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A PRECISION HYBRID AMPLIFIER FOR VOLTAGE CALIBRATION SYSTEMS

Henrik Lavrič[1], Danijel Vončina[1], Peter Zajec[1], France Pavlovčič[2], Janez Nastran[1]

[1]University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenija
[2]Ministry for Environment, Spatial planning and Energy; Environment Agency of the Republic of Slovenia, Ljubljana, Slovenija

Key words: voltage amplifier, hybrid power amplifier, feedforward-feedback, high efficiency, harmonic distortion

Abstract: The paper describes a voltage amplifier that is capable of accurate amplifying voltages up to 300 V rms within the frequency range from 40 Hz to 70 Hz with or without the presence of higher harmonic components up to 1.4 kHz. Its sophisticated topology consists of a supreme linear amplifier and an inner hybrid power amplifier with an output transformer. The hybrid power amplifier, which acts as a self-oscillating system, is based on a parallel connection of a superior three-stage class AB linear power amplifier and a switch-mode inverter. The latter provides a full load current while the former filters the waveform ripple. In this way a power efficient system is obtained whose efficiency at a nominal output power of 60 VA exceeds 90%. The experimental results demonstrate good performance of the proposed hybrid topology.

Precizijski hibridni ojačevalnik za napetostne kalibracijske sisteme

Kjučne besede: napetostni ojačevalnik, hibridni močnostni ojačevalnik, visok izkoristek, nelinearno popačenje

Izvleček: V članku je predstavljen napetostni ojačevalnik za precizijsko ojačevanje napetosti do 300 V efektivne vrednosti na frekvenčnem območju od 40 Hz do 70 Hz z možnostjo superponiranja višjeharmonskih komponent do 1.4 kHz. Celotna topologija je zgrajena okoli hibridnega močnostnega ojačevalnika z izhodnim, večodcepnim transformatorjem. Slednji narekuje uporabo notranje regulacijske zanke za odpravljanje parazitne enosmerne komponente napetosti. Hibridni močnostni ojačevalnik, ki deluje kot lastno-oscilirajoči sistem, sestavljata paralelno vezana linearni močnostni ojačevalnik in stikalni inverter. Takšen moderen koncept zagotavlja, da izkoristek pri nazivni izhodni moči 60 VA preseže 90%, kajti celoten bremenski tok zagotavlja inverter. Linearni ojačevalnik skrbi le za odpravljanje visokofrekvenčne valovitosti. Za linearizacijo odziva celotnega vezja je dodana zunanja regulacijska zanka s »feedforward-feedback« principom povratne zanke. Posledica tega je majhno nelinearno popačenje izhodne napetosti. Poleg tega eksperimentalni rezultati dokazujejo stabilno kratkotrajno delovanje ojačevalnika, ter odlično obnašanje tudi v primeru, ko ga obremenimo z nelinearnim, pretežno kapacitivnim bremenom.

1. Introduction

Over the past two decades an extensive growth in the number of nonlinear loads, such as rectifiers in electronic equipment, and a rapid development of the static power converters have been noticed. Because of the nonsinusoidal waveform of the current, which they draw from the grid, and the grid impedance, which is not zero, the voltage waveform at the end user differs from the sinusoidal one. Besides other undesirable phenomena, performing voltage measurements in presence of harmonics is also quite a task. However, they are not only the voltage meters but also wattmeters and energy meters that are exposed to the distorted environments. Especially the last ones are the most widespread. To assure the ability of accurate measurement in distorted conditions, treated meters must be calibrated at the end of manufacturing process and periodically, after they are put in use. This demands special equipment, which is capable of performing the harmonics analysis.

The focus of this paper is a precision voltage amplifier designed for a portable three-phase power calibrator. The calibrator is used to calibrate three-phase energy meters in the phantom load test arrangement with the fundamental power and also with harmonics power components added in accordance with the International Standard /1/. Besides three voltage amplifiers, three current amplifiers are needed. The voltage amplifier for one phase should provide maximum power of 60 VA within the voltage range from 30 V to 300 V rms. Moreover, the output waveform should also be accurate in amplitude (±0.2%) and phase (±0.1°). Within the frequency range from 40 Hz to 70 Hz its distortion (THD) should not exceed 0.5%. To allow for a harmonics analysis of the unit under test, the amplifier has to amplify a frequency spectrum up to 1.4 kHz. The magnitude of the first four higher harmonics should measure up to 50% and the rest of the harmonics up to 10% of the voltage magnitude at the fundamental frequency.

Till now, such stringent demands have been efficiently solved using only the linear power amplifiers /2/. Their main disadvantage is low efficiency, which leads to excessive power losses for which reason an efficient cooling system is required. This may result in an unacceptable contribution to the volume and mass of the portable calibrator.

To meet the above requirements, an advanced topology combining a switch-mode and linear technique was developed. Such concept was first applied in low voltage audio power amplifiers /3, 4/.

2. Description of the proposed topology

The overall diagram of the precision voltage amplifier is shown in Fig. 1. The key element of the topology is the hybrid power amplifier (HPA) having its output connected to the primary winding of the transformer. By means of a local voltage feedback loop, HPA controls the voltage of the transformer primary to be the exact template of the signal applied on the noninverting input of HPA. The secondary of the transformer has three taps. In this way the operation of the voltage amplifier is split into three ranges. Output voltage u_o, which is the voltage on the secondary of the transformer, is controlled by a supreme voltage control loop. In order to obtain stable operation, the feedforward-feedback principle is followed.

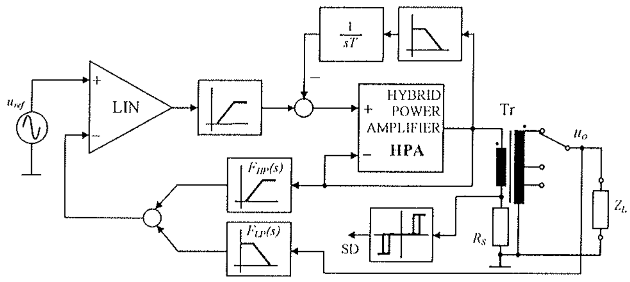

Fig. 1: Overall diagram of the precision voltage amplifier

2.1 Hybrid power amplifier

HPA is composed of a three-stage class AB linear power amplifier (LPA) /5/ and a switch mode inverter. They are connected in parallel as shown in Fig. 2. In this configuration LPA plays the leading role because it directly controls the voltage at the output of HPA. The inverter can be treated as a slave since its control signals are derived from the output current of LPA.

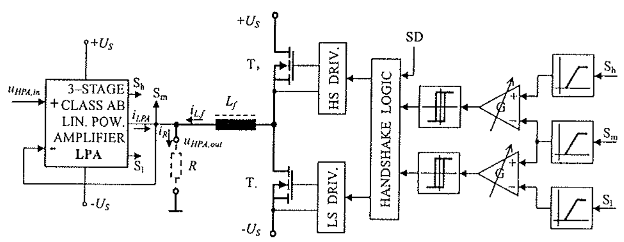

Fig. 2: Block diagram of the hybrid power amplifier

If we assume that T_+ is turned on (conducting) and T_- is turned off, the current through inductor L_f increases. Depending on the output voltage of HPA $u_{HPA,out}$ and load resistance R, part of it flows into the load and the rest sinks into LPA. When a certain value of the latter ($-I_{tr}$) is reached, we turn T_+ off and T_- on. The current through L_f decreases. After a while it becomes smaller than the load current and LPA starts to deliver the deficit. At the value $+I_{tr}$, we again turn T_+ on and T_- off. The self-oscillating system is thus obtained. Its frequency f_{so} is defined by

$$f_{so} = \frac{U_S^2 - \left(u_{HPA,out} + \frac{L_f}{R} \cdot \frac{du_{HPA,out}}{dt}\right)^2}{4 \cdot I_{tr} \cdot L_f \cdot U_S}. \tag{1}$$

The inverter can supply most of the load current as long as the slew rate of the load current is smaller than the slew rate of the inductor current. The inverter power bandwidth PB_{inv}, this is the highest frequency of $u_{HPA,out}$ at which the upper condition still holds, is

$$PB_{inv} = \frac{R}{2\pi L_f} \cdot \sqrt{\frac{1}{\left(U_{HPA,out}/U_S\right)^2} - 1}, \tag{2}$$

where $U_{HPA,out}$ is the amplitude of the output voltage and U_S is the supply voltage.

The LPA current is sensed as a voltage drop across the emitter resistors in the LPA output stage. The signals (S_h, S_m, S_l) are then led through high-pass filters (Fig. 2) in order to block the low frequency content that belongs to the amplified signal. It is important that the crossover frequencies of the aforementioned filters are matched. If they are not, the load current i_R and the inverter current $i_{L,f}$ are out of phase. In this case LPA not only filters the switching frequency current ripple but also delivers part of the fundamental and higher harmonics components of the load current. The differential amplifiers with an adjustable gain adapt the signals to the threshold levels of the Schmitt-triggers. These signals are further processed inside the handshake logic in a digital way. An interlock delay between the switching maneuvers of transistors is generated here. Optional blocking of the inverter is also possible by an external signal SD.

2.2 Suppressing the parasitic dc component

The voltage error, being the result of asymmetry and nonlinearities inside LPA, can lead to a considerable dc voltage component at the HPA output. If such dc component were applied to the output transformer, its magnetic core would become saturated and operation of the circuit would be unreliable or even impossible.

In order to cope with the above problem, two methods were investigated. The first addressed the use of an additional dc voltage sensor in the form of a differential transformer with an extracting circuit as proposed in /6/. Because of its complexness and high cost, the solution was not accepted. An autonulling control circuit was applied instead.

It consists of a low-pass first order filter and an integrator (Fig. 1). The latter integrates the output of the filter, where the low frequency content is present including the dc component. The result is then subtracted from the signal of the supreme control loop. The voltage drop, resulting from the dc current through the transformer primary winding, is relatively small because the resistance of the winding is small, too. Better performance of the autonulling circuit can be achieved by applying a higher voltage drop for the same value of the dc current. Hence a resistor with a small resistance (R_S = 0.1 Ω) is added in series with the transformer primary winding. Its impact on the overall efficiency can be neglected. A high-pass filter, positioned right after the superior amplifier, assures an autonomous operation of the autonulling circuit.

2.3 Supreme feedforward-feedback control loop

The use of a superior linear amplifier and a supreme control loop is of a paramount importance in providing a linear response of the system. The output voltage u_O of the amplifier is measured with a precision noninductive film resistor divider. The high frequency response of the measured voltage is attenuated as a result of its passing through the transformer. If we want to obtain a stable operation of the supreme loop, accurate information about the high frequency response in the feedback should be made available. This can be done by using the feedforward path from the output of HPA and thus bypassing the transformer. The feedforward-feedback network should have a transfer function $F_F(s)$ that can be written as

$$F_F(s) = F_{LP}(s) + F_{HP}(s) = 1. \quad (3)$$

In other words, the constant-voltage condition must be fulfilled. This can only be achieved by using the first order low-pass $F_{LP}(s)$ and high-pass $F_{HP}(s)$ filters with matched crossover frequencies. Equation (3) can be written as

$$F_F(s) = \frac{1}{1+s/\omega_{LP}} + \frac{s/\omega_{HP}}{1+s/\omega_{HP}} \quad (4)$$

and finally with regard to $\omega_{LP} = \omega_{HP} = \omega$,

$$F_F(s) = \frac{1}{1+s/\omega} + \frac{s/\omega}{1+s/\omega} = \frac{1+s/\omega}{1+s/\omega} = 1. \quad (5)$$

The crossover frequency has to be high enough to avoid any remarkable impact on the linearity of the supreme control loop for the reason of the nonideality of the transformer.

3. HPA efficiency enhancement

Practically all power losses of the hybrid voltage amplifier have their origin inside the hybrid power amplifier or more precisely inside the output stages of LPA and inverter. If a power efficient system with low *THD* is to be obtained, an adequate ratio between the quiescent current of LPA and the threshold current I_{tr} has to be chosen. An additional guidance for the design is the condition that the minimum switching frequency of HPA must be beyond the perceptibility of the human ear, which is about 20 kHz. Considering the maximum loading of HPA, the minimum switching frequency and the threshold current I_{tr} = 100 mA, the inductance L_f = 1 mH is obtained. This results in the inverter power bandwidth (2) much higher than the frequencies of the amplified voltage and enables the inverter to provide most of the load current. To have evidence of this, we need some parameters that are given below.

The class AB linear power amplifier is designed to withstand the highest amplitude of its output voltage of 45 V at the supply voltage of ±50 V. The quiescent current through the output power transistors is set to 25 mA. Under these conditions the saturation and the clipping are eliminated. Though the quiescent current of a relatively small value generates small quiescent power losses, it is large enough to minimize the crossover and switching distortion. The power losses of HPA at a low output current are higher compared to the LPA losses alone. Because of this the hysteresis element is used to form the control signal SD. The inverter is enabled only when the current through the primary of the transformer exceeds 120 mA. When it falls under 100 mA, the inverter is disabled again.

The whole range of the voltage amplifier operation is split into three subranges with the nominal voltages of 75 V, 150 V and 300 V. However, the output power of 60 VA is to be provided in each subrange. When connected with the aforementioned solution, this solution leads to a higher efficiency of LPA due to the longer operation with the output voltage swing closer to $\pm U_S$ provided the desired output voltage is amplified within an appropriate voltage range.

Since the hybrid topology is an efficient exchange for the pure linear topology, it is reasonable to compare their efficiencies. Evaluation will be done in particular working points where extreme values are expected. The first point is at maximum output power P_R = 60 W and voltage amplitude $U_{HPA,out}$ = 45 V. Under these conditions HPA supplies the load R = 16.88 Ω. To answer the question what would be the efficiency if at this working point the inverter were disabled, we have to determine power losses on the power transistors in the output stage of LPA. Power losses P_T on the upper transistor are generated as a consequence of the voltage difference between the supply voltage $+U_S$ and the output voltage of HPA

$$u_{HPA,out} = U_{HPA,out} \cdot \sin\Theta \quad (6)$$

and the current through the load

$$i_R = \frac{u_{HPA,out}}{R} = \frac{U_{HPA,out}}{R} \cdot \sin\Theta. \quad (7)$$

As the ratio between the amplitude of the load current I_R and the quiescent current is very high (2.67 A : 25 mA), the quiescent current can be neglected. Calculation of P_T

can be done in the same way as for the class B amplifier where each transistor conducts only half of the period

$$P_T = \frac{1}{2\pi}\int_0^{\pi}\left\{\frac{u_{HPA,out}}{R}\cdot\sin\Theta\cdot\left(U_S - U_{HPA,out}\cdot\sin\Theta\right)\right\}\cdot d\Theta. \qquad (8)$$

The efficiency is defined by

$$\eta = \frac{P_R}{P_R + 2P_T} \qquad (9)$$

and for the assumed conditions amounts to 70%. In other words, for 60 W of the output power 25 W are dissipated inside the linear amplifier.

An accurate calculation of the efficiency for the hybrid topology is difficult to perform because power losses of the inverter are hard to be determined exactly. Although the conductive losses and the choke losses are known, the calculation of the switching losses is almost impossible because of the variable switching frequency (1) inside the period of the output voltage. Our evaluation will therefore be based on the assumption that the efficiency of the inverter h_{inv} is 95%. This value can be obtained if we use high-speed switching transistors with low $R_{DS,ON} \leq 0.18\ \Omega$ and the choke with a low loss ferrite core. Furthermore, in this topology of the inverter only one transistor is in series with the load at a time. This is not the case with the bridge topology where two transistors are in series. LPA now only filters the high frequency ripple and its output current is of a triangular shape with the peak value of I_{tr}. The shape of the current through the transistor in the output stage of LPA is of a triangular shape, too, but it has two slopes because of the quiescent current. Its average value $I_{T,av}$ is 31.25 mA. In this case power losses on the upper transistor are defined by

$$P_T = \frac{1}{2\pi}\int_0^{2\pi}\left\{I_{T,av}\cdot\left(U_S - U_{HPA,out}\cdot\sin\Theta\right)\right\}d\Theta \qquad (10)$$

and the overall efficiency by

$$\eta = \frac{P_R}{P_R/\eta_{inv} + 2P_T}. \qquad (11)$$

Thus the calculated dissipated power of LPA and the overall efficiency are 3.1 W and 90.5%, respectively.

The second working point worth the while of being considered is in the situation when the voltage at the voltage amplifier output is the lowest possible (30 V rms). For R = 16.88 Ω, HPA has to deliver 9.6 W at an 18 V peak. The overall efficiency is more than 72% while that of LPA alone is some 28%.

Compared to the linear amplifier, the essential advantage of the hybrid voltage amplifier are low power losses in case of reactive load. For the 60 VA reactive power LPA would dissipate more than 65 W, while HPA dissipates ten times less.

When the amplifier is in the idle state, the reference signal and the output voltage are zero. The power dissipated by LPA is 3.1 W when the inverter is enabled. With the inverter disabled, only 2.5 W are dissipated. When the amplifier is unloaded, losses are the same regardless of the output voltage. Moreover, disabling the inverter at low output currents abolishes the switching noise.

4. Experimental results

The performance of the precision hybrid voltage amplifier was tested under various conditions. A special attention was particularly paid to the determination of *THD*, voltage error and phase error. Fig. 3 shows the voltage error and the phase error versus frequency of the amplifier within the 300 V range. The magnitude of the output voltage inside the frequency ranges was set according to the foreseen target values. The amplifier was loaded with a 6600 Ω resistor. Our measurements were made with a dynamic signal analyzer (DSA) HP 35665A. The performance of the amplifier within the ranges of 75 V and 150 V is better than at the 300 V range.

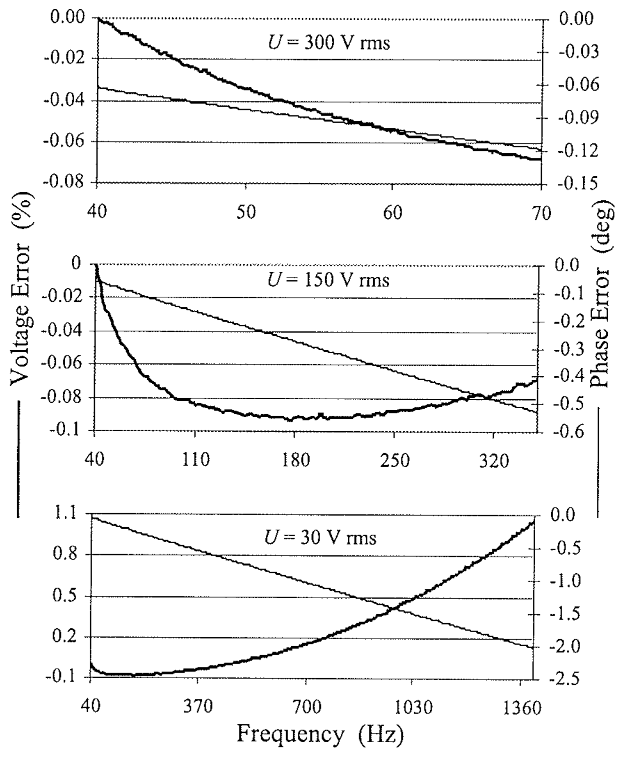

Fig.3: Voltage and phase error versus frequency

Short-term stability of the amplifier was measured after a warm-up period using an automatic measuring system consisting of PC with a LabWIEV™ software and a digital multimeter (DMM) HP 34401A. Rms voltage readings were recorded at 30 s intervals over a five-hour period. The results are presented in Fig. 4. The amplifier was loaded within a particular voltage range with resistive loads as noted in Table 1. According to the DMM specifications, the meas-

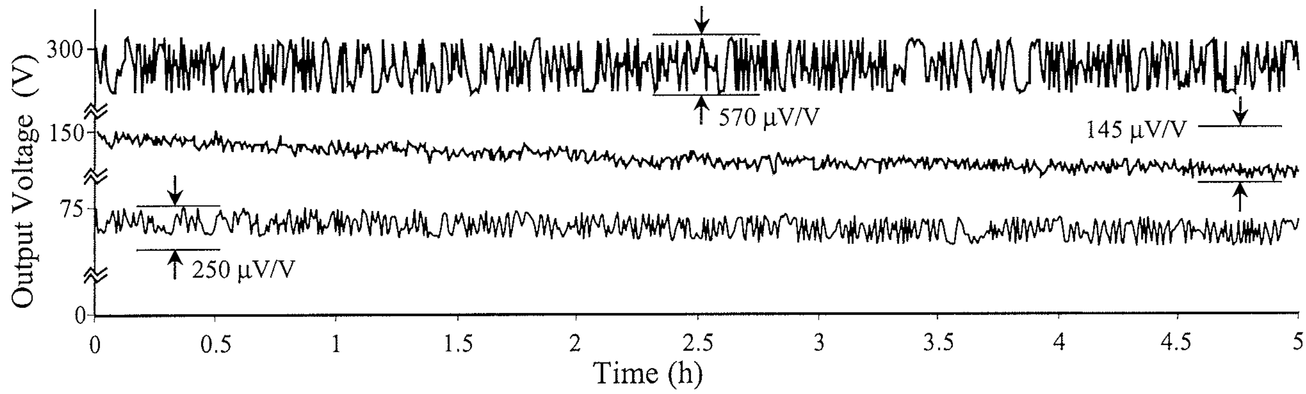

Fig. 4: Short-term stability

uring uncertainties for 300 V, 150 V and 75 V were 0.09%, 0.14% and 0.07%, respectively.

THD of the amplifier was measured using a digital low distortion sine wave generator and DSA. Values for certain set points within the different voltage ranges are shown in Table 1. All the measurements were made at 50 Hz and a spectrum containing 30 higher harmonics was observed.

Table 1: THD of the precision voltage amplifier

f = 50 Hz N = 30	75 V range R_L = 560 Ω			150 V range R_L = 2100 Ω			300 V range R_L = 6600 Ω			
U (V)	25	50	75	75	100	150	150	200	250	300
THD (%)	0.05	0.025	0.015	0.028	0.023	0.015	0.025	0.017	0.015	0.013

In order to test the performance of the amplifier under nonlinear load conditions, an electronic energy meter was applied to its output. *THD* of the voltage and current shown in Fig. 5 is 0.11% and 16%, respectively. The current is heavily distorted because of the rectifier and dc-dc converter, which are used as a power supply for the electronic circuits inside the energy meter. Although the load is of a capacitive nature, the stability of the amplifier is not impaired.

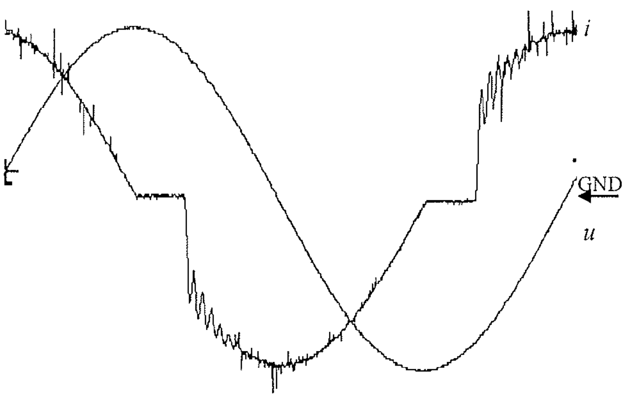

Fig. 5: Output voltage and load current (k_u = 100 V/div, k_i = 20 mA/div, k_t = 2 ms/div)

5. Conclusion

A precision hybrid voltage amplifier is presented. By means of a novel topology combining linear and switching techniques, upgraded by a supreme feedforward-feedback control loop, a power efficient system with low output voltage distortion is obtained. Owing to the use of the output transformer, the output voltage is free of the dc component. This is extremely advantageous when calibrating meters, which contain input voltage transformers.

As expected, the amplifier meets the amplitude inaccuracy and *THD* specifications. It is only the phase error that slightly exceeds the limit value when approaching the frequency of 70 Hz. This can be compensated by a voltage reference generator. Since the long-term inaccuracy depends only on the absolute stability of very few components in the supreme feedback circuit, it is expected that it will not exceed the limit value.

The proposed topology is not necessarily limited to the discussed application. It can be also exploited in applications with even more rigorous demands. A further improvement of the amplitude and phase accuracy within a wider frequency range could be achieved by using a digital control loop /7/.

For more powerful applications a topology survey of the switch mode inverter is presented in /8/. However, with only minor changes of the design parameters the output power of the topology, presented in this paper, can be increased significantly.

Refereces

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as. mag. Henrik Lavrič, univ. dipl. inž.
Fakulteta za elektrotehniko,
Tržaška 25, 1000 Ljubljana
tel.: +386 1 4768 466, fax: +386 1 4768 487
e-mail: henrik.lavric@fe.uni-lj.si

doc. dr. Danijel Vončina, univ. dipl. inž.
Fakulteta za elektrotehniko,
Tržaška 25, 1000 Ljubljana
tel.: +386 1 4768 274, fax: +386 1 4768 487
e-mail: voncina@fe.uni-lj.si

doc. dr. Peter Zajec, univ. dipl. inž.
Fakulteta za elektrotehniko,
Tržaška 25, 1000 Ljubljana
tel.: +386 1 4768 479, fax: +386 1 4768 487
e-mail: peter.zajec@fe.uni-lj.si

dr. France Pavlovčič, univ.dipl.inž.
Ministrstvo za okolje, prostor in energijo
Agencija RS za okolje, Vojkova 1b, 1000 Ljubljana
tel.: +386 1 4784 098, fax: +386 1 4784054
e-mail: france.pavlovcic@gov.si

prof. dr. Janez Nastran, univ. dipl. inž.
Fakulteta za elektrotehniko,
Tržaška 25, 1000 Ljubljana
tel.: +386 1 4768 282, fax: +386 1 4264630
e-mail: andreja.kladnik@fe.uni-lj.si

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