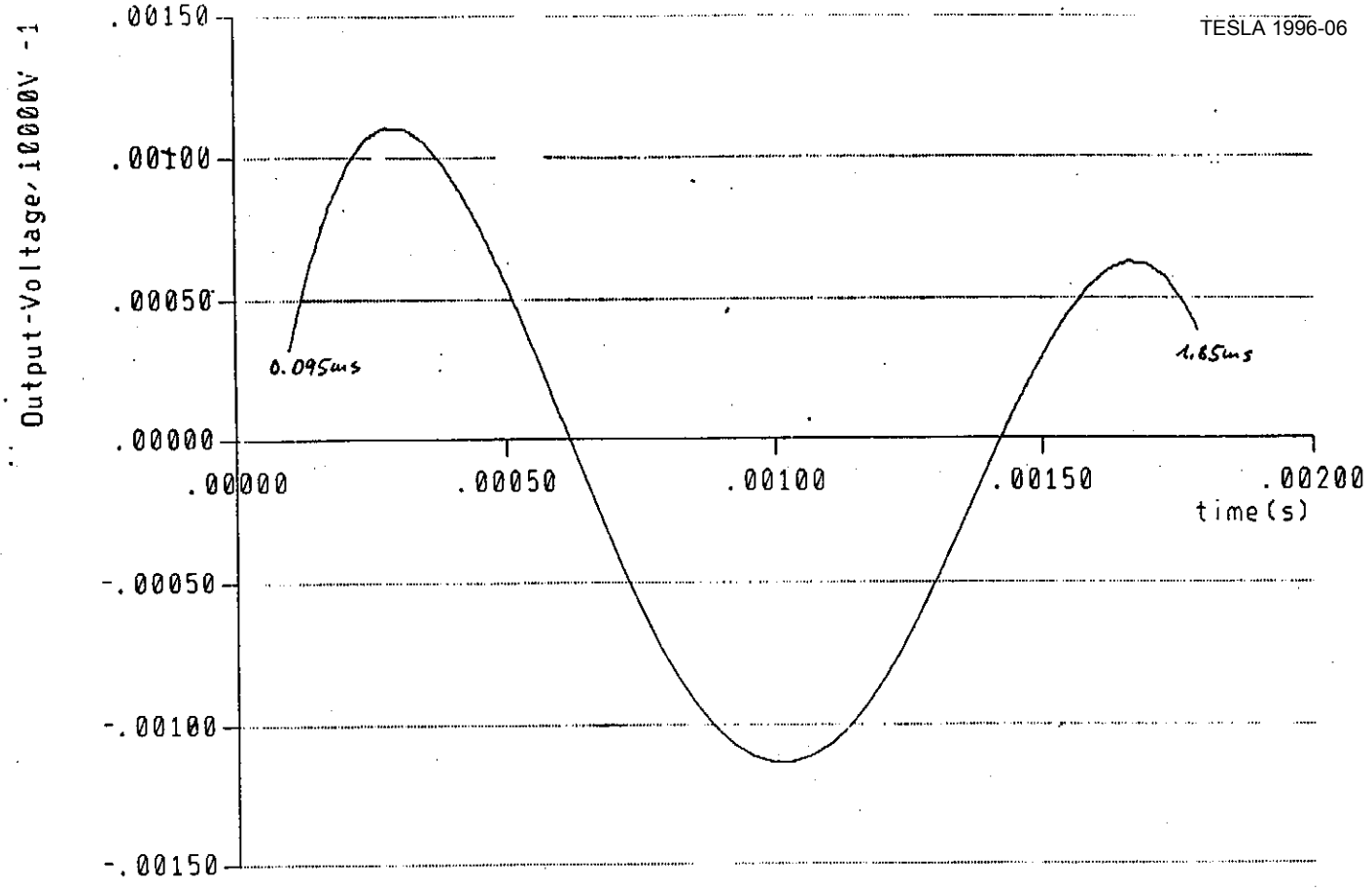

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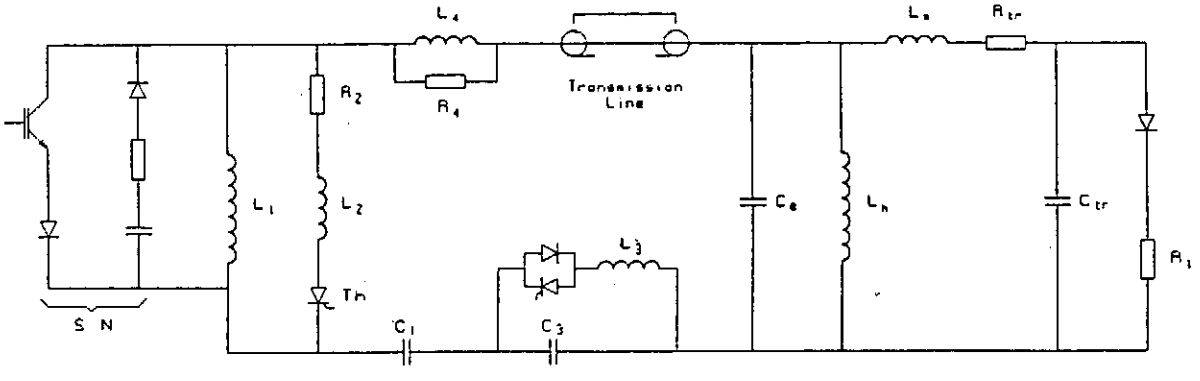


Figure 8 BDSM–Circuit with Transmission Line
(S.N. Suppression Network)

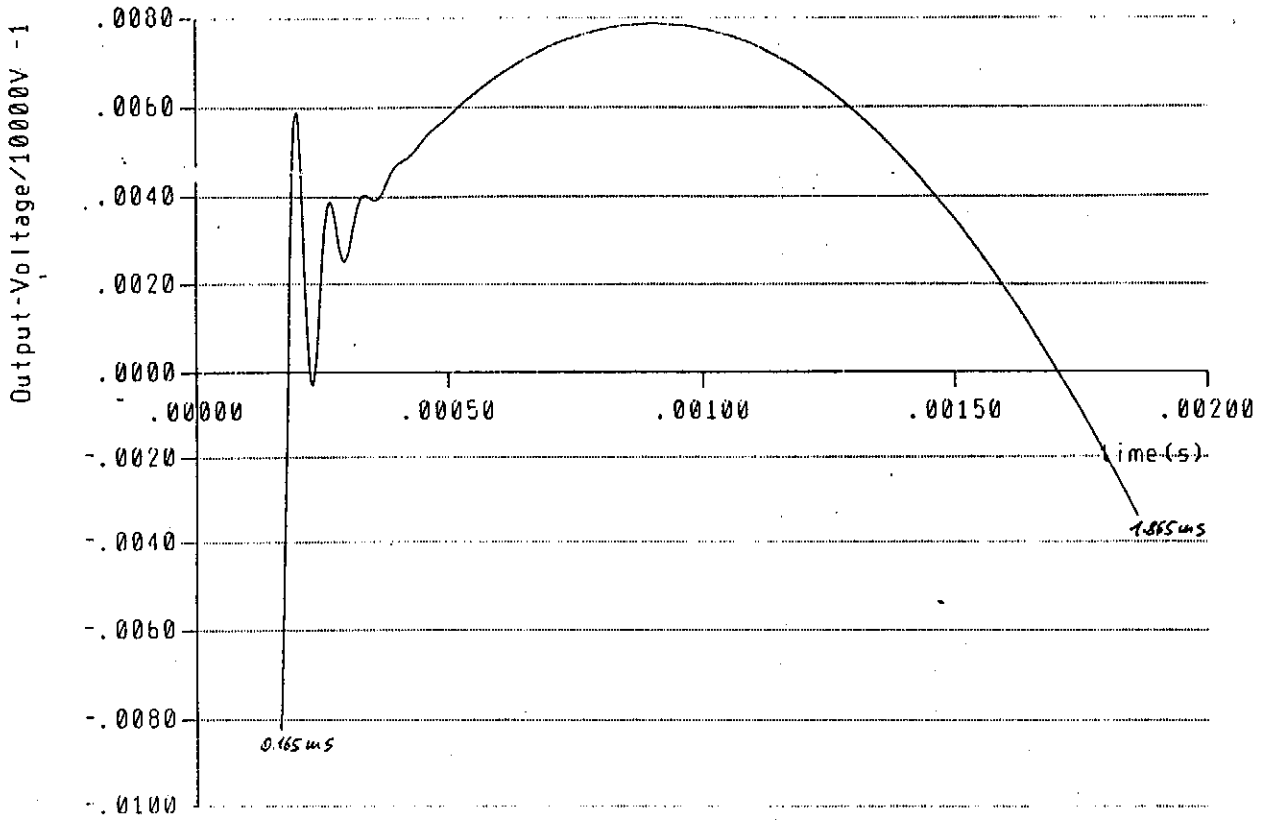


Figure 9

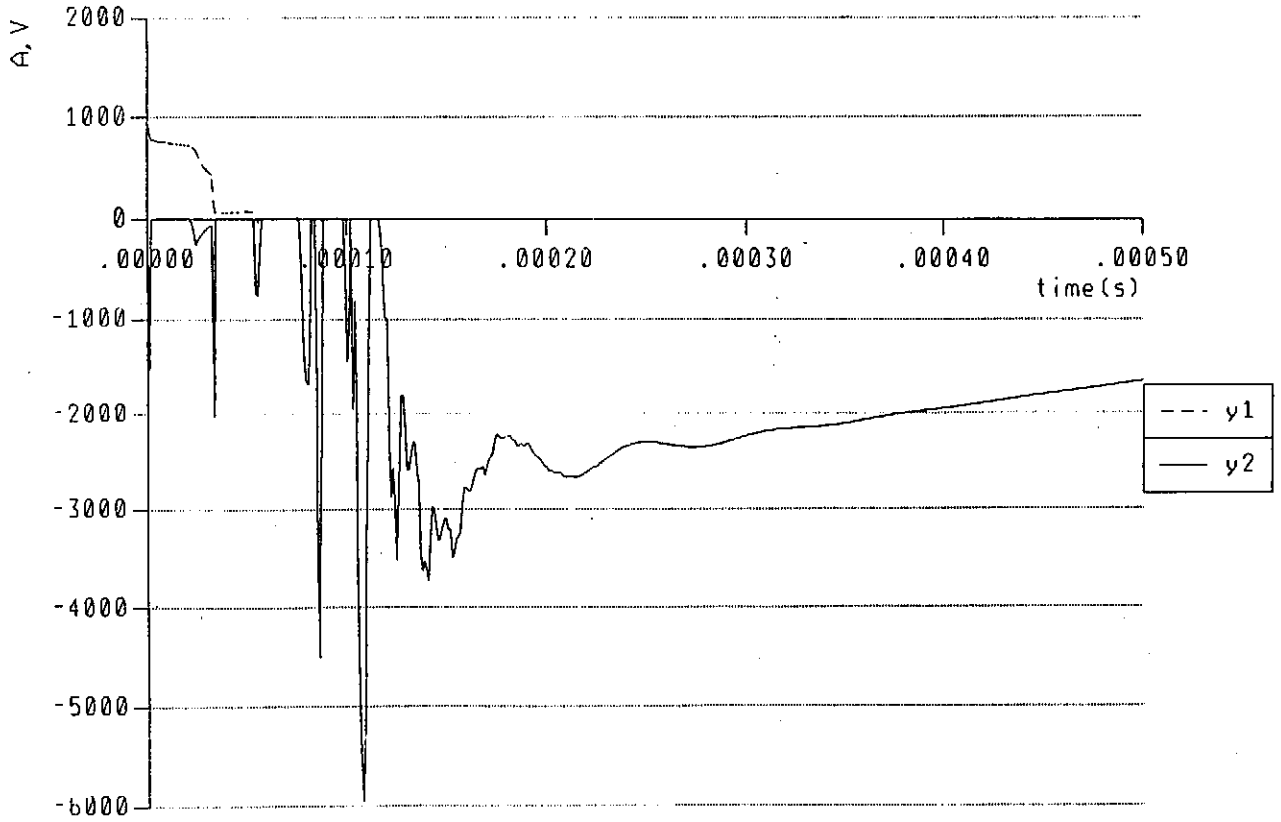
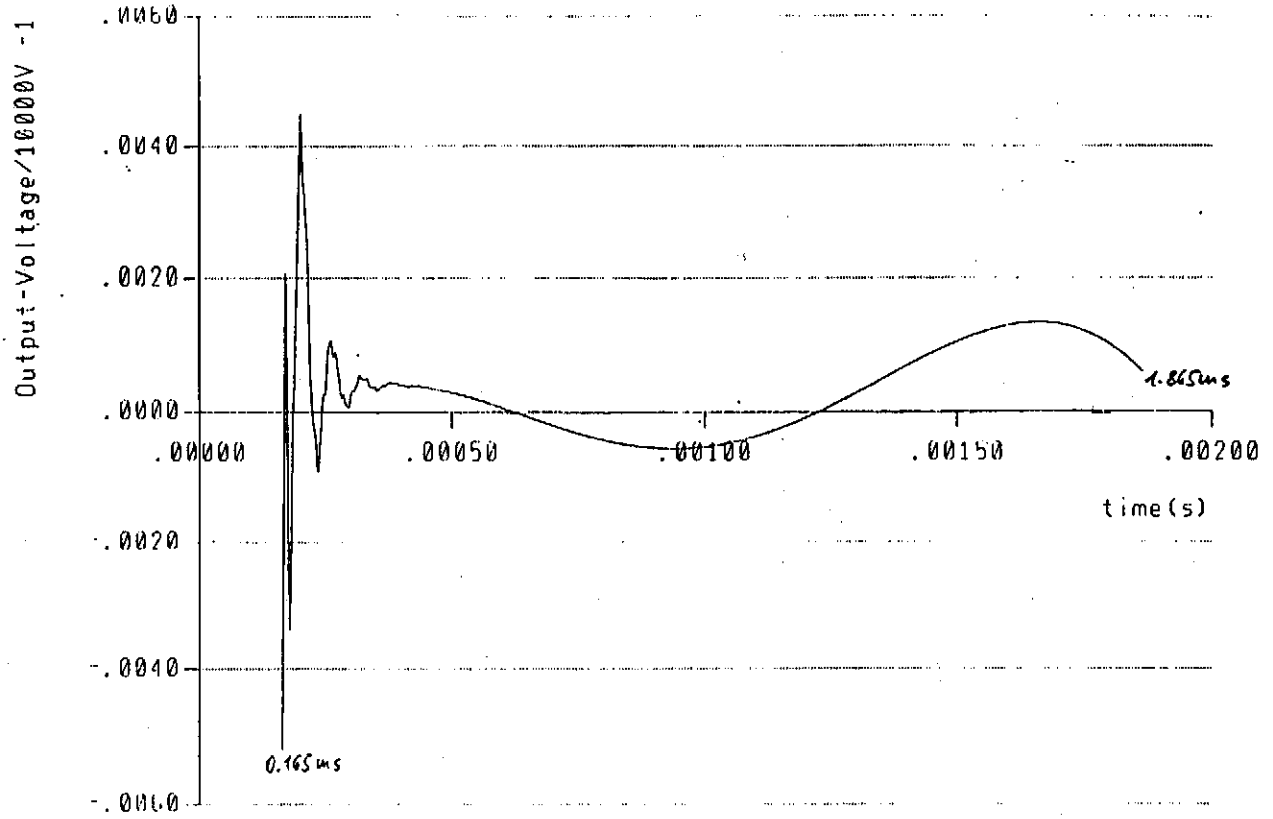


Figure 10



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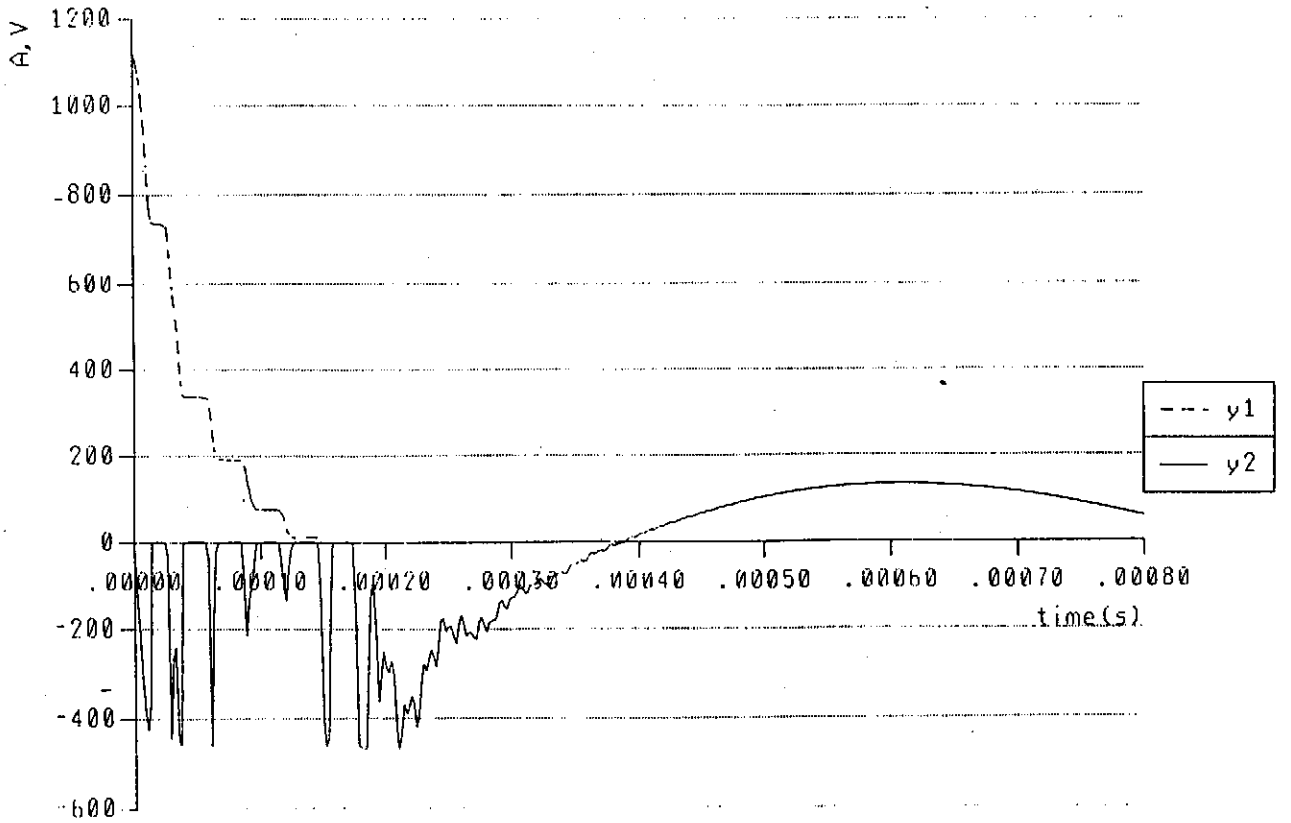


Figure 12

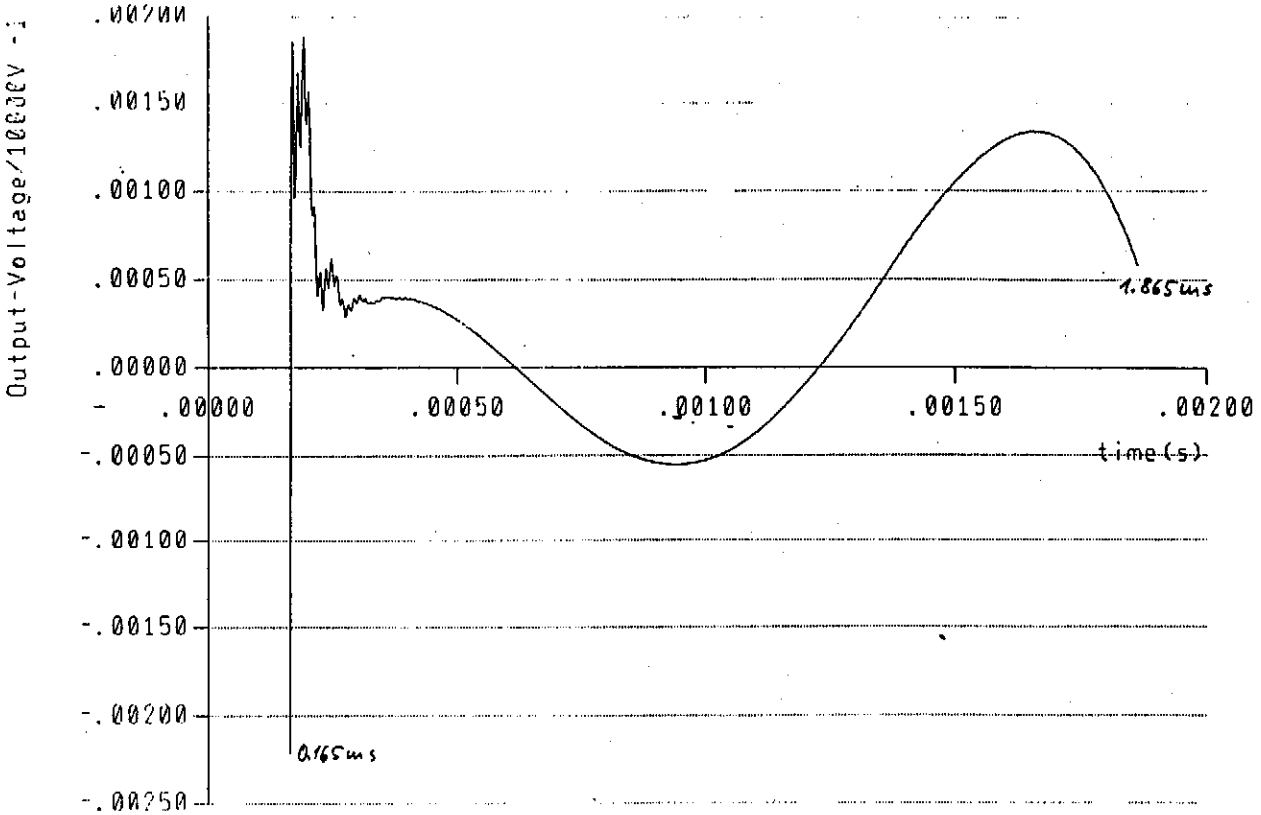
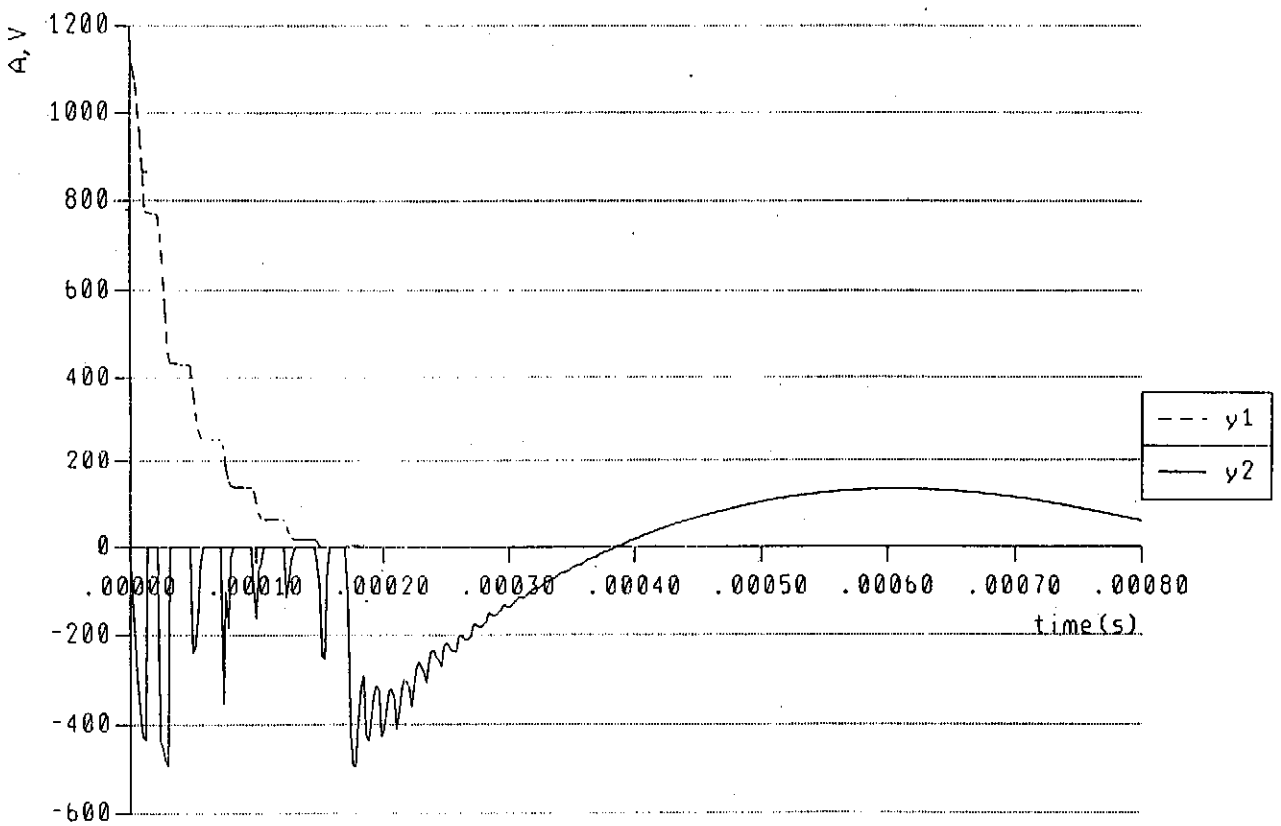


Figure 13



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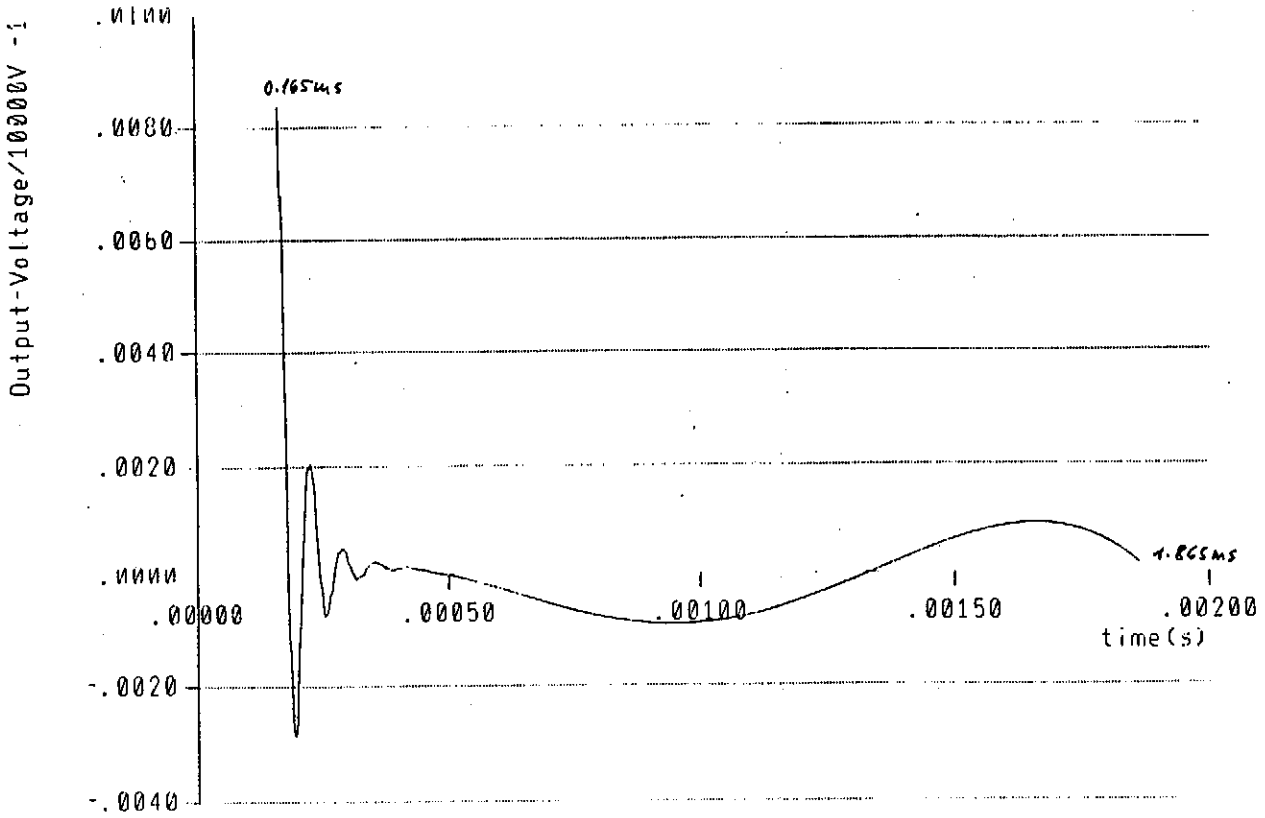

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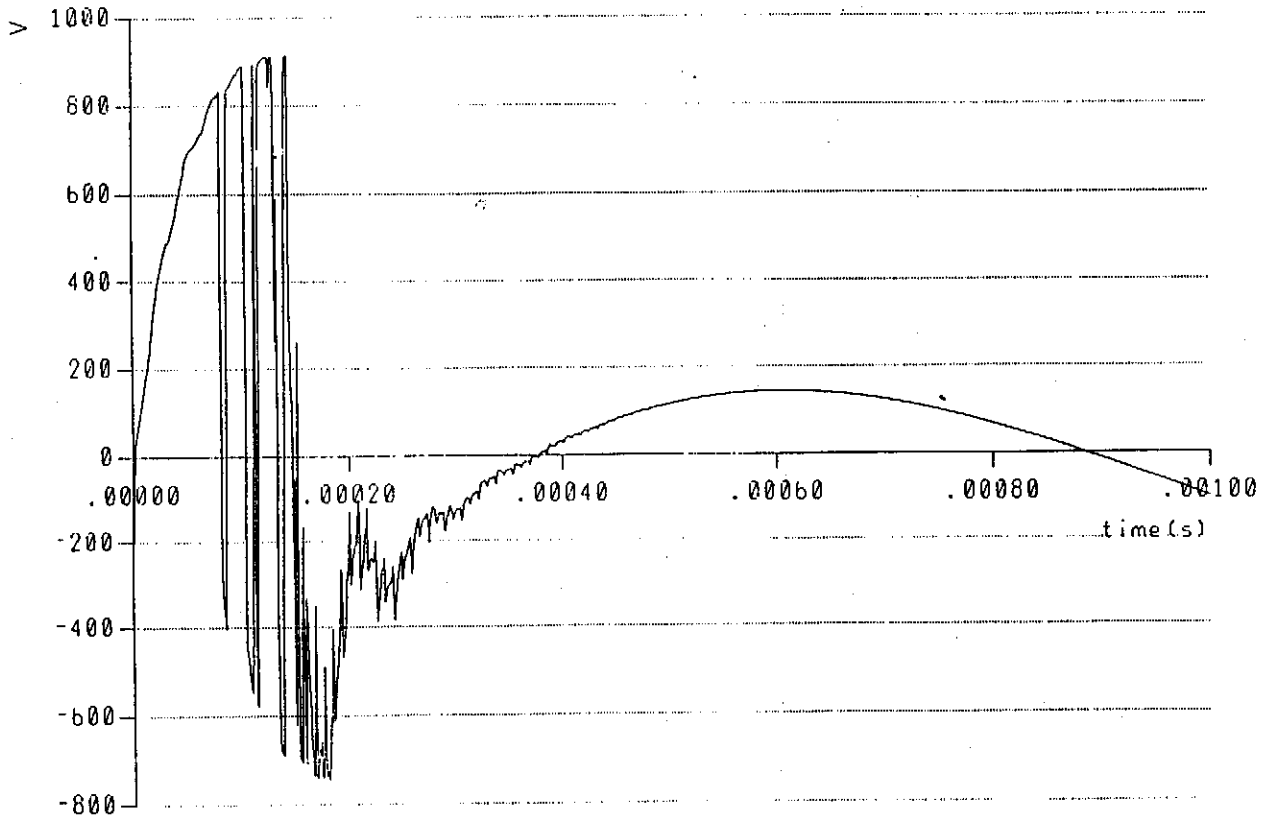

Figure 16

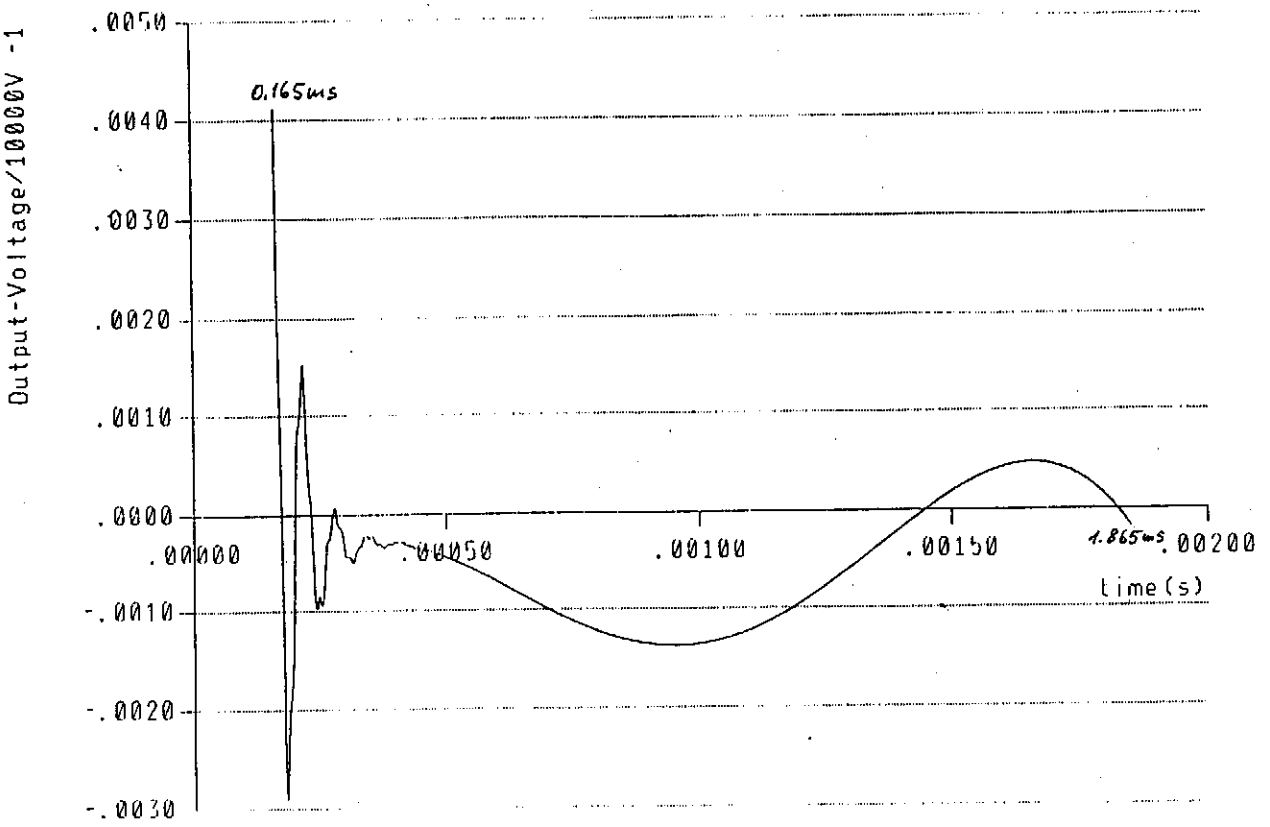

Figure 17

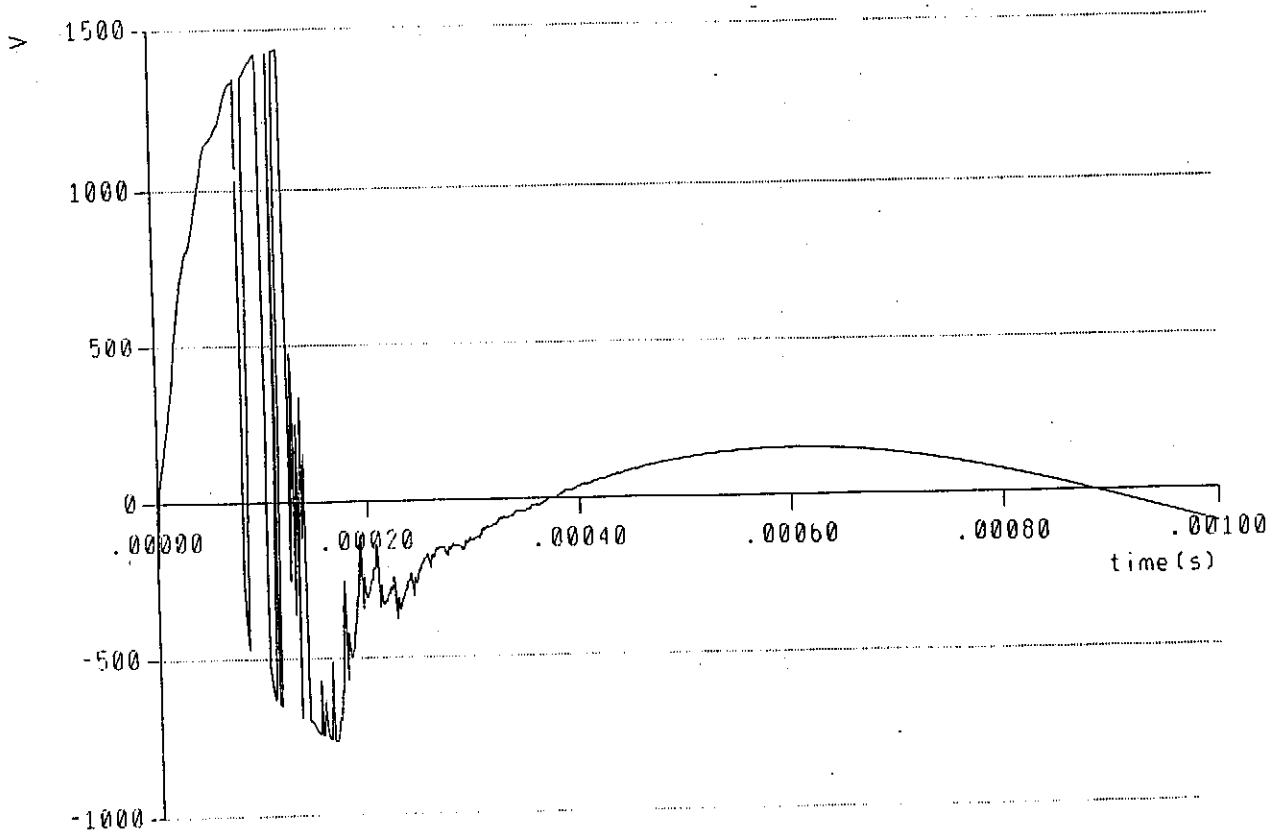

Figure 18