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2. Konferenca ENRE v Termah Čatež 2010

Fakulteta za energetiko Univerze v Mariboru letos že drugič organizira konferenco ENRE (*ENergy and REsposibility*). Konferenca bo potekala v Termah Čatež med 22 in 24. junijem. Tudi letos želimo združiti znanstvenike, raziskovalce, razvojne inženirje, teoretike in strokovnjake na področju širše energetike. Letos mineva 30 uspešnih let Nuklearne elektrarne Krško, zato bo osrednja tema letošnje konference posvečena predvsem trajnostni energetiki, učinkoviti rabi energije in obnovljivim energetskim virom. Predvideno je devet ožjih sekcij, v katerih bodo združene tematike s področij: Učinkovite rabe energije, Hidro- in Aero-energetike, Termo- energetike, Alternativne energetike, Jedrske energetike, Obnovljivih energetskih virov, Konvencionalnih energetskih virov, Prenosa električne energije in omrežij ter (3E) -energije, izobraževanja in okolja.

Prvi dan je namenjen trem vabljenim predavanjem, ki jim bo sledila okrogla miza na temo : »Energy, quo vadis?«. Drugi dan je namenjen sekcijam, oz. predstavitvam konferenčnih prispevkov. Tretji dan je namenjen neformalnemu druženju in navezovanju stikov. Organiziran bo izlet po okoliški krajini, če bo dovolj velik interes – tudi golf turnir na igrišču v Mokricah.

Menim, da je tematika konference zanimiva tudi širšemu krogu, zato vas vabim, da se je v čim večjem številu udeležite. Skupaj bomo oblikovali tudi sporočilo konference ob njenem zaključku in tudi tako prispevali v ozaveščanju energetske problematike v naši bližnji in daljni prihodnosti. Še enkrat vabljeni.

2nd Conference ENRE in Terme Čatež 2011

The Faculty of Energy Technology of the University of Maribor has organized its second ENRE (ENergy and REsposibility) conference. The conference will be held at Terme Čatež between 22 and 24 June. This year, we are bringing together scientists, researchers, engineers, theorists and experts in the broader energy sector. As this year marks 30 successful years of the Krško nuclear power plant, the central themes of this year's conference will be sustainable energy, energy efficiency and renewable energy sources. Nine specific sections are planned, bringing together issues from the following areas: energy efficiency, hydro- and aero-energy, thermo-energy, alternative energy, nuclear energy, renewable energy, conventional energy sources, energy transmission and networks, and (3E): energy, education and the environment.

The first day is devoted to three invited lecturers, who will be followed by a round table on the theme of "Energy, quo vadis?" The second day will be dedicated to the specific sections, during which the conference contributions will be presented. The third day is for informal socializing and networking. There will be an organized tour of the surrounding landscape attractions; if there will be sufficient interest, a golf tournament at the course in Mokrice will be arranged.

I think that the theme of the conference is both wide ranging and interesting, so I invite you to attend. Together, we will bring the conference to its conclusions and in this way contribute to raising awareness of energy issues in our near and distant future. Once again, you are invited.

Krško, January, 2011

Andrej PREDIN

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MODERNIZATION OF THE APPARATUS FOR TESTING CARBON ANODE SAMPLES IN THE ALUMINIUM INDUSTRY

POSODOBITEV NAPRAVE ZA PREIZKUŠANJE ANODNIH VZORCEV V ALUMINIJSKI INDUSTRIJI

Edvard Detiček, Mitja Kastrevc[ℜ]

Keywords: electro-hydraulic, servo-drive, adaptive force control, testing machines

Abstract

The proper quality of carbon anodes is an important factor in the production of aluminium. The deterioration of anode quality disturbs the electrolysis cell conditions and may cause the pot to overheat. The alumina cover has to be reduced in order to lower the bath temperature, which leads to an excessive air burn attack of the anodes and thus to higher carbon consumption, which increases operating costs. Testing of anodes is therefore an important tool to optimize performance and to reduce the costs of aluminium production. This article presents a modernization of the apparatus for testing carbon anode samples with the introduction of dynamic testing.

Povzetek

Pomemben dejavnik pri proizvodnji aluminija predstavlja ustrezna kvaliteta ogljikovih anod. Poslabšanje kvalitete anod motilno vpliva na delovne pogoje v elektroliznih celicah. Slednje lahko povzroči pregrevanje peči. Aluminijski plašč se mora stanjšati v smislu ohranjanja nižje temperature, kar vodi do izrazitega vdora vročega zraka. S tem se poveča izgorevanje in

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vsebnost ogljika, kar postopek podraži. Testiranje anod predstavlja tako, pomemben pripomoček pri optimiranju in zmanjševanju stroškov proizvodnje aluminija. V članku je predstavljena posodobitev naprave za preizkušanje ogljikovih anodnih vzorcev, z uvedbo dinamičnega testiranja.

1 INTRODUCTION

The proper quality of carbon anodes is an important factor in the production of aluminium. The deterioration of anode quality disturbs the electrolysis cell conditions and may cause the pot to overheat. The alumina cover has to be reduced in order to lower the bath temperature, which leads to an excessive air burn attack of the anodes and thus to higher carbon consumption, which increases operating costs. Testing of anodes is therefore an important tool to optimize performance and to reduce the production costs of aluminium.

Among static tests such as flexural strength, compressive strength and three-point bending tests, it is also important to determine the dynamic modulus of elasticity with pulse excitation. Existent mechanical testing equipment has been modernized to provide not only static, but also dynamic testing. For that reason, the common electro-hydraulic drive has been replaced with a servo-hydraulic drive, equipped with corresponding sensors and control electronics. The control computer, which controls the entire device, also contains an algorithm for closed loop force control. This paper describes an effective digital algorithm for computer closed loop force control, based on the combination of a PID controller and adaptive feed-forward velocity compensation.

2 MATHEMATICAL MODEL OF THE CONTROL LOOP

Due to its high power-to-weight ratio and the easy transformation of hydraulic power into mechanic power, i.e. longitudinal movements and forces, hydraulic cylinders became standard parts of testing machines and devices (Figure 1).

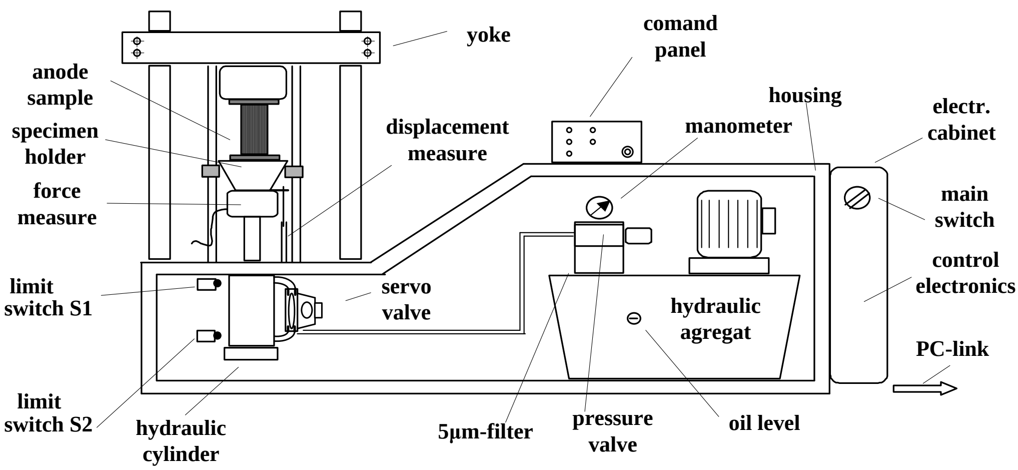


Figure 1: *Schematic representation of apparatus for testing anode samples.*

It is now quite common that such testing facilities are computer controlled. Therefore, the hydraulic drives are equipped with electronically controlled servo-valves, as well as with position transducers and force sensors, together creating closed control loops (Figure 2).

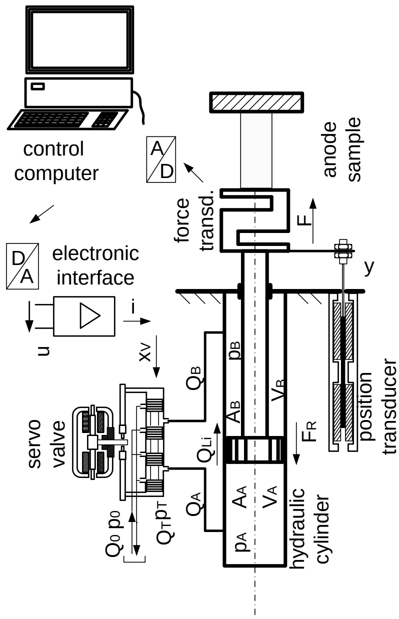


***Figure 2:** Schematic of an electro-hydraulic servo-drive.*

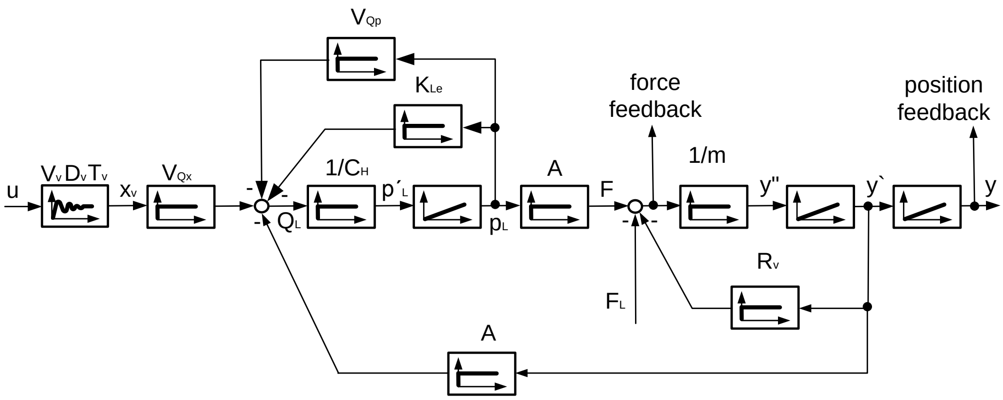
The appropriate control strategy must ensure an accurate and precise force control so that the hydraulic drive is be able to reproduce mechanical loads on carbon anode samples, according to the standard ASTM prescription.

When the closed loop force control is realized with an ordinary PID controller, the problem of the specimen starting to move during the experiment often occurs. Such movement may destabilize the control loop. In addition, there are also the problems with the low damping ratio of the hydraulic system, the non-linearity of the valve cylinder combination, friction forces and fluid compressibility.

A mathematical model of the hydraulic servo-system can be obtained considering the valve-cylinder combination. The flows can be described on the basis of Bernoulli and continuity equations, taking into account the oil compressibility and leakage, while the dynamics of the moving parts are expressed by the force equilibrium. Figure 3 shows the block diagram of the linearized open loop system.

The Laplace transformed mathematical relation between the servo-valve voltage as the input variable and force as the output variable can be expressed as follows:

$$F(s)=\frac{V_V V_{Qx} A}{\left(V_{Qp}+K_{Le}\right)\left(1+\frac{C_H}{V_{Qp}+K_{Le}}s\right)\left(T_V{}^2 s^2+2D_V T_V+1\right)}u(s)-$$
$$-\frac{A^2}{\left(V_{Qp}+K_{Le}\right)\left(1+\frac{C_H}{V_{Qp}+K_{Le}}s\right)}sy(s) \qquad (2.1)$$



R_v -viscous friction coefficient

Q_L – load flow

T_v – servo valve time constant

u – servo valve input voltage

V_{Qp} – valve flow-pressure coefficient

V_{Qx} – valve flow coefficient

V_V – valve gain

x_v – valve spool displacement

R_v -viscous friction coefficient

Q_L – load flow

T_v – servo valve time constant

u – servo valve input voltage

V_{Qp} – valve flow-pressure coefficient

V_{Qx} – valve flow coefficient

V_V – valve gain

x_v – valve spool displacement

Figure 3: *Block diagram of linearized mathematical model of the hydraulic drive*

It is obvious that the velocity of the piston rod acts like a disturbance variable. The influence of the disturbance variable can be theoretically totally compensated by introducing an input signal of the form:

$$u(s)=\frac{A}{V_V V_{Qx}}\left(T_V{}^2 s^2+2D_V T_V+1\right)sy(s) \qquad (2.2)$$

or approximately, without regarded to servo-valve dynamics:

$$u(s)=\frac{A}{V_V V_{Qx}}\,sy(s) \qquad (2.3)$$

The equation (2.3) obtains in the time domain the form:

$$u(t) = \frac{A}{V_V V_{Qx}} \frac{dy}{dt} = V_A \dot{y} \tag{2.4}$$

Therefore, an approximately feed-forward compensation of the disturbance can be achieved with measurement of the piston rod velocity and the addition of this signal to servo-valve input voltage, amplified with an appropriate gain factor V_A. Due to the non-linear dynamic behaviour of the hydraulic drive in practice, the gain factor V_A should be adapted to each actual situation.

3 ADAPTION OF VELOCITY GAIN FACTOR

The idea is based on earlier studies of adaptive self-tuning position control of the hydraulic drive. Specifically, the same identification procedure as in the case of a self-tuning position controller is used for adaptation of the velocity gain factor. The identification assumes that the system is described with an identification model, i.e. a transfer function with unknown parameters, which change their values when the system moves from one operating point to another. For the identification procedure to be effective, fast and convergent, it is important to select a simple, but still representative identification model. In the case of hydraulic drives, the simplest mathematical model can be obtained by ignoring servo-valve dynamics, inertial forces and oil compressibility. The block diagram of such a simplified mathematical description, of an open loop system, is shown in Figure 4.

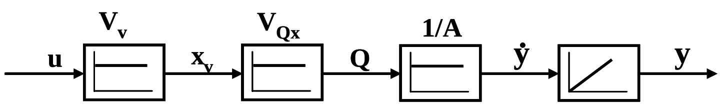


Figure 4: *Block diagram of the simplified mathematical model.*

The simplified position transfer function takes now the form:

$$G_y(s) = \frac{y(s)}{u(s)} = \frac{V_V V_{Qx}}{A} \frac{1}{s} = \frac{V_s}{s}, \tag{3.1}$$

With unknown gain V_s, which changes its value in real life situations. The above simplification still involves the main system non-linearity, namely the square root shaped pressure-flow characteristic of the servo-valve; it expresses the interdependency of the valve flow and the valve pressure drop. The latter is directly influenced by the actual load pressure, which is the consequence of inertial forces, friction forces, external forces etc. It can be assumed, therefore, that the all system changes are reflected in the gain factor V_s.

In digital control systems, the unknown parameters can be estimated on-line by using recursive estimation methods (Ref.3). In this case, the recursive least square method has been chosen. By the definition of signal vector $\underline{\psi}$ and parameter vector $\underline{\hat{\theta}}$ and their multiplication, we can obtain the model output vector $\underline{\hat{y}}$. The errors between estimated outputs and measured

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outputs $e(k)=y(k)-\hat{y}(k)$ and their squares give us cost-functional $J=\underline{e}^T\underline{e}$, which needs to be minimized $dJ/d\underline{\hat{\theta}}=\underline{0} \Rightarrow \underline{\hat{\theta}}=\left[\underline{\psi}^T\underline{\psi}\right]^{-1}\underline{\psi}^T\underline{y}$. With the substitution $\underline{P}=\left[\underline{\psi}^T\underline{\psi}\right]^{-1}$ we obtain the equations for parameter vector estimation. For the on-line parameter estimation, the following three equations are to be computed in each sampling interval:

$$\underline{\gamma}(k)=\underline{P}(k+1)\underline{\psi}(k+1)=\left(\frac{1}{\underline{\psi}^T(k+1)\underline{P}(k)y(k+1)+\lambda}\right)\underline{P}(k)\underline{\psi}(k+1) \tag{3.2}$$

$$\underline{\hat{\theta}}(k+1)=\underline{\hat{\theta}}(k)+\underline{\gamma}(k)\left[y(k+1)-\underline{\psi}^T(k+1)\underline{\hat{\theta}}(k)\right] \tag{3.3}$$

$$\underline{P}(k+1)=\left[\underline{I}-\underline{\gamma}(k)\underline{\psi}^T(k+1)\right]\underline{P}(k)\frac{1}{\lambda} \tag{3.4}$$

where $\underline{\gamma}$ is the correction vector and λ is the forgetting factor.

By putting the time continuity transfer function (3.1) into a time discrete form, using the Z-transformation: $G'(z)=(1-z^{-1})Z(V_S/s^2)=TV_S z^{-1}/1-z^{-1}=b_1 z^{-1}/1-z^{-1}$ we finally obtain the difference equation $y(k+1)-y(k)=b_1 u(k)$, with only one unknown parameter $b_1=TV_S$. The equations (3.2)–(3.4) for on-line parameter estimation take now the form:

$$\gamma(k)=\frac{P(k)u(k)}{P(k)u^2(k)+\lambda} \tag{3.5}$$

$$\hat{b}_1(k+1)=\hat{b}_1(k)+\gamma(k)\left[y(k+1)-y(k)-b_1(k)u(k)\right] \tag{3.6}$$

$$P(k+1)=\frac{1}{u^2(k)+\dfrac{\lambda}{P(k)}} \tag{3.7}$$

To obtain a fast and simultaneously convergent identification process, the forgetting factor can be selected inside a very narrow range $\lambda=0.9\div 0.995$, which is sensitive for the practical implementation. Because of that, a certain modification was introduced at this place, i.e. the second term in the denominator of the equation (3.7) was replaced by $\lambda/P(k)=c^2$, where $c\in IR$. This modification enabled an effective monitoring of the convergence and rate of the identification process.

The most important conclusion for the realization of the adaptive velocity feed-forward compensation can be obtained by comparison of equations (2.3) and (3.1). Specifically, the gain of the additional input signal $u_v(s)$ has the form of the reciprocal value of the gain factor V_s. The digital realization of the differential equation (2.4) now takes the form of the following difference equation with sampling interval T:

$$u_v(k) = V_A(k)\,\dot{y}(k) = \frac{1}{V_s(k)}\,\dot{y}(k) = \frac{1}{\hat{b}_1(k)}\left[\frac{y(k)-y(k-1)}{T}\right] \tag{3.8}$$

where the reciprocal value of the estimated parameter $\hat{b}_1$ is used for on-line estimation of velocity gain factor V_A.

4 FORCE CONTROL STRATEGY

The proposed control structure is depicted schematically in Figure 5.

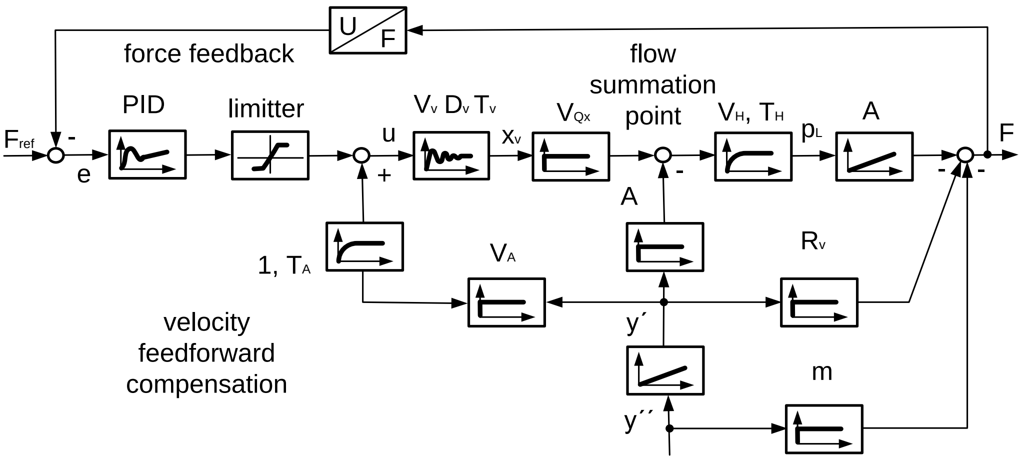

Figure 5: *Block diagram of improved force control concept.*

The above structure is realized as a digital control algorithm. The main force feedback loop is controlled by an ordinary PID-controller (Ref.4):

$$u_r(k) = K_p\left\{e(k) + \frac{T}{T_i}\sum_{n=1}^{k}\frac{e(k-1)+e(k)}{2} + \frac{T_d}{T}\left[e(k)-e(k-1)\right]\right\} \tag{4.1}$$

The parameters of the above controller are tuned experimentally using Ziegler-Nichols direct method [1]. With this method, a system should be excited to the stability limit. After determination of critical gain factor $K_{crit.}$ and critical period of oscillation $P_{crit.}$, the parameters of the PID controller can be computed as follows: $K_p=0.6K_{crit.}$, $T_i=0.5P_{crit.}$, $T_d=0.125P_{crit.}$. Also a limiter for the integral part of the controller is used to prevent large overshooting of the control variable. Finally the PID-controller is combined with an adaptive feed-forward velocity loop, realized by equation (3.8). This signal is due to stability reasons slightly lagged for a lag time constant T_A.

The proposed control structure simultaneously enables a good reference tracking and well disturbance rejection.

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5 EXPERIMENTAL RESULTS

Before the new control strategy was implemented on the apparatus for testing anode samples (Figure 5), the control strategy was verified in a safe laboratory environment.

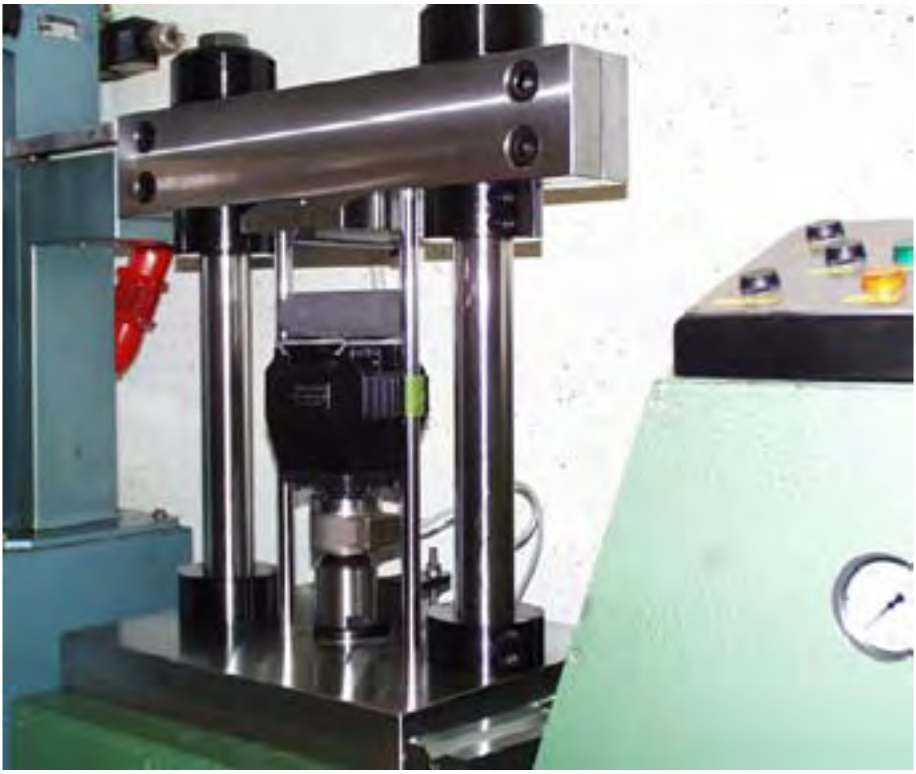

Figure 6: *Apparatus for testing anode samples.*

The laboratory test system, built from hydraulic components, is shown in Figure 6.

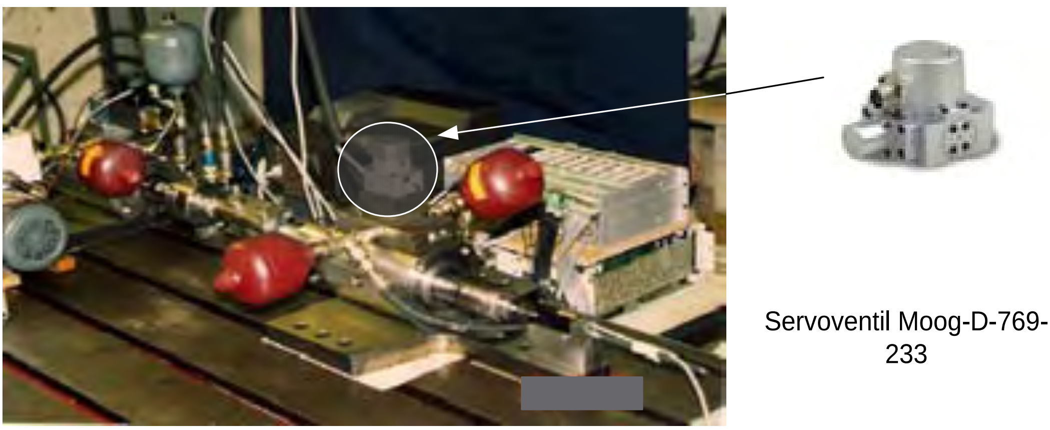

Figure 7: *Laboratory device for experimental adjustment of servo-hydraulic drives.*

It consists of a servo-valve-controlled main hydraulic cylinder equipped with a position transducer and a force sensor, and proportional-valve-controlled load cylinder. The piston rods

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of both cylinders are connected. There are also electronic amplifiers and the control computer, which operates with a sampling period of T=1ms. The characteristics of the equipment are collected in Table 1.

Table 1: *Test equipment data.*

Main cylinder (load cylinder) Rexroth CD-250 (CG-250) -piston diameter: $d_p = 75$ mm -piston rod diameter: $d_r = 63$ mm -stroke: h =100 mm	**Servovalve** Moog 769-233 -nominal flow: Q_n= 19 l/min -supply pressure: p_s = 210 bar
Proportional valve *Bosch NG6* -nominal flow: Q_n= 12 l/min -supply pressure: p_s = 140 bar	**Force sensor (strain gauge)** Hottinger N2A -operating range: +/- 50 kN -sensitivity: 3 mV/V
Position transducer (inductive) Precisor Elect. TV-150 S2 -operating range: 150 mm -sensitivity: 00 mV/V	**Control computer** GESCOMP-8420 -68020 CPU, 68881 FPU -12-bit A/D, D/A

The quality of reference tracking is tested at reference steps from 12kN to 18kN with a blocked load cylinder, while the tests of disturbance rejection are conducted at a constant reference signal of 12kN. The disturbance, i.e. the movement of the load cylinder, is obtained by rapid opening of the proportional valve, so that the velocity is changed from ≈ 0 mm/s to ≈ 20 mm/s. The force signals in diagrams are marked + and – for strain and press forces, respectively.

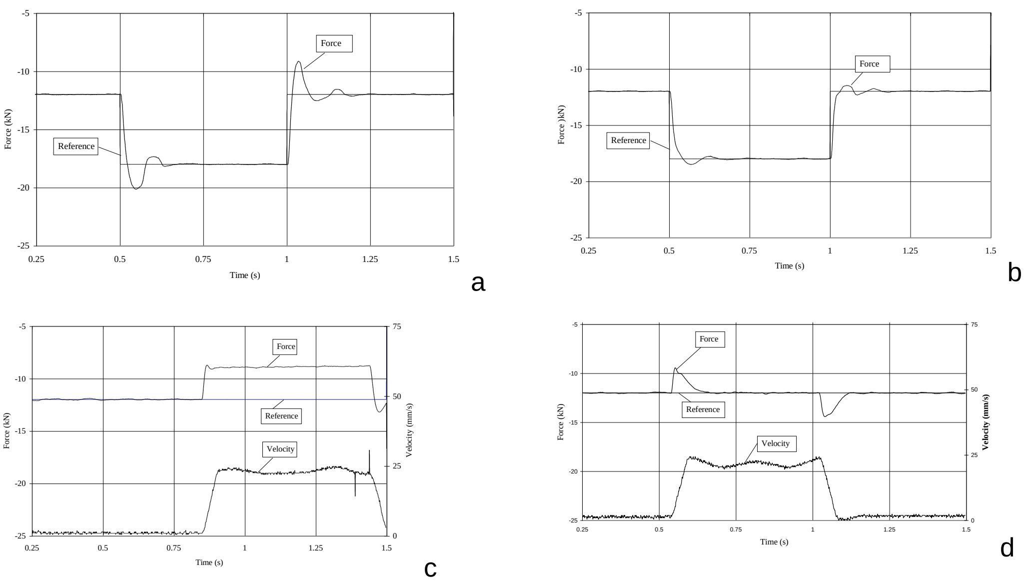

Figure 8: *a) Step response of the hydraulic drive force control loop with PID-controller.*
b) Step response of force control loop with anti-wind-up protected PID-controller.
c) Disturbance rejection of the hydraulic drive force control loop with anti-wind-up PID controller.
d) Disturbance rejection of the hydraulic drive force control loop with anti- wind up PID controller and the adaptive velocity feed-forward compensation.

Among the multiple experiments, only a few representatives are shown here. The first, shown in Figure 6a, was obtained using a PID controller in its original form. It serves for comparison.

However, with the zero steady state error, is the overshoot of the control variable (≈25%) too large for practical implementation? A satisfactory improvement of control behaviour has been achieved by introducing the limiter for integral part of the above controller (Figure 6b). Consequently, due to this limitation, the disturbance rejection became poor. Specifically, the controller is unable to minimize the steady state error in case of movement of the object that the hydraulic drive is pushing against. Disturbance rejection of the hydraulic drive force control loop using a PID-controller with anti-windup is poor. As was mentioned earlier, the reasonable further step is the use of adaptive velocity feed-forward compensation. The time response of the control system is shown in Figure 6d.

The time responses from the above figures prove the effectiveness of the proposed control concept. Regardless of how large the disturbance velocity is, the steady state error remains zero, while the overshoot of the control variable is less than 5%.

Finally, the modernized device for testing anode samples has been experimentally proved. Determination of the dynamic modulus of elasticity has been realized with approximated pulse excitation, using sinusoidal force signal. In fact, the reference signal of the force control loop was realized so as to obtain the constant preload stress of 1 kN and variable compressive stress in range of 1kN – 7kN (Figure 7).

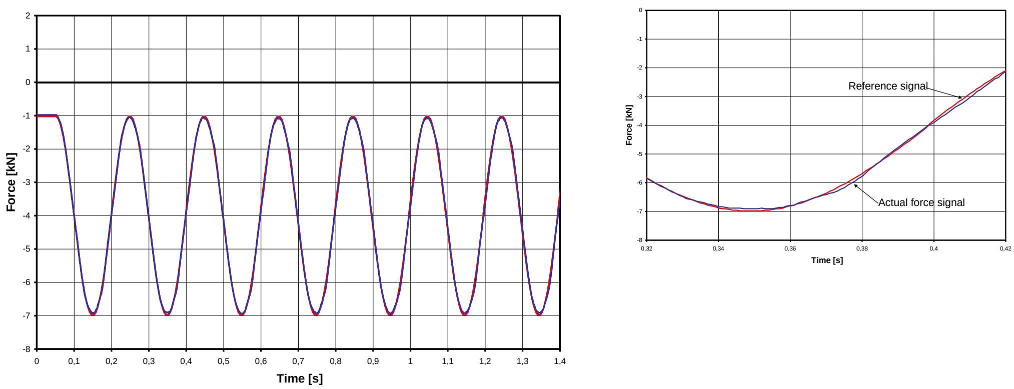

Figure 9: *Experimental result of approximated pulse excitation of specimen*.

6 CONCLUSION

Testing of anodes is an important tool to optimize the performance of aluminium production and to reduce production costs.

Among the static tests, such as flexural strength, compressive strength and three-point bending tests, it is also important to determine the dynamic modulus of elasticity with pulse excitation. Existing mechanical testing equipment has been modernized to provide not only static, but also dynamic testing. For that reason, the common electro-hydraulic drive has been replaced with a servo-hydraulic drive, equipped with corresponding sensors and control electronics. The control

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computer, which controls the entire device, also contains an algorithm for closed loop force control.

A good performance of closed loop force control is easy obtainable with slightly modified conventional PID controllers, when the hydraulic cylinder acts against a rigid body. However, this is not the case with anode sample testing. Troubles may occur when the anode sample starts to move during the experiment. In that case, more sophisticated control algorithms are needed.

The development of such a control algorithm is shown in this paper. It consists of a PID controller with a limited integral part and an additional adaptive feed-forward velocity loop. This combination ensures good reference tracking and well disturbance rejection of the control system simultaneously. To avoid the use of another sensor, the velocity is computed from the signal of the existing position transducer. The necessary accommodation of the velocity gain factor to changes of the operating regime is solved in an original way. Specifically, the mathematical relation between velocity signal and servo-valve input voltage is derived first on the basis of simplified position transfer function and then on basis of the simplified force transfer function of the hydraulic drive. The comparison of both shows that they differ only in the reciprocal value of the velocity gain factor. By selecting the simplified position transfer function to be an identification model of the system, the adaption of the velocity gain factor is then obtained using the on-line least square estimation technique.

This demonstrates the possibility of applying more sophisticated control structures in a hydraulic drive force control loop to deal with non-linear, internal and external, dynamic changes of the system for anode sample testing in the aluminium industry.

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DETERMINATION OF OPTIMAL CAPACITOR BANK ALLOCATION BY AN ADAPTED EVOLUTIONARY ALGORITHM WITH USE OF CONSTRAINT FUZZIFICATION

DOLOČITEV OPTIMALNE LOKACIJE KONDENZATORSKIH BATERIJ S PRILAGOJENIM EVOLUCIJSKIM ALGORITMOM

Marinko Barukčić, Željko Hederić[ℜ], Miralem Hadžiselimović

Keywords: capacitor bank allocation, distributive network, evolutionary algorithm, fuzzy logic, optimization

Abstract

This paper presents the determination of optimal capacitor placement in radial distribution networks, during which a mathematical record of the optimization problem in the form of the objective function is carried out. To solve the previously set optimization problem, a customized evolutionary algorithm has been used. Adjustment is done by modification of the way of individual coding and presentation of the new reproduction operator. During the performance of evolutionary algorithms, individuals that exceed the set limits of the objective function are rejected or penalized. Problems can occur when the algorithm rejects quality individuals from the population due to the slightest excess of limitation. In succeeding generations, these individuals may provide good offspring; it is therefore advisable to retain them in the population. To ensure the survival of individuals who exceed the limits of the objective function by small amounts, a fuzzification of restrictions is used. This paper presents the fuzzification of

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voltage limits and the determination of the voltage constraint coefficient, using fuzzy set theory and fuzzy logic. For individuals that exceed the voltage limits obtained, the objective function value is multiplied by the voltage constraint coefficient. The presented algorithm is implemented on a test network with 34 buses.

Povzetek

V delu je predstavljena določitev optimalne lokacije za postavitev kondenzatorskih baterij v radialnih distribucijskih omrežjih. Pri tem je izveden matematični zapis optimizacijskega problema v obliki ciljne funkcije. Za rešitev predhodno postavljenega optimizacijskega problema je uporabljen prilagojen evolucijski algoritem. Prilagoditev je izvedena z načinom določitve osebkov, ki izpolnjujejo vnaprej zastavljene robne pogoje. Vsi osebki, ki ne zadovoljijo robnih pogojev so izločeni. Tako se lahko v iteracijskem postopku evolucijskega algoritma izločijo tudi osebki, ki zaradi najmanjšega odstopanja od robnih pogojev ne ustrezajo zastavljenim kriterijem. Izločeni osebki pa imajo možnost, da v naslednjih generacijah generirajo sprejemljive osebke. Da bi se zagotovil obstoj tovrstnih osebkov, je uporabljena mehka logika. Tako je v tem delu prikazana uporaba napetostnih omejitev in določitev koeficientov napetostnih omejitev za primer testnega elektroenergetskega omrežja z uporabo mehke logike. Za osebke, ki prekoračujejo robne pogoje se dobljena ciljna funkcija množi s pripadajočimi koeficienti napetostnih omejitev. Predstavljeni evolucijski algoritem je izveden na testnem elektroenergetskem omrežju s 34 zbiralkami.

1 INTRODUCTION

Because of their relatively simple installation and high availability, the application of capacitor banks in the power distribution network is quite extensive. The installation of capacitor banks, with the goal of reducing active losses and improving voltage conditions in the network, also changes the size of many other electrical network values and significantly reduces the current value in the lines. The direct economic benefits for the network distributor, achieved by reducing the active losses in the network through the installation of capacitor banks, are reduced by the cost of acquisition, installation and maintenance of capacitor banks, which can vary considerably. In addition, due to certain technical reasons, voltage must be kept within certain limits, which limits the theoretical possibility of improving voltage conditions. Also, lower voltage drops affect the increase of indicators of the quality of electrical energy, which has recently become a matter of concern. Thus, throughout the installation of capacitor banks in a distribution network, the distributors must decide on the placement and power of the capacitor bank to be installed in order to ensure that the installation is economically justified and that the electrical values remain within the prescribed and technically limited boundaries. Losses in distribution networks and voltages in the network nodes are usually calculated using various iterative methods of numerical mathematics. It follows that the problems of optimal distribution of capacitor banks in the network may be described with numerical mathematics as an optimization problem of the state space, subject to the restrictions. In this respect, we should define the objective function optimization problem, the problem constraints and variables that affect the objective function value. By solving the mathematical optimization problem previously described, the distributor obtains answers about the optimal number, powers and placements for installing capacitor banks. It should be kept in mind that for reasons

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of maintenance, security and installation requirements, the capacitor banks are usually installed in the switching and transformation nodes in the network. From the analysis of the previously mentioned facts, two important characteristics of this optimization problem can be derived. The first characteristic relates to the objective function. The dependence of active network losses of reactive power of capacitors, without omissions and approximations, cannot be explicitly expressed as analytical functions. The second characteristic is the discrete value of power capacitors and locations for mounting the battery in the network. Finally, from a strictly mathematical point of view, the observed problem is the optimization problem with constraints, discrete variables and a non-derivative objective function. Applying the classical methods that use trend analysis (derivative) of the objective function in this kind of optimization problem is quite problematic, because we do not have an analytical expression in this optimization problem that describes the dependence of the active losses of the locations and the powers of capacitor banks. Recently, there has been a trend to solve similar problems by using numerical computation methods such as artificial neural networks, algorithms based on fuzzy logic, genetic and various other types of evolutionary algorithms, ant colony methods, the method of simulated annealing and the method based on the tabu algorithm. There are also hybrid methods that combine the above, such as genetic algorithms and fuzzy logic, simulated annealing and fuzzy logic, neural networks and genetic algorithms, etc.

Examples of the application of genetic algorithms in optimization of capacitor banks in distribution networks can be found in Ajjarapu, [1], Alencar de Souza**,** [2], Reddy, [3], Rojas, [4], Defanti, [5], Masoum, [6], Abou-Ghazala, [7] and Levitin, [8]. Often, a presentation of individual and genetic operators in its original form as the simple genetic algorithm is used, as in Ajjarapu, [1], Reddy, [3], Rojas, [4] and Masoum [6]. In Abou-Ghazala, [7] and Levitin, [8] non binary representation and coding of individuals with classical crossover and mutation operators are used. In some papers, such as Defanti, [5], there is a binary coding of the location and power capacitors, so that a traditional crossover operator is used while the mutation operator is omitted. In such cases, the introduction of new genes into the population (which provides the mutation) provided a different reproduction of individuals. The adjustments of the basic genetic algorithm are done through a different presentation of individuals and a new genetic operator.

2 CLASSIC OBJECTIVE FUNCTION

The classic objective functions of the optimization problem for the displacement of the capacitor banks imply a means of optimizing the distribution according to economic criteria. A difference of financial savings due to the reduction of active losses from mounting batteries and the cost for the supply and maintenance of batteries is observed. With the default network parameters (line impedances, loads etc.) on which the installation of capacitor banks has no effect, the objective function is defined depending on the locations and the power capacitor banks at certain locations, and for the basic restriction limits it is taken the power of all nodes.

Mathematically, this optimization problem can be written as:

$$\begin{aligned} &OF(\vec{x}_{CB},\vec{Q}_{CB}) = C_P \cdot P_{mC}(\vec{x}_{CB},\vec{Q}_{CB},\vec{P}_L,\vec{Q}_L) + \\ &+ C_E \cdot E_P(P_{mC}) + C_{CB}(\vec{Q}_{CB}) \rightarrow \min \\ &V_{\min} \le V_j(\vec{x}_{CB},\vec{Q}_{CB},\vec{P}_L,\vec{Q}_L) \le V_{\max}, \quad za\ \forall\ j \in (1,n) \end{aligned} \tag{2.1}$$

As a solution of this optimization problem, a displacement of capacitor banks in which the difference between gross savings and costs are the highest is obtained. In doing so, of course, the lower and upper limits of voltage in all nodes should not be exceeded. The objective function (2.1) is most common in the optimal allocation of capacitor banks in distribution networks. Also, additional constraints, such as permissible current load lines, etc. can be introduced.

3 REVIEW OF THE BASIC ELEMENTS OF GENETIC ALGORITHMS AND THEIR ADAPTATION

Some of the problems that may arise in the application of a genetic algorithm for the optimization of capacitor banks in its basic form are those with the coding of variables of the objective function, those associated with determining the values of the parameters of genetic algorithm and the those of impact parameters on the speed of execution and the quality of the obtained solution. The basic structure of the genetic algorithm and the general evolutionary algorithm is shown in Figure 1.

```
Start Evolutionary Algorithm
        Set g = 0
        Make start population of solutions P_S(0) in start generations g = 0
        While end condition is not satisfied do:
                Set g = g+1
                Select individuals for reproduction P_R(g) from current population P_S(g)
                Make crossover for parent individuals P_R(g) and save offspring individuals
                Make mutation of offspring individuals
                Make population of individuals in next generation P_S(g+1)
        Write the solution.
End Evolutionary Algorithm
```

Figure 1: *The structure of evolutionary algorithm*

3.1 Overview of Variables for the Objective Function – Individual Coding

The basic units with which the genetic algorithm operates are individuals. In accordance with the idea of genetic algorithms as models of natural evolution, an individual in the genetic algorithm represents a chromosome. Individual chromosomes are the usual numeric characters (number or array of numbers), although they can exist in some other fields (string), and in the genetic algorithm containing information or data on the structure of the system. Each chromosome in a genetic algorithm represents a possible solution of the problem. In order for the genetic algorithm to be supplied with useful data, it is necessary to define a way of projecting the system state in an individual chromosome. How to display information about the

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structure of the system depends largely on the efficiency of genetic algorithms (solution quality, speed of execution) as well as defining other procedures and operators of genetic algorithms. The usual binary coding of the individual in the genetic algorithm applied to the observed optimization problem can be found in Mudnić, [9] and is shown in Figure 2.

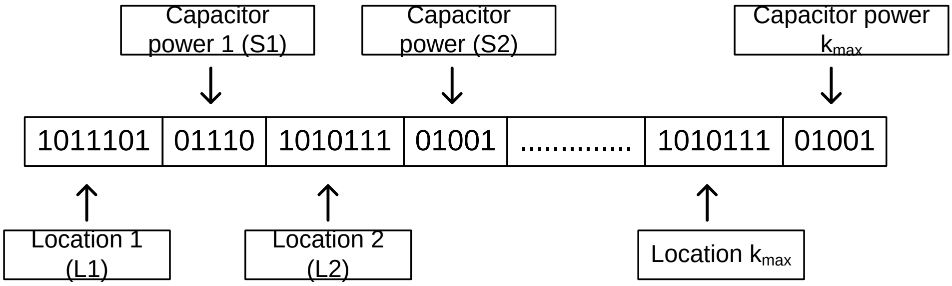

Figure 2: *Binary code of chromosome with a coded locations and the capacitor banks power, Mudnić, [9]*

The most common problem with such coding, as in Figure 2, is the possibility that some binary code that does not correspond to any node in the network or any available capacitor power. If we assume a network with three nodes, then the binary code of node 1 will be coded as 00, that of node 2 as 01 and node 3 as 10. If, during the crossover operations and mutation in some individuals, 11 appears, it is clear that this code does not correspond to any node in the network. To solve this problem, it is necessary to take additional actions so that in such cases, by some predefined criterion, a binary code is assigned to one of network existing nodes. An example of how to solve this problem can be found in Mudnić, [9].

To avoid this and other similar problems, this paper proposes a very simple integer coding of the location and power of capacitor banks in distribution networks. The coding process is carried out as follows: first, an integer number is assigned to each network node, and then a numeric string with a number of positions corresponding to the number of nodes in the network is formed. Eventually, every position in the numerical series is assigned a numeric value that corresponds to the power capacitor banks. If the node does not have built-in capacitor batteries at the appropriate position in a numerical series, a value of 0 will be recorded; if there is a capacitor in the node, an integer corresponding to the power capacitor banks will be added. For coding capacitor bank power, the simplest way of coding can be applied, which consists of the fact that the smallest battery is assigned a value of 1, followed by the value 2, etc. They may even be directly entered according to battery power in position into a numeric series (e.g. in kvar) without additional coding. Figure 3 shows the number of individuals designated as described above. In doing so, there are 4 available batteries of powers: 25 kvar, 50 kvar, 100 kvar and 200 kvar, which are coded in order as: 1, 2, 3 and 4.

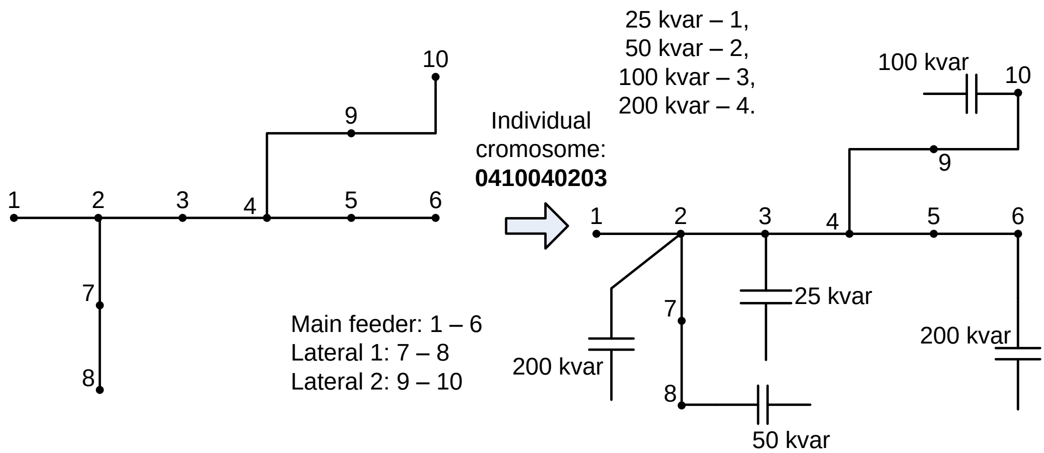

***Figure 3:** Coding the location and size of capacitor banks in the network*

With the described method of coding, the obtained individual chromosome is presented as an integer numeric string.

3.2 Crossover and Mutation Operators in Evolutionary Algorithm

The usual crossover and mutation operators for binary coding of the individual in the genetic algorithm are shown in Figure 4. A crossover operator creates individuals by combining parts of the chromosomes (binary code) of both parents; you can combine parts of chromosomes to perform the replacement on one or more positions in the chromosome (break points). Changing the value of mutations by a certain amount prompts the operator to change the value of binary bits in the chromosome (from 0 to 1 and vice versa).

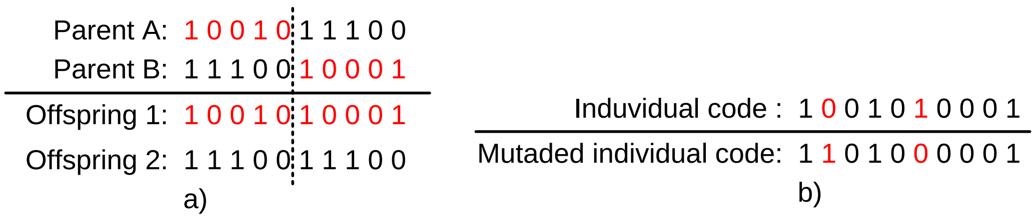

***Figure 4:** The basic form of genetic operators: a) crossover at one break point and b) the mutation of individual*

The creation of the offspring of individuals by the action of crossover and mutation operators is called “a reproduction of individuals” in the genetic algorithm. Before the presentation of the proposed reproduction operators, a two-dimensional display of the state space of optimization solutions for the described problems should be observed. If a network has n nodes as positions of possible locations and m capacitor sizes (power), then every possible combination of locations for installation and a power sequence combination of capacitor banks make this problem $n \times m$ dimensional. However, if every possible combination of locations for the installation of 1, 2 ... ... n capacitor banks is marked as a variable, and every possible sequence of installation of capacitor banks for the i-th combination of location is a second variable, then this problem can appear in two or three dimensions. Figure 6 shows a two-dimensional display

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of the state space with the objective function value for a particular combination of location and sequence of capacitor bank power. On Figure 6, the ordinate axis is causing the value of objective function, and the axis of abscissa shows a combination of location capacitor. For example, in Figure 6, the value of *OF* (L_j, R_i) on the ordinate axis represents the value of objective function for the *j*-th combination of location (L_j) and the *i*-th order (R_i) capacitor banks. This preview shows that the objective function of the optimization problem has a local extreme for each possible combination of capacitor bank locations. The reproduction operator follows from this preview of solution space and the described integer coding. One offspring inherits only locations from the first parent and order of bank powers from the second. The second offspring would inherit the other way around, from the first parent order of battery power and inherit locations where to install capacitor banks from the second parent. In fact, if the number of locations with both parents is different, the offspring inherits the number of sites from which it inherits locations, and the value of the first parent will remain on positions that other parents do not have. The change of value at a position in the chromosome depends on the difference between the parents' powers order, so subsequent mutation is not required. Another way of reproduction is to use only one individual, which will inherit locations for installation of capacitor banks from the parent site; the power sequence would be selected randomly. The rest of the decedents (one or more of them) would inherit only order of powers from the parents, and the location would be chosen randomly. It should be noted that another way of reproduction because of a random variable (location or order of capacitor’s power) immediately subsumes the characteristics of mutation operators. A presentation of these operators is given in Figure 5.

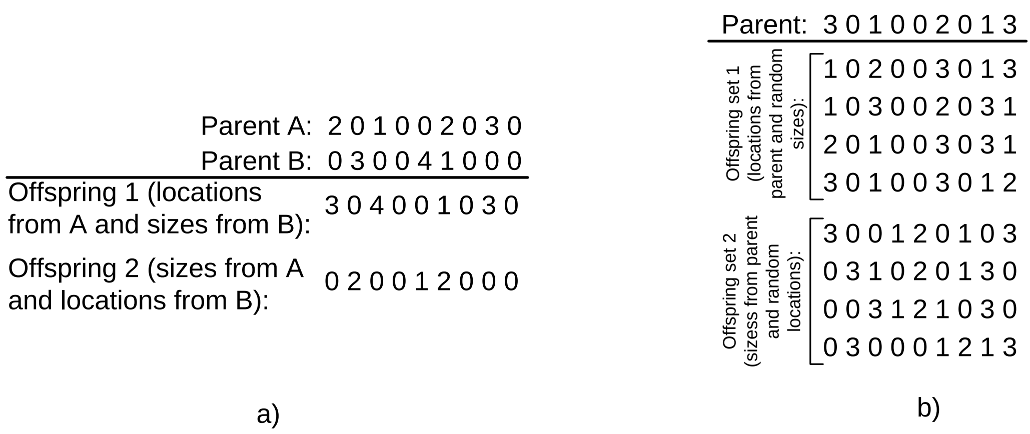

Figure 5: *Proposed reproduction: a) with two parents and b) with one parent*

With the proposed reproduction, the operator state space is searched for the combination of locations and combinations of the order of capacitor powers. Searching for the proposed operator of reproduction in four consecutive generations is shown in Figure 6, with only the offspring of the best individual in each generation.

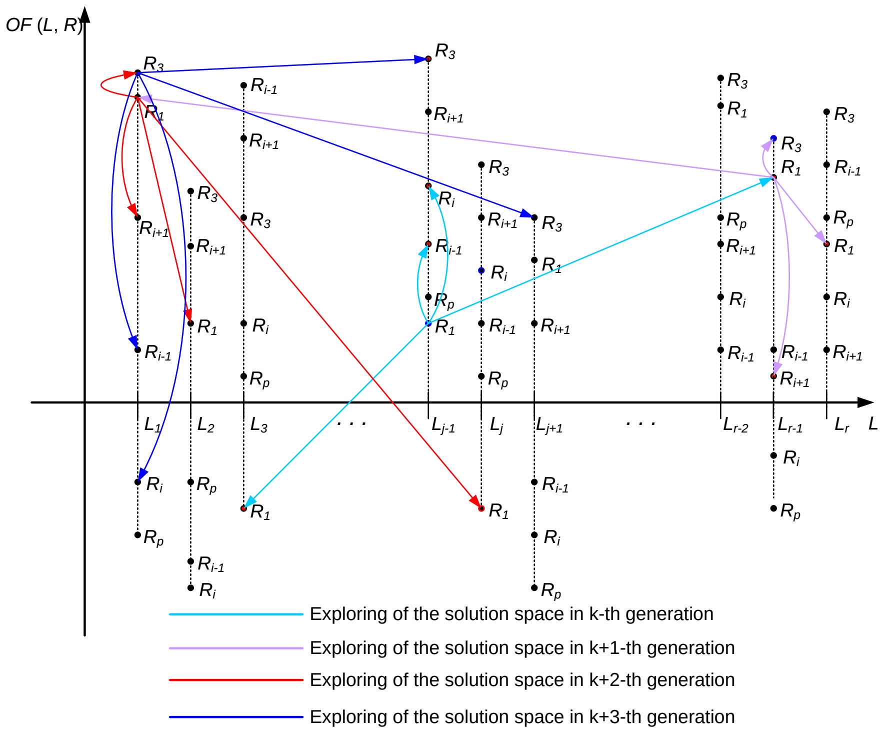

Figure 6: *Two-dimensional presentation of the solution space and exploring of the solution space by the proposed reproduction operator*

4 VOLTAGE CONSTRAINT FUZZIFICATION

The usual way to add constraints in the objective function for the application of genetic algorithms to optimal capacitor bank displacement is the penalization method, with which the objective function value is deteriorated (increases or decreases) for all values of variables (individuals in the evolutionary algorithm) to which they exceeded the default limit. A penalty can be given as a function of the level of overdraft limits, or all the individuals for which the limit is exceeded can be rejected regardless of the objective function value. The rejection of all individuals for which there is a minimum of excess voltage seems logical, because the voltage limits in distribution networks are firmly set and regulated by appropriate standards. However, it often happens that individuals who have little excess voltage also have very good values of the objective function, which means that their chromosome contains information on good locations and battery power and therefore can reproduce high-quality offspring. These individuals often need only one or two changes of location and/or power so that the voltage is within limits. Thus it is justified to retain such individuals in the population, although there is little excess of voltage limits. The problem is how to estimate the size of the exceeded voltage limits and how to express the impact of exceeding the objective function value; thus it is necessary to assess how well the limits have been overrun. Due to the properties of fuzzy sets, the application of fuzzy set theory is proposed here to solve this issue. First, we define a linguistic variable as voltage deviation observed for one node in a network that has the highest

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absolute deviation from the nominal voltage. Furthermore, for a given linguistic variable three linguistic values must be defined: small, medium and large deviation. The display of linguistic variable voltage deviation (ΔV), the linguistic values and membership functions (μ_V) are given in Figure 7a. This can also be viewed as three fuzzy sets with their membership functions. The absolute value of the permissible voltage limit ΔV_b is expressed in per unit. Typically, voltage constraints in distribution networks are ± 5% or ± 10%.

Membership functions in Figure 7a analytically can be expressed as:

$$\begin{aligned}
\mu_{Vs} &= \frac{-\Delta V}{0.15 \cdot \Delta V_b} + 7.67 \quad \textit{for small } \Delta V_b \le \Delta V \le 1.15 \cdot \Delta V_b \\
\mu_{Vm1} &= \frac{\Delta V}{0.15 \cdot \Delta V_b} - 6.67 \quad \textit{for medium } \Delta V_b \le \Delta V \le 1.15 \cdot \Delta V_b \\
\mu_{Vm2} &= \frac{-\Delta V}{0.15 \cdot \Delta V_b} + 8.67 \quad \textit{for medium } 1.15 \cdot \Delta V_b \le \Delta V \le 1.30 \cdot \Delta V_b \\
\mu_{Vl} &= \frac{\Delta V}{0.15 \cdot \Delta V_b} - 7.67 \quad \textit{for large } 1.15 \cdot \Delta V_b \le \Delta V \le 1.30 \cdot \Delta V_b
\end{aligned} \tag{4.1}$$

To take into consideration the voltage limitation, the objective function with incorporated voltage limitation given with (2.1) can be expressed as:

$$OF_V(\vec{x}_{CB}, \vec{Q}_{CB}) = K_V \cdot OF(\vec{x}_{CB}, \vec{Q}_{CB}) \to \min \tag{4.2}$$

To determine the value of the coefficient K_V, which takes into account the impact of exceeding the voltage limits on the quality of individuals in evolutionary algorithm, define the following fuzzy rules:

- R1: If the exceeding of the voltage limits is small, the coefficient K_V is small.
- R2: If the exceeding of voltage limits is medium, the coefficient K_V is medium.
- R3: If the exceeding of voltage limits is large, the value of coefficient K_V is large.

With three fuzzy sets, linguistic variables are defined by with their K_V values: small, medium and large. Linguistic variables with linguistic values of K_V are shown in Figure 7b.

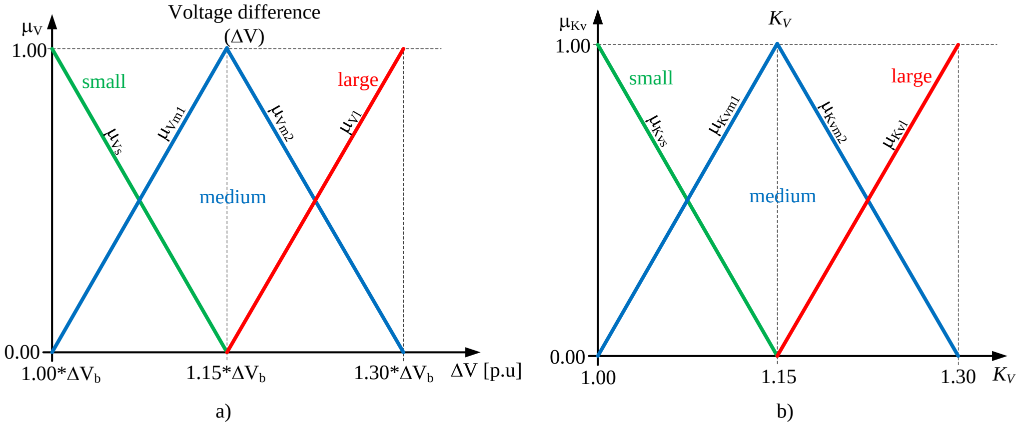

***Figure 7:** Fuzzy sets and membership functions for small, medium and large exceeding of a) voltage limits and b) coefficient K_V*

Analytical expressions for the membership functions of coefficient K_V are:

$$
\begin{aligned}
\mu_{Kvs} &= \frac{-K_V}{0.15} + 7.67 \quad \text{for small } 1.00 \le K_V \le 1.15 \\
\mu_{Kvm1} &= \frac{K_V}{0.15} - 6.67 \quad \text{for medium } 1.00 \le K_V \le 1.15 \\
\mu_{Kvm2} &= \frac{-K_V}{0.15} + 8.67 \quad \text{for medium } 1.15 \le K_V \le 1.30 \\
\mu_{Kvl} &= \frac{K_V}{0.15} - 7.67 \quad \text{for large } 1.15 \le K_V \le 1.30
\end{aligned}
\tag{4.3}
$$

Determination of the degree of truth for the set of fuzzy rules based on the voltage deviation from the nominal value finally comes to determining the value of the coefficient K_V. Defining the voltage deviation and the coefficient K_V, as in Figures 7a and 7b, means K_V = 1.00 for all the individuals for which the voltage is within limits. Also, the coefficient is K_V = 1.30 for all the individuals for which the voltage deviation from the nominal value greater than $1.30\Delta V_b$. For certain voltage deviations, firstly determine the value of membership functions for each fuzzy set from Figure 7a according to (4.1), and for each voltage deviation assign the following values of membership functions: μ_{Vs}, μ_{Vm} i μ_{Vl}. Then determine the truth degrees of fuzzy rules R1, R2 and R3, and from them the membership degrees of coefficient K_V assign to fuzzy sets from Figure 7b, as: R1: $\mu_{Kvs} = tv_{R1} = \mu_{Vs}$, R2: $\mu_{Kvm} = tv_{R2} = \mu_{Vm}$, R3: $\mu_{Kvl} = tv_{R3} = \mu_{Vl}$. The fuzzy set of linguistic variable K_V with its linguistic values and membership degrees, based on membership function values from Figure 7b, is:

$$
\mu_{Kv} = \left\{ \frac{\mu_{Kvs}}{small}, \frac{\mu_{Kvm}}{medium}, \frac{\mu_{Kvl}}{large} \right\}
\tag{4.4}
$$

Based on fuzzy sets (4.3) and fuzzy sets (4.4), create modified membership functions (μ'_{Kv}) for the coefficient K_V. These modified membership functions are created using the fuzzy AND operator as:

$$\begin{aligned}
\mu'_{Kvs} &= \mu_{Kvs}\ AND\ \mu_{Kv} = \min(\mu_{Kvs}, \mu_{Kv}) \quad for\ small\ 1.00 \le K_V \le 1.15 \\
\mu'_{Kvm} &= \mu_{Kvm}\ AND\ \mu_{Kv} = \min(\mu_{Kvm}, \mu_{Kv}) \quad for\ medium\ 1.00 \le K_V \le 1.30 \\
\mu'_{Kvl} &= \mu_{Kvl}\ AND\ \mu_{Kv} = \min(\mu_{Kvl}, \mu_{Kv}) \quad for\ large\ 1.15 \le K_V \le 1.30
\end{aligned} \tag{4.5}$$

After this, use the fuzzy OR operator of the modified membership functions for each value of the variable K_V to create aggregated membership functions (μ''_{Kv}) for the coefficient K_V. The aggregated membership functions can be written as:

$$\mu''_{Kv} = \mu'_{Kvs}\ OR\ \mu'_{Kvm} OR\ \mu'_{Kvl} = \max(\mu'_{Kvs}, \mu'_{Kvm}, \mu'_{Kvl}) \quad for\ 1.00 \le K_V \le 1.30 \tag{4.6}$$

For example, take the voltage deviation $\Delta V = 1.1\Delta V_b$. This voltage deviation has the following membership degrees to fuzzy sets in Figure 7a: $\mu_{Vs} = 0.33$; $\mu_{Vm} = 0.67$ and $\mu_{Vl} = 0.00$, and membership degrees of coefficient K_V to the fuzzy sets in Figure 7b are: $\mu_{KVs} = 0.33$; $\mu_{KVm} = 0.67$ and $\mu_{KVl} = 0.00$. Applying (4.5) and (4.6) constitutes the modified membership functions as well as aggregated membership function for coefficient K_V, which are shown in Figures 8a and 8b.

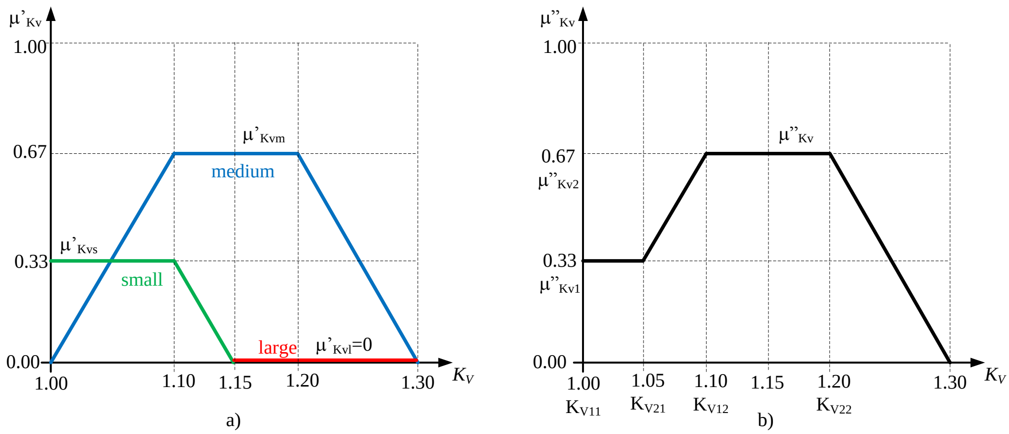

Figure 8: *a) Modified and b) aggregated membreship functions of coefficient K_V*

Finally, the obtained unique features belonging to the application of some of the methods of defuzzification obtain the value of the coefficient K_V as a crisp number. The obtained unique features belonging to the application of some of the methods of defuzzification obtain the value of the coefficient K_V as a clear number. There are several methods of defuzzification, Siler [10] and Usenik, [11]; we used the weighted average maxima method here. According to this method, the value and range of local maximums from the aggregated membership function are determined. Then crisp value of coefficient K_V calculated as:

$$K_V = \frac{\sum_i \left[\left(\frac{K_{V1i} + K_{V2i}}{2} \right) \cdot \mu''_{Kvi\max} \right]}{\sum_i \mu''_{Kvi\max}} \tag{4.7}$$

In the example on Figure 8b, there are two maximums (i=2). For the first maximum: K_{V11} = 1.00, K_{V21} = 1.05 and μ''_{Kv1max} = 0.33; for the second: K_{V12} = 1.10 , K_{V22} = 1.20 and μ''_{Kv2max} = 0.67. According (4.7) to the observed example of voltage exceeding of 1.10 ΔV_b, the coefficient of voltage exceeding as crisp number is K_V = 1.11.

5 APPLICATION ON THE TEST NETWORK

The evolutionary algorithm presented in Section 2 with a custom reproduction operator with a fuzzification voltage limit has been tested on a network with 34 nodes. Information on network configuration, load, serial impedance and transverse admittance can be found in Mekhamer [12] and Bhattacharya [13]. The algorithm is written in the software package MathCAD and load flow is performed using the classical Newton-Raphson algorithm. The 34-bus network has a main feeder and four laterals; the system voltage is 11 kV. Numeration of the main feeder nodes is the same, whereas numeration of lateral nodes correspond to numeration presented in Bhattacharya, [13] as follows: nodes 12–15 correspond to nodes 2_1–2_4, nodes 16–26 correspond to nodes 5_1-5_11, nodes 27–29 correspond to nodes 6_1–6_3 and nodes 30–33 correspond to nodes 9_1–9_4. Data for capacitor cost and cost coefficient for peak power loss are the same as for the 10-bus network. The largest capacitor is 2 850 kvar. The cost coefficient for peak power loss (C_P) as reported in Bhattacharya [13] is used here, C_P = \$ 168 / (kW-Year). To compare the results with those given in the literature, Bhattacharya, [13], in calculation of the objective function, the cost of energy losses (C_E = 0) is not taken into account as it is in literature, Bhattacharya, [13]. Voltage limitation is taken as 5%, i.e. V_{min} = 0.95 p.u. and V_{max} = 1.05 p.u. The results of data for the uncompensated and compensated network are given in Table 1, which shows the results obtained by performing the described algorithm five times. While executing the evolutionary algorithm, the reproduction from Figure 7b is used. During the selection procedure, only one of the best individuals in the next generation of individuals was chosen for adding to their offspring. This kind of selection of only one individual is quite uncommon in genetic and evolutionary algorithms, but has been shown to produce good results because of using the reproduction operator presented in Figure 7b. Because of such a defined operator of reproduction and the survival of only one individual, the entire population is not filling up with the same genetic material; furthermore, introducing new genes provided a diversity of genetic material in each generation. The evolutionary algorithm was performed in 30 generations with a population of 30 individuals with a random starting population.

***Table 1.** Results for 34-bus test network in which the algorithm is executed five times*

	Uncompensated network	Compensated network				
		I	II	III	IV	V
Allocation of capacitors (node-kvar)	-	10-600 16-750 22-450 25-600	10-600 12-150 16-1 200 24-900	11-600 16-900 22-1 050	8-600 17-900 23-900	8-900 17-900 20-300 24-600
Real loss (kW)	221.72	160.29	161.16	161.32	160.76	160.26
Loss cost ($)	37 249.55	26 928.05	27 074.04	27 101.26	27 006.84	26 923.68
Capacitor cost ($)	0.00	584.80	575.75	536.17	461.33	566.60
Network cost ($)	37 249.55	27 512.85	27 649.79	27 637.43	27 468.17	27 490.28
Benefit ($)	0.00	9 736.70	9 599.76	9 612.12	9 781.38	9 759.27
Min. V (p.u.)	0.941 69	0.950 49	0.951 07	0.950 24	0.950 33	0.950 73
Max. V (p.u.)	1	1	1	1	1	1

Comparing these results with those given in the literature for the same test network shows that the proposed algorithm gives good results. The best result from Table 1 is less than 1% of the bad results in Bhattacharya [13].

6 CONCLUSIONS

This paper describes the solving of the optimization problem of capacitor bank allocation in radial distribution networks by using an evolutionary algorithm. Within it, the impact of installing capacitor banks to reduce network active losses in a network from which follows a direct economic benefit to the distributor is observed. In the evolutionary algorithm, very simple integer coding of individuals that is different from binary coding used with genetic and evolutionary algorithms is presented. The unique reproduction operator that includes the genetic operator crossover and mutation is also presented. The evolutionary algorithm, which is simpler than the classic genetic algorithm, was obtained with simpler individual coding and by reducing the number of operators. When solving set optimization problems with an evolutionary algorithm, it has been noted that individuals that exceed voltage limits by small amounts often provide excellent value of the objective function and so carry information on good locations and the power capacitor. Therefore, those individual should be kept in the population during an evolutionary algorithm, in spite of their exceeding the voltage limits, because it is very likely that they will give offspring that will satisfy the voltage limits and the

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good value of the objective function. For quality evaluation of such individuals in this paper, the coefficient of voltage restrictions by which the multiplied value of the objective function for each individual is used. During that, if an individual gave the voltages that are within the limits, this coefficient is 1; if it exceeds the limits, the coefficient is greater than 1. To determine the value of this coefficient, fuzzy set theory and fuzzy logic were used. First, fuzzification of the voltage of some individual is made and then, based on the amount of voltage by fuzzy rules, a certain degree of belonging of voltage limits coefficient is determined according to settled fuzzy sets. In the end, the value of the voltage limits coefficient as a crisp number is determined by the defuzzification procedure. The presented evolutionary algorithm with fuzzification of voltage limitation was tested on a test radial distribution network with 34 buses. The results are comparable with results presented in the literature for the same network.

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Nomenclature

(Symbols)	(Symbol meaning)
C_{CB}	cost of allocated capacitor banks
C_E	cost coefficient of energy loss [$/kWh],
C_P	cost coefficient of peak power loss [$/kW],
E_P	losses of energy with allocated capacitor banks
K_V	voltage constraints coefficient
n	number of network nodes
OF	objective function value
OF_V	modified objective function value by voltage constraints
$\vec{P}_L$	vector of active power loads
P_{mC}	active power losses with allocated capacitor banks
$\vec{Q}_L$	vector of reactive power loads
$\vec{Q}_{CB}$	vector of capacitor banks
V_j	voltage in the *j*-th network node
V_{min}	lower voltage limit
V_{max}	upper voltage limit
$\vec{x}_{CB}$	vector of capacitor bank location in the network nodes,
ΔV	voltage difference between node voltage and nominal voltage
ΔV_b	voltage difference between limit voltage and nominal voltage
μ_{Kv}	membership function of voltage constraint coefficient
μ'_{Kv}	modified membership function of voltage constraint coefficient
μ''_{Kv}	aggregated membership function of voltage constraint coefficient
μ_V	membership function of voltage deviation

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POSSIBILITIES FOR WIND ENERGY EXPLOITATION IN SLOVENIA

MOŽNOSTI IZKORIŠČANJA VETRNE ENERGIJE V SLOVENIJI

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Keywords: wind energy, utilizing wind energy;

Abstract

Slovenia, from an energy point of view, is not a country rich with constant winds. Due to its geographical location and terrain, there are relatively few sites where wind speeds reach an annual average of 5 m/s. However, there are small locations where the wind speed is significantly higher. Particularly interesting is the coastal zone, or wider Primorska region, the sites of regional wind speed records. This year, gusts over 52.7 m/s (190 km/h) have been recorded. Of course, there is still the problem, a challenge in fact, of how to harness wind power. From the technical point of view, it is a challenge for exceptional operational flexibility and material durability. Large commercial implementations are unsuitable for such conditions; the overload of wings could be critical with such speeds. Such overloads could cause the wings to fail or the destruction of material and thus a threat to the immediate environment. Flying wing parts and parts of pillars are extremely dangerous. Therefore, operating in such extreme changing environments is more suitable for the small, compact wind turbines with robust design that have been developed recently.

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Povzetek

Slovenija, iz energetskega vidika, žal ne spada v dežele, bogate s konstantnim vetrom. Zaradi zemljepisne lege, konfiguracije terena in poraščenosti tal je razmeroma malo lokacij, kjer hitrosti vetra v povprečju dosegajo 5 m/s. Imamo pa kar precej mikro-lokacij, kjer so hitrosti vetra tudi v povprečnih vrednostih čez vse leto precej višje. Še posebej je zanimiv priobalni pas, oz. širša Primorska regija, kjer zna burja dosegati hitrostne rekorde. Samo letos so že bile izmerjene hitrosti vetra, sicer v sunkih, tudi čez 52,7 m/s (190 km/h). Seveda še vedno ostaja problem in hkrati izziv, kako izkoristiti tudi to vetrno energijo. Iz tehniškega stališča pomeni to izjemno obratovalno prilagodljivost in vzdržljivost materiala. Velike komercialne izvedbe so za takšno obratovanje neprimerne, saj bi bila obremenitev kril, pri takšnih hitrostih prevelika. To bi povzročalo lom kril, oz. trajno porušitev materiala in s tem nevarnost za neposredno okolje. Leteči deli delov kril in stebra so izjemno nevarni. Zato so za obratovanje v takšnih ekstremnih okoljih primernejše manjše vetrnice, kompaktnih robustnih izvedb, ki se v zadnjem času vse hitreje razvijajo.

1 INTRODUCTION

The complex landscape of Slovenia does not provide good locations for wind-measuring sites. Consequently, it is relatively underserved by its network for measuring wind speeds (Figure 1). Single-site wind measurements are frequently inadequate for generating useful results for the energy industry, because the sampling points are intended for the provision of meteorological data, mostly in urban areas. At these locations, the measurements are strongly influenced by wind obstacles, including buildings, trees and other urban obstacles, in the vicinity of the set of instruments. Another problem is that wind speed measurements are suitable in the last decade only; they are carried out by the Environment Agency of Slovenia (ARSO).

Figure 1: *Network of automatic weather stations to track wind speed in 2007, [1].*

Figure 2 shows the average annual value of wind velocity at an elevation of 10 m. Higher velocities are evident in the mountainous part of Slovenia, particularly with the wind called the “Burja” in the wider coastal area.

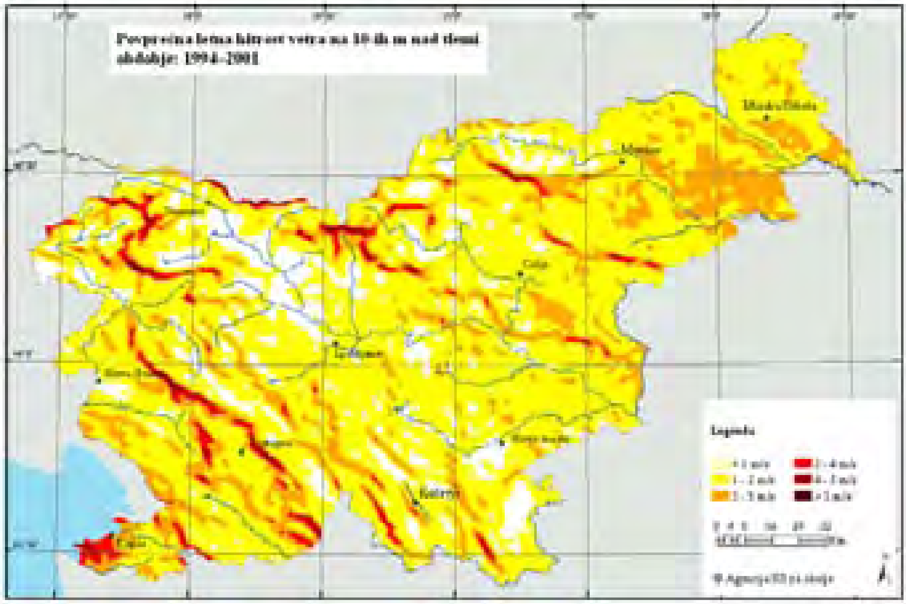

Figure 2: *Average annual (between 1994 and 2001) wind velocities at 10 m elevation, [2]*

ARSO’s data on the extreme values of wind speed locations in Slovenia are listed in Table 1. It is clear that the average value is within a relatively wide range between 4 to 51 m/s, sometimes up to 60 m/s.

Table 1: Extreme average wind velocities measured by location and time, source: ARSO.

Type of extreme	Speed* [m/s]	location	year
Average velocity	5.1	Kredarica	1997–2006
Average velocity at locations below 500 m a.s.l.	4.0	Portorož-Beli Križ	1982–1991
Average annual velocity	5.4	Kredarica	2001
Average annual velocity at locations below 500 m a.s.l.	4.5	Portorož-Beli Križ	1982
Higher half-hour velocity	32.0	Kredarica	1998
Highest hour avarege velocity at locations below 500 m a.s.l.	26.0	Ajdovščina	1978
Highest measured velocity	51.0	Kredarica	2008
Highest measured velocity at locations below 500 m a.s.l.	50.0	Bovec, Vipava	2002, 1996

***Velocities were measured 10 m above the ground level.**

According to this information, Slovenian wind conditions require turbines operating well in a wide range of wind speeds ranging from 4 to 50 m/s. This means that we need wind turbines with a low starting wind speed, operating on large loads and able to withstand high wind speeds with powerful gusts.

2 WIND FORCE DEFINITIONS

Winds are driven almost entirely by the sun's energy, causing differential surface heating. Heating is most intense on the land masses closer to the equator, and the greatest heating occurs in the daytime, which means that the region of the greatest heating moves around the earth's surface as it spins on its axis. Warm air rises and circulates in the atmosphere and sinks back to the surfaces in cooler areas. The resulting large-scale motions of the air are significantly influenced by the Coriolis force due to the earth's rotation, [3].

It is well known that income flow act to a surface creates compressive force on the surface, [4]. However, we must consider the fact that the wind is created by the earth's surface, which turns. Therefore, we must also at least consider the Coriolis force caused by the rotation of the earth and consequently the inertial forces of the airflow (wind) to trace a circular motion and friction forces on the ground. The kinetic energy of the wind is

$$E_k = \frac{1}{2} m U^2, \tag{2.1}$$

where *m* is air mass and *U* is the wind velocity.

The pressure created over the surface in normal direction is kinetic pressure

$$p_k = \rho \frac{U^2}{2}, \tag{2.2}$$

where ρ is air density and *U* is wind velocity. This pressure causes the force that is defined as

$$F_p = -\frac{1}{\rho} \frac{\partial p_k}{\partial n}, \tag{2.3}$$

Where *n* is normal in the direction of wind moving with velocity *U.* The streamlines are parallel to constant pressure lines (isobars). $\partial p_k / \partial n$ is the defined pressure gradient in the normal direction to the constant pressure lines (isobar lines).

Coriolis force over mass unit is defined as

$$F_C = U 2\omega \sin\theta = Uf, \tag{2.4}$$

where, $2\omega \sin\theta = f$, ω *is* the angular velocity of the earth, and θ is the earth's latitude. That means that Coriolis force influences wind velocity as well as the earth's latitude, where the wind turbine is paced. The Coriolis force is perpendicular to the direction of the air's movement. The resulting force is parallel to the isobars and it is often called "geostrophic wind". The magnitude is U_g that is a function of resulting force and could be given as

$$U_g = -\frac{1}{f\rho} \frac{\partial p_k}{\partial n}. \tag{2.5}$$

The above equation is valid as an ideal example of an area with high and low pressure atmosphere. It is assumed as a circular or elliptic form of curves (isobars) with constant

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pressure. The pressure decreases in a radial direction. The resulting wind or its velocity is called "gradient wind", which would also be parallel to the isobars, as a result of forces being compensated:

$$\frac{U_{gr}^2}{R} = -fU_{gr} - \frac{1}{\rho}\frac{\partial p_k}{\partial n}, \tag{2.6}$$

or arranged

$$U_{gr} = U_g \frac{U_{gr}^2}{fR}. \tag{2.7}$$

A final force on the wind is due to friction at the earth's surface that exerts a horizontal force upon the moving air, the effect of which is to retard the flow. This force decreases as the height above the ground increases and become negligible above the boundary layer. Friction at the surface causes the wind to be diverted more toward the low-pressure region. In order to exactly determine wind velocity, air flow turbulence must also be considered. Turbulence refers to fluctuations in wind speed on a relatively fast time-scale, typically less than 10 minutes. The turbulence intensity is a measure of the overall level of turbulence. It is defined as

$$I_{turb} = \frac{\sigma}{\overline{U}}, \tag{2.8}$$

where σ is the standard deviation of wind speed variations about the mean wind velocity $\overline{U}$, usually defined over 10 min. or one hour. Locally turbulent wind velocity variations can be considered with a Gaussian (normal) distribution, but the tails of such distributions may be significantly non-Gaussian. Therefore, this approximation is not reliable for the estimation of (for example) the probability of a large gust within a certain period. In practice, the turbulent intensity is simply estimated to be 20%.

2.1 Mean and Mode of Weibull Distribution for Wind Velocity

The mode of a Weibull distribution is:

$$Mode = A\left(\frac{k-1}{k}\right)^{1/k} \tag{2.9}$$

$$Mean = \overline{U} = A\Gamma\left(1 + \frac{1}{k}\right) \tag{2.10}$$

$$Variance = \sigma^2 = U^2\left(\frac{\Gamma\left(1+\frac{2}{k}\right)}{\Gamma^2\left(1+\frac{1}{k}\right)} - 1\right) \tag{2.11}$$

where *A* determines the scale (scale factor), *k* is the shape factor, Γ(x) is the gamma function; if x is an integer, then Γ(x)=x!

Computations of *A* and *k* give means, and variance requires approximations:

$$k = \left(\frac{\sigma}{U}\right)^{-1{,}086} \tag{2.12}$$

$$A = \frac{U}{\Gamma\left(1+\frac{1}{k}\right)}. \tag{2.13}$$

Equation (2.12) gives a good approximation when k is in the range ($1 < k < 10$). Some examples that contain sample values of mean and mode are given in Table 2.

Table 2: *Mean and Mode of a Weibull Distribution for Different Shape and Scale Factors.*

K	A	Mean	Mode
1	8	8.000	0.000
1.5	8	7.222	3.846
2	8	7.090	5.657
2.5	8	7.098	6.522
3	8	7.144	6.989
1	10	10.00	0.000
1.5	10	9.027	4.807
2	10	8.862	7.071
2.5	10	8.873	8.152
3	10	8.930	8.736

2.2 Power Density

Power density is an issue that helps us to understand the impact of the statistical distribution of wind velocity on power generation. Power density, when the statistical distribution is considered, is defined as

$$PD = \int_0^\infty \frac{1}{2}\rho U^3 pd(U)dU, \tag{2.14}$$

where $pd(U)$ is the Weibull probability density function. Some examples of Power Density calculations are given in Table 3.

Table 3: *Some examples of Power Density calculations.*

Average Wind Velocity [m/s]	Power Density [W/m^2]
3	32
5	146
7.5	494
10	1170

2.3 Air Density as a Function of Elevation

With increased elevation, air density decreases, as a consequence of air pressure. Air pressure changes with elevation

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$$p = p_0 \left(1 - \frac{Lh}{T_0}\right)^{\frac{gM}{RT}}, \tag{2.15}$$

where p_0 is 101.325 Pa (air pressure at sea level – 0 m a.s.l.), L is the temperature lapse rate, which is 6.5 K/km, h is the elevation form sea level in [km], g is gravitational constant ($g=9.80665\ m/s^2$), M is the molecular weight of dry air in grams (28.9644 g/mole), and R is the general gas constant (8.31432 J/mole K).

Air density could be calculated as a function of elevation

$$\rho = p \frac{1}{R(T_0 - Lh)} \frac{M}{1000}. \tag{2.16}$$

Table 4: *Air Density as a Function of elevation (Dry Air)*

Elevation [m]	**Air Density [kg/m^3]**
0	1.224999
5	1.224411
10	1.223824
50	1.21913
100	1.213282
150	1.207456
200	1.201651
250	1.195867
500	1.167268
1000	1.111642
1500	1.058067
2000	1.0058067

From Table 3 it is obvious, that density change is up to 17.8% between 0 and 2000 m. The same could be concluded for the power, since the density is proportional to power.

2.4 Air Density as a Function of Humidity

The molecular weight of dry air is 28.964 g/mole. If vapour is added to air, water (H_2O) of molecular weight 18 displaces heavier molecules in dry air. Therefore, moist air is lighter and has lower density, and delivers less power. The difference is smaller than changes of elevation. From zero to 100% humidity, air has a density change of less than 0.6%. This is so small that it can be considered negligible.

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3 WIND ENERGY AND POWER

A basic concept was developed by the German physicist Betz, today known as Disc Theory. The best way to explain wind energy and power is to start with the kinetic energy of air flow, from equation (2.1). It is convenient to think of a mass in a cylinder of air in radius *r*. The mass in cylinder of length U (one meter) and *r* is amount of mass that will pass through the impeller per second. Therefore, it is convenient to use mass per second $\dot{m}$, directly giving the power (energy/time = power). Equation (2.1) becomes

$$\dot{E} = \frac{1}{2}\dot{m}U^2, \tag{3.1}$$

where mass flow is

$$\dot{m} = \rho A U, \tag{3.2}$$

and where *A* is the cross-section area of cylinder. Energy per second, as mentioned, is the same as power

$$P = \frac{1}{2}\rho AUU^2 = \frac{1}{2}\rho AU^3. \tag{3.3}$$

The above equation is often defined as ideal power of wind kinetic energy. Equation (3.3) shows that the power of wind increases with cube of wind velocity *U* and linear with actual cross-section *A*. For HAWT, $A=\pi r^2$, where *r* is the radius of the rotor, and therefore

$$P = \frac{1}{2}\rho\pi r^2 U^3 \tag{3.4}$$

As it is known, the Betz limit, reduce this ideal power to

$$P_{Betz} = c_p \frac{1}{2}\rho\pi r^2 U^3, \tag{3.5}$$

where C_P is the Betz coefficient that is derived as

$$\frac{Max\ power\ extracted}{Power\ avilable} = 0.593. \tag{3.6}$$

3.1 Example of HAWT

As an example, we consider the HAWT (horizontal axis wind turbine) with a 1.128 m diameter (cross-section A = 1m^2). The available wind power, estimated with equation (3.5), in the range up to 45 m/s, is given in Figure 3. An area is shown where, due the high wind, velocities might be used. At these wind velocities (above 25 m/s), the flow around the blade profile surface starts to separate from the profile surface. At these conditions, the lift force at the profile drops and consequently the power at the turbine runner decreases. The challenge, however, is that these wind velocities are very interesting in the coastal region of Slovenia, where (as mentioned) a wind called the Burja blows. Therefore, it would be advisable to develop specific types of wind turbines, which would be able to take advantage of the available winds in this range. The solution probably lies in the development of multi-stage turbines that would exploit the available wind velocities in stages, similar to in turbo-compressors but in the opposite direction.

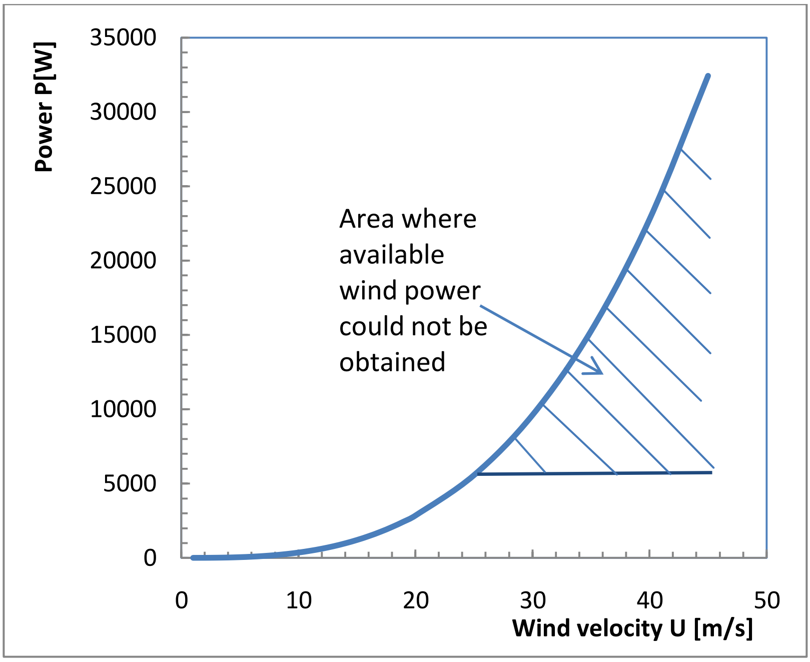

Figure 3: *Available wind power, depending on wind velocities.*

4 CONCLUSIONS

With wind power, even in Slovenia, electricity could be produced in an environmentally friendly way. This could be achieved by taking advantage of already degraded areas, such as land along roads, railways, industrial areas, bridges, viaducts etc., thus preventing additional damage to the environment. In all these areas, we already have accessible electrical grids, so new wind turbines could be included in the electricity network system in a relatively straightforward manner.

In Slovenia, there are companies that are able to be integrated into the complete production cycle, not only in the development and construction of wind turbines. This would mean new high-quality jobs for Slovenia, in the present economic crisis. Furthermore, non-refundable subsidies could be obtained, thus accelerating the momentum of this production in Slovenia.

Independent production of wind turbines, with accompanying new original technologies would certainly mean a greater recognition of Slovenia in the world, including in the technological and scientific development areas, which would bring us closer to the most technologically well-developed countries.

To meet the Kyoto environmental/climatic goals, Slovenia has to increase the share of green-energy up to 25% of its consumption. This requirement will be very difficult to achieve without installing wind farms in Slovenia.

For the long term of sustainable energy supply, the only realistic way in that direction is to cover energy needs using renewable resources. Therefore, the construction of wind farms cannot be a question of community acceptance or environmental objections.

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MEASURING WIND RESOURCES

MERJENJE VETRNE KARAKTERISTIKE

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Keywords: wind resources, wind turbine, wind speed, wind direction, air temperature, relative humidity, anemometer, wind wane

Abstract

Starting a wind farm, like starting any other business, requires a significant amount of research, start-up capital, and development before the first turbine begins to spin. If we know what to expect before we begin, the project will run more smoothly. Specialized services of consultants, contractors, and legal representatives are necessary to avoid problems that could end the operation before it starts.

Professional wind measurement, and its accuracy and reliability are thus very important in predicting economic viability before starting a wind farm (projecting), as well as in monitoring already-installed wind farms (verifying).

Even a small change in the wind speed in a particular area can significantly affect the power yield efficiency of the wind turbine. Therefore, for the prospective development of a wind turbine, it is important to consider the wind resources and information on how regularly the wind blows, the direction of the wind, variations in wind speed and so on. On the basis of this information, performance control mechanisms are integrated in the wind turbine.

Before the installation of a wind farm, analyzing the space professionally is recommended. The collected meteorological data should accurately describe the wind potential of the space. This is

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why the measuring systems should meet the highest quality demands in terms of accuracy and reliability.

We have therefore decided to develop system equipment for measuring wind resources. This paper describes the basic properties of the measurement technique and our approach for measurements, data collection, and data mining.

Povzetek

Vzpostavitev vetrne elektrarne zahteva številne raziskave, zagonski kapital in razvoj preden turbina prične s svojim obratovanjem. Zato je že pred samim začetkom pomembno postaviti jasne zahteve in želene cilje. Pri tem si pomagamo s kvalificiranimi strokovnjaki in pravnimi zastopniki.

Zaradi tega so meritve vetrne karakteristike ter njihova natančnost in zanesljivost zelo pomembne, tako za napoved ekonomskega dobička pred postavitvijo (predvidevanje) kot tudi za poznejše spremljanje že nameščenih vetrnih elektrarn (preverjanje).

Že najmanjša sprememba v hitrosti vetra na določenem področju lahko v veliki meri vpliva na učinkovitost vetrne turbine. Zato so pri postavitvi vetrne turbine pomembne informacije o tem, kako redno piha veter, v katero smer, razlike v hitrosti vetra, temperatura in vlaga zraka. Na osnovi teh podatkov se izbere ustrezna vetrna turbina.

Pred postavitvijo vetrne elektrarne je priporočljivo analizirati želeno mesto postavitve. Iz izmerjenih meteoroloških podatkov je potrebno natančno opisati vetrni potencial (karakteristiko) mesta. Zato morajo merilni sistemi izpolnjevati najvišje kakovostne standarde v zvezi z zanesljivostjo in točnostjo.

Zato smo se odločili, da bomo razvili merilno opremo za merjenje vetrne karakteristike. Članek v nadaljevanju opisuje osnovne lastnosti merilne opreme in naš pristop k merjenju.

1 INTRODUCTION

Monitoring climate change and global agreements on influencing climate change with the use of renewable energy sources have led to an increased global trend in the research of new energy sources. Renewable energy sources include solar energy, wind energy, water energy and biomass with geothermal energy.

The EU's environmental policy is the first important step in reducing greenhouse gas emissions and thus establishing global balance. The main objective of the Kyoto protocol is the commitment of the signatory states to reduce their emissions in the 2008–2012 period by at least 5% in comparison with the year 1990. However, the EU has set an even more ambitious goal of reducing the emissions in its member states by 8% in that period; moreover, in 2007 this target was expanded to reducing emissions by 20% by the year 2020 [1].

Today much work is directed into use of solar-cell energy, biogas and biomass, and small hydro-electric power stations, but very little into wind farms. Before investment, it is necessary to acquire information on wind resources for an individual area, which would justify building a wind farm. In practice, there is a general standard area map (the data of meteorological centres and nearby airports), but measurements must be done for each individual micro-location.

The efficiency of wind farms depends on the suitability of the location and its windiness. The wind potential is a selective factor in searching for appropriate locations for establishing and operating wind farms.

Wind farms, in comparison with other power-generation technologies, undoubtedly best fulfil the ever stricter criteria of sustainability development. Eliminating the negative consequences caused by greenhouse gases in recent decades is one of the priorities not only of environmental organizations, but also governments, local authorities and least but not last economic operators [2].

2 OBJECTIVES

A study of the geographical distribution of wind resources on a certain micro-location (topography, local wind flow, wind speed) must be conducted for the successful and economically justified operation of a wind farm. To acquire the characteristics of a certain micro-area, it is necessary to carry out measurements on a larger area [3]. The initial measurement area is selected on the basis of the existent meteorological data. This area can be fairly large, even encompassing a whole state. The process of selecting the initial location is directed to the most appropriate areas, with regards to efficiency. The existent wind data and analyses of topographical maps can be of help in this. Throughout the measurement time, we monitor the data of certain points. If any of the measured areas' data are particularly negative, we move the point to another location.

To measure wind resources, a data-capture system is needed. This is an independent, autonomous, and affordable measuring point. It consists of watertight housing with an appropriate IP protection, CPU with a memory to store the measurements, communication (usually GPRS), sensor input, internal battery and a solar cell.

The data-capture system provides advanced functionalities; it is easily installed in the field and is in a low-energy-consumption mode most of the time. The solar cell enables complete autonomy, meaning that the system can be installed in places with no external power supply. Captured data are stored in internal memory and sent to the collection centre at predefined time intervals. The data are sent with an internal GPRS modem. The internal battery enables the operation of the device, and is charged by the connected solar cell. The system thus enables continuous remote control of the device and the corresponding sensors.

The main goal of the measurement is determining potential windy areas. The following useful data are also acquired with measurements:

- identification of potentially windy areas,
- shortlist of candidate areas,
- selection of actual locations for establishing measuring points.

3 EXPERIMENTAL STATION

The basis for monitoring wind resources is collecting data on wind speed and direction, and air temperature and humidity. These data are basic for acquiring key information needed to assess the reasonableness of establishing a wind farm.

This article further presents the basic measured quantities with the corresponding sensors and their technical characteristics [7].

3.1. Wind speed

Wind speed data are the most important indicator of a site's wind energy resources. Multiple measurement heights are encouraged for determining a site's wind shear characteristics and conducting turbine performance simulations at several turbine hub heights [4].

A cup anemometer is the most commonly used type for the measurement of near-horizontal wind speed. The instrument consists of a cup assembly (three cups) centrally connected to a vertical shaft for rotation; at least one cup always faces the oncoming wind. The aerodynamic shape of the cups converts wind-pressure force into rotational torque. The cup rotation is nearly linearly proportional to the wind speed over a specified range. A transducer in the anemometer converts this rotational movement into an electrical signal, which is sent through a wire to a data logger. The data logger then uses known multiplier and offset constants to calculate the actual wind speed.

We used a model **PA2** cup anemometer with two pulses per revolution [5].

Figure 1: *PA2 cup anemometer*

The PA2 lightweight cup anemometer is based on the Hall effect principle. The measuring range is 0 to 60 m/s with a threshold of 0.5 m/s, two pulses per rotation and 67 pulses at 30 m/s. The PA2 is an affordable high quality cup anemometer with ceramic magnets, and stainless steel bearings and mounting hardware [5].

Table 1 shows the technical characteristics of the anemometer PA2 [5]:

Table 1: *Technical specifications of the cup anemometer PA2*

Measuring principle	Hall effect with magnets
Air velocity range	0 to 60 m/s
Threshold	0.5 m/s

Operating temperature	-30 to +70°C
Pulses	2 per rotation
Frequency	67 Hz at 30 m/s

3.2. Wind direction

Wind direction information is important for identifying preferred terrain shapes and orientations, and for optimizing the layout of wind turbines within a wind farm [4].

A wind vane is used to measure wind direction. The vane constantly seeks a position of force equilibrium by aligning itself into the wind. It uses a potentiometer-type transducer that outputs an electrical signal relative to the position of the vane. This electrical signal is transmitted via wire to a data logger and relates the vane's position to a known reference point (to the true north). Therefore, the alignment (or orientation) of the wind vane to a specified reference point is important.

The data logger provides a known voltage across the entire potentiometer element and measures the voltage where the wiper arm contacts a conductive element. The ratio between these two voltages determines the position of the wind vane. This signal is interpreted by the data logger system, which uses the ratio and the offset to calculate the actual wind direction.

We used a model PRV wind vane with 5 kOhm potentiometer output [5].

Figure 2: *PRV Wind vane*

Figure 2 shows a lightweight, long-life potentiometer vane. The mechanical angle is 360° without a stop. The electrical angle is 350°±3° and the threshold between 1.2 and 1.5 m/s [5].

Table 2 shows technical characteristic of the wind vane PRV [5]:

Table 2: *Technical specifications of the wind vane PRV*

Life expectation	> 20 x 10^6 rotations
Electrical angle	350 ± 3°

Mechanical angle	360° without stop
Damping ratio	0.35
Threshold	1.2 to 1.5 m/s
Linearity	1%
Resistance value	5 kOhm +/-10%
Operating temperature	-30 to +80°C
Temperature coefficient	± 200 ppm/°C

3.3. Air temperature and relative humidity

Air temperature is an important descriptor of wind farm's operating environment, and it is normally measured either near ground level (2 to 3 m), or near hub height. In most locations, the average near ground level air temperature will be within 1°C of the average at hub height. It is also used to calculate air density, a variable required to estimate the wind power density and a wind turbine's power output [4].

A typical ambient air temperature sensor is composed of three parts: a transducer, an interface device and a radiation shield. The transducer contains a material element with a relationship between its resistance and temperature. The resistance value is measured by the data logger, which uses an established and accepted equation to calculate the actual air temperature. The transducer is housed within a radiation shield to protect it from direct solar radiation.

Relative humidity may be defined as the ratio of water vapour density (mass per unit volume) to the saturation water vapour density.

We used a **HTM2500LF** combined sensor model, which is an all-in-one sensor (temperature and relative humidity module in one) [6].

Figure 3: *Temperature and Relative Humidity Module HTM2500LF*

The HTM2500LF sensor is specified for accurate measurements within 10 to 95% RH [6].

Table 3 shows the technical characteristics of the sensor:

Table 3: *Technical characteristics of the sensor*

- Humidity characteristics [6]:

Measuring Range	1 to 99% RH

Accuracy (10 to 95% RH)	± 3%
Temperature Coefficient (10 to 50°C)	± 0.1% RH/°C
Hysteresis	± 1.5% RH
Long term stability	± 0.5% RH/yr

- Temperature characteristics [6]:

Measuring Range	-40 to 125°C
Nominal Resistance Tolerance @25°C	1%
Beta Value Tolerance	1%
Response Time	10 s

3.4. Communication module

Remote communication with the use of an internal GSM/GPRS modem is used for data transfer. The advantage of this method is that data can be sent at any desired time interval (depending on the settings), several times a day. This enables simultaneous data checks and fast interventions in cases of possible operation failure or incorrect measurement data. The only condition that must be fulfilled is a sufficiently strong GSM signal. If this is not present on the area, such a mode of data transfer is not possible. On the areas with poorer signal strength, additional external antennas that strengthen the GSM signal can be used.

We used a low power GSM/GPRS module. By default, it is turned off. We turned it on only a few times a day, to send logged measurement data from internal memory to the server database.

3.5. Power management

The measurement device is powered exclusively by an internal battery. The measurements are recorded on an internal flash memory. Minimal energy consumption is achieved in the low-consumption operation mode. In practice, this means that the peripheral units are turned off when they are not needed. For example, the modem is turned on only when data needs to be sent to the data server; analogous adjustments at the input of the measurement part are activated only during measurement, and the CPU is in sleep mode during measurement.

The internal battery is used as the only energy source. A connected solar cell acts as the battery charger in the part of the day when the sunlight is at the level where the solar cell can transmit the energy needed for charging. The battery is able to maintain a charge for several “dark” days, when the solar cell energy is not sufficient for charging; this occurs in winter. Because of this, the current level of the battery (voltage) is sent with every communication of the measurement device as a precautionary measure. We thus know the state of the battery at all times, and we can take the necessary steps (replace it) before its failure.

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4 MEASUREMENT SYSTEM

The minimum period for monitoring an individual micro-location is one year [8]. This is sufficient to determine the daily and seasonal variability of the wind resources. If the time period is shorter, we can make use of the reference stations' data (nearby airports, meteorological data). In this case, the wind resources of the rest of the year, which were not measured, are evaluated using the measured data and the abovementioned reference stations' data.

The data saved in the internal memory are divided into smaller packets when they are being transferred through the GPRS network, and are sent to the server in this form. Each packet is equipped with a checksum (CRC16), which enables verification of accuracy on the reception side. If the checksum does not match, a repeated transfer of the same packet is requested. When a packet with a certain number of measurements is successfully transferred to the server, it is marked as successfully sent and is deleted from the internal memory. Only then is the next packet sent. This ensures the consistency of all the sent data.

The data are sent using a TCP/IP protocol. For this, a private APN channel (a protected 3DES/IPSEC channel) is used. This ensures that the data transfer is safe, and no additional protection needs to be implemented in encrypting the sent data.

On the server, a service is installed that operates in the TCP/IP server mode and "listens" to a specified port. This means that it receives connections in parallel from several measurement stations. Simultaneous connections of measurement stations are thus enabled, regardless of their set data-transfer time intervals.

Every measurement includes the time of the measurement, and the data on the wind speed and direction, and air temperature and relative humidity. This set of data corresponds to one measurement at an exact time. The data are encoded and transferred in the RAW format. This has the advantage of all corrections and temperature compensations being done on the side of the server. It also means that the corrections can be changed later or re-implemented throughout the measurement history.

The data are saved in an SQL database. Measurements from all measurement stations are entered into the database. For accuracy, it is important that the ID of the station is also stored with every measurement. This ID is later referenced in processing, analyzing and presenting the data.

The settings of the measurement station enable setting the data-sampling time, the average-value storing time and the time of the data transfer through GPRS network to the data server. The default settings are as follows: measurement lasts 10 seconds. In this time, an averaging of one-second measured values is performed. After this, the packet is stored in the internal memory as a whole. The unit is then in hibernation mode for 50 seconds. After this, the process is repeated. Every six hours the modem is turned on, a GPRS connection is enabled, and the data is sent to the data server. After the data are successfully sent, the modem is turned off. This achieves optimal operation on the internal battery and charging of the latter on sufficiently sunny days.

An automatic remote firmware update mechanism is implemented to automatically retrieve firmware upgrades from the remote server through the GPRS network.

A web application is implemented on the server, enabling registered users to access the measurement stations' data. The data of any time interval can be viewed graphically, in tables, or they can be exported to a local file for processing in other specialized applications.

5 DATA VALIDATION, PROCESSING, AND REPORTING

When the data are delivered to the local database, they are validated, processed, and reports are generated [4].

Validating data means verification of all the measured data in terms of integrity and adequacy, and the elimination of all the incorrect values. Valid data are then used to compose the report summary needed for further analysis. This step is important with regards to data accuracy during the process of field measurement. The data are therefore monitored daily, and if any irregularities (sensor failure, erroneous measurements because of other factors, communication failure during data transfer, etc.) are found, immediate action can be taken. The sooner the irregularities are detected, the lower the chance of loosing the measured data is.

5.1. Data validation

Data are validated manually or automatically (computer-supported validation). The latter is used in the majority of cases, as it is faster and simpler; however, more time is needed in the beginning to set all the required boundary conditions and criteria.

It is necessary to understand the limitations of data validation before beginning the process. There are several reasons for incorrect data: malfunctioning or defected sensors, connectors, busses, sensor drift etc. The aim of data validation is to determine as many mistakes as possible during measurements.

To be able to further eliminate errors, we keep the initial unprocessed data (RAW data), but only calculated values are used in reports.

5.2. Data processing and reporting

When data validation is finished, the data are arranged into logical sets intended for the required report types. This includes calculation, association and sorting the measured data. The results of the processed data are type reports, tables and graphs.

6 PROTOTYPE

We have prepared a prototype that entirely realizes the above-described requirements of wind resource measurements. The used sensors are presented in the third section of this paper.

The system diagram is presented in Figure 4.

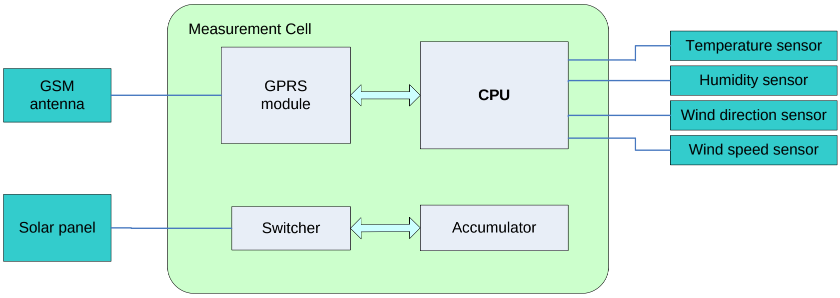

Figure 4: *Measurement cell block diagram*

The above diagram represents a closed whole in the middle, where the entire measurement part, including the battery, is closed in its housing. A type IP 66/67 housing provides sufficient protection for the internal elements. Only elements that do not belong inside the housing are outside, e.g. an antenna outside the housing ensures a better GSM signal. The solar cell is mounted above the housing and turned in such a direction that it is perpendicular to sun's rays for the longest possible part of the day. The busses going directly through the sensors are on the other side. Special attention should be devoted to fixing the sensor in the wind direction. It should be installed directly towards the north, as its output is in degrees, internally calculated to cardinal points.

For the system to provide practically useful results, several measurement points should be connected into a network and all measurements should be monitored simultaneously. On this basis, we determine wind-resources distribution on a certain area.

7 CONCLUSION

The precise assessment of wind resources on a certain area is the key element in successfully establishing an economically justified wind farm. Wind resources are normally assessed in several stages. The first stage is a general determination of windy areas using the existent data from airports, meteorological data and topographical maps. The second step is searching for a micro-location and assessing the presumed costs of installation. This includes finding the closest electricity take-up point (electric generating stations, through which the energy generated at the wind farm is distributed into the network). The third and final stage is a feasibility study, in which the measurements described in this article are performed.

The longer the period of the measurements on a certain micro-location is, the better the profile of this terrain is. This led us to contribute to this area and develop a measurement device that is completely autonomous, that performs measurements on the mentioned sensors, and that sends the data in defined time intervals to the database. These data are then used in analyzing the viability of establishing wind farms. Because of high investment costs, investment into a wind-resources assessment system is completely justified.

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UNDERGROUND COAL GASIFICATION (UCG) – THE VELENJE COAL MINE EXPERIENCE

PODZEMNO UPLINJANJE PREMOGA (PUP) – IZKUŠNJE PREMOGOVNIKA VELENJE

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Keywords: coal, gasification, underground, unconventional utilisation of coal, syngas, clean coal technology

Abstract

The energy, economic and environmental demands of 21st century favour the development of underground coal gasification (UCG). It is essential that all the previous experience and knowledge gained from the pilot and/or commercial experiments are put to use for successful commercial UCG technologies. Underground coal gasification is the unconventional (non-mining) utilisation of coal with use of injection and production boreholes from the surface that render the conversion of coal to gas. The technology assures that coal stays under the surface and the obtained mix of combustible gases is useful for a variety of purposes. UCG as a clean coal technology contributes globally to the reduction of emissions of greenhouse gases (GHG).

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Current concerns about GHG and increasing global prices gas have intensified interest in underground coal gasification.

In the USA, between 1975 and 1996, more than 30 pilot experiments on different kinds of coal were made. Before this, much research was done in the former Soviet Union: pilot and commercial projects, including a power station in Angren, Uzbekistan, that remains in service after 47 years. Since 1991, China has carried out 16 UCG experiments and has some commercial UCG projects for making different chemicals and fertilizers. In the year 2000, Australia started a controlled process of UCG production of synthetic gas; after three years they stopped it and started it again. More UCG projects are currently in different phases of development in the US, Canada, Southern Africa, India, Australia, New Zealand, Europe and in China.

In Slovenia, UCG was started at the beginning of 1980s with laboratory investigations of smaller samples and continued with test gasifying of larger blocks of lignite. Research was done on Velenje lignite and Zasavje brown coal. In 2002, a feasibility study of UCG was done in the Velenje coal mine. Because the research was interrupted, some important parts of UCG are still missing: assessment of use of process products, economic and final evaluation. We intend to find this missing knowledge and establish the possibility of UCG in the coal layer of the Velenje cavity. One very important challenge in the UCG process is utilising the cavities that remain after burning the coal for the storage of CO_2.

Povzetek

Energetske, ekonomske in okoljevarstvene zahteve 21. stoletja so v prid razvoju podzemnega uplinjanja premoga (PUP). Pri čemer je bistveno, da se vse dosedanje izkušnje in pridobljeno znanje pri že izvedenih pilotnih in/ali komercialnih poskusih čim bolje izkoristijo z namenom pridobiti uspešno komercialno tehnologijo PUP. Podzemno uplinjevanje premoga (PUP) je nekonvencionalno (ne-rudarsko) izkoriščanje premoga z uporabo injekcijske in produkcijske vrtine iz površja, ki omogočajo pretvorbo premoga v plin. Tehnologija zagotavlja, da premog ostane pod zemljo, pridobljeno mešanica gorljivih plinov pa je mogoče izrabiti v različne namene. PUP kot čista premogovna tehnologija prispeva globalno k zmanjšanju emisij toplogrednih plinov (TGP). Trenutno stanje in dogodki, ki se nanašajo na TGP in povišanje globalnih cen plina, zelo povečujejo zanimanje za podzemno uplinjanje premoga.

V ZDA je bilo v letih med 1975 in 1996 izvedenih več kot 30 pilotnih poskusov na različnih vrstah premoga. Še pred tem so v bivši Sovjetski zvezi izvedli ogromno raziskav, pilotnih in komercialnih projektov, vključno z elektrarno v Angrenu, Uzbekistan, ki še danes po 47. letih deluje. Po letu 1991 je Kitajska izvedla 16 poskusov PUP in ima nekaj komercialnih PUP projektov za izdelavo različnih kemikalij in gnojil. V letu 2000 se je v Avstraliji (Chinchilla) začel kontroliran proces PUP s proizvodnjo sintetičnega plina, ki so ga po 3. letih ustavili in ponovno zagnali. Trenutno poteka več projektov PUP, ki so v različnih fazah razvoja, v ZDA, Kanadi, Južni Afriki, Indiji, Avstraliji, Novi Zelandiji, Evropi in na Kitajskem.

V Sloveniji se je PUP pričelo v začetku 80-ih let z laboratorijskimi preiskavami manjših vzorcev in nadaljevalo s poizkusnim uplinjanjem večjih blokov lignita. Raziskave so se nanašale na velenjski lignit in zasavski rjavi premog. Leta 2002 je bila narejena študija izvedljivosti PUP v Premogovniku Velenje. Ker so bile raziskave v nadaljevanju prekinjene, še vedno manjkajo nekateri pomembni deli PUP, kot so: ocena uporabe produktov procesa, ekonomska in zaključna ocena. Navedene manjkajoče sklope nameravamo dopolniti in tako utemeljiti možnost PUP v premogovem sloju velenjske kadunje.Zelo pomemben izziv pri procesu PUP je tudi izkoriščanje nastalih votlin po izgorevanju premoga za skladiščenje CO2.

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1 INTRODUCTION

The possibilities for the application of UCG are increasing throughout the world. The reason for this is found in the current energy and financial crisis. According to the best data, globally there are approximately 1.7 Gt of coal reserves and resources are still not mined and potentially reachable through UCG. This possibility can represent a reliable fuel supply in future. The concept of the UCG process is simple: *in situ* coal combustion in a mixture of air/oxygen with some steam. The product is a synthetic gas, whose main component parts are hydrogen and carbon monoxide; the others are the hydrocarbons, H_2S, CO_2, tar and other dirt, depending on coal composition. The possible uses of synthetic gas are various, from power generation to chemicals to diesel fuel.

***Figure 1**: UCG scheme with possible structures on the surface*

The UCG concept may be simple but the control of the formation of gas with consistent qualities and quantities while simultaneously minimising environmental impact is highly complex. Therefore, UCG requires a multidisciplinary approach of knowledge in geology, hydrogeology, drilling, engineering, chemistry and the thermodynamics of the gasification reactions occurring in the cavity where the coal is burning.

In the US, more than 30 pilot UCG tests were done in different coal types from 1975 to 1996. Before that, in the former Soviet Union, many research projects, pilot tests and commercial projects were made, including the still-operating power plant in Angren, Uzbekistan. In China, 16 UCG tests have performed since 1991, and some commercial UCG projects for different chemicals and fertilizers production are in progress. In Chinchilla, Australia, a controlled UCG process began in 2000, producing synthetic gas. This process was put on hold after three years and started again. At present, several UCG projects in different development phases are running in the USA, Canada, South Africa, India, Australia, New Zealand, Europe and China.

2 UCG POSSIBILITIES

In principle, all UCG requires are two boreholes (so-called wells: injection well and production well) that are drilled into the coal seam at a certain distance and are then connected, to establish the gasification circuit (the possibility of gas flowing from one well to another). Both boreholes can be vertical or inclined, partly made in seam by guided drilling; it is also possible to use the underground passages in mines (Chinese prefer this method). Through the injection well, air/oxygen and steam are introduced, while the synthetic gas exits through the production well. In the previous 20 years, major progress has been made with directional drilling techniques and in-seam guided drilling.

Many factors affect the UCG process, including the characteristics of coal and adjacent rock, the geological and hydro-geological characteristics of the deposit, operating conditions, quantity and composition of the synthetic gas, process efficiency and interaction with the environment (pollution and subsidence).

The main differences between underground gasification and gasification on the surface are simultaneously advantages and disadvantages of either process:

- **on the surface**, the reactions take place in a closed reactor, in which it is possible to control and measure the pressure and the temperature and to add coal and oxidants. In this way, the composition and quality of the products is controlled and exact.
- **underground**, the shape and location of the reaction zone (reactor, cavity) is changing constantly and the measurements and control of the operating conditions is not as accurate as on the surface. During UCG, coal combustion occurs and cavities begin, while thermal deformations affect the adjacent rock. The reaction can move into different parts of the seam where this shifting is not predictable or controllable. A portion of the gas products can migrate (escape) from the reaction zone into surroundings (gas losses); furthermore, underground water can flow into the reaction zone. It is not possible to control the water inflow totally, as aquifer characteristics can change. One possible way of controlling the water inflow partly is using pressure control.

Some other UCG advantages compared to conventional mining and additional coal use in power plants are as follows (Burton et al., 2006, Bowen, 2008, Friedmann et al., 2007):

Economic advantages:

- Operating costs of UCG are minor, as there are no excavation costs, transport costs, fly ash depositing etc.
- Minor capital costs, as no boiler on surface is needed.
- Major flexibility of synthetic gas use: power generation, chemicals production, fuel production, H_2 etc.

Environmental advantages:

- Most ashes remain underground, minor emissions of Hg and other heavy metals, SO_X and NO_X; therefore, less gas cleaning needed.
- Minor CO_2 emissions.

CO_2 treatment:

- Minor CO_2 separation costs.
- Potential possibility for CO_2 storage in extinct reactors and adjacent rocks.

The obstacles for commercial UCG development are as follows (Couch 2009):

- Operating risks due to the lack of large-scale UCG trials and the many problems occurring during tests in the USA and western Europe.
- Unreliability of the UCG process with regard to environmental impacts.
- Public scepticism.
- Lack of precise criteria or recommendations for the selection and characterisation of the gasification site.

3 UCG TEST REVIEW

UCG tests throughout the world have been made at different operating conditions in different coal types, at different depths and in different thicknesses of coal seams, as can be seen in Diagram 1. All of these tests show how the variations in geological setting, hydro-geological conditions, coal composition, and UCG process realisation affect the process control, dirt transport, economy of the process, environment and people's health.

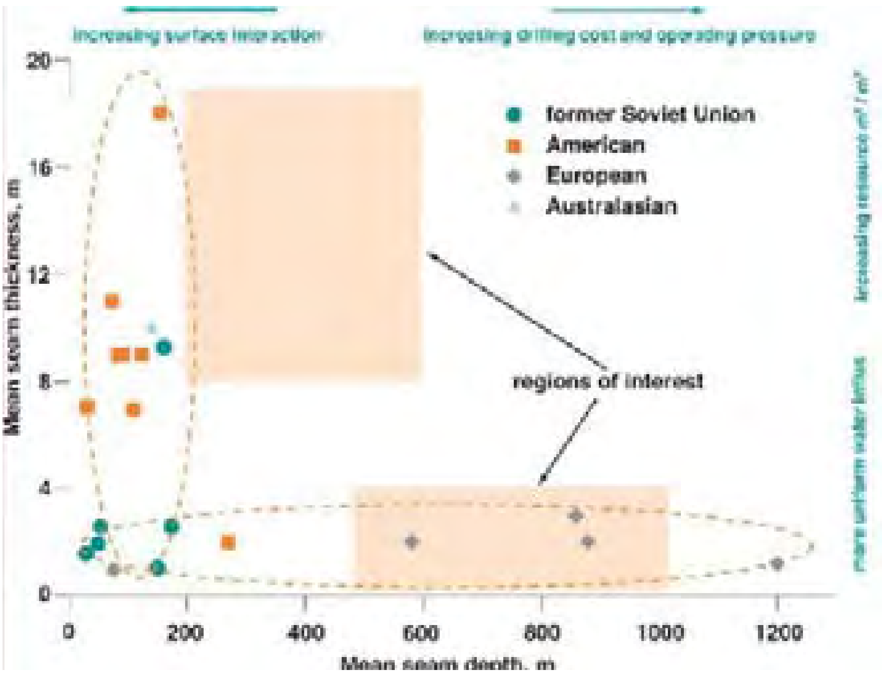


***Figure 2**: UCG experience worldwide*

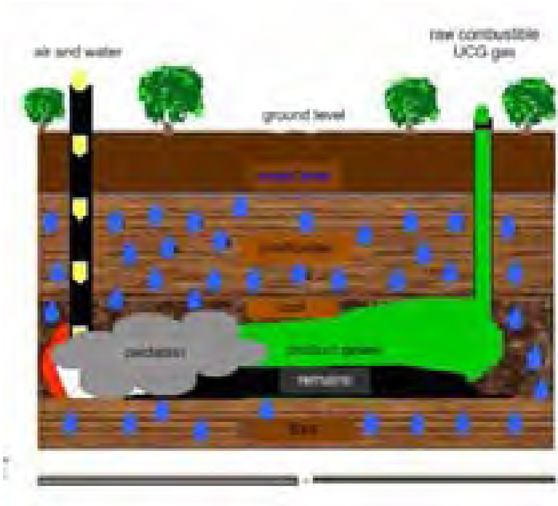
The very different conditions in which individual tests took place must mean that any generalisation of the results is not acceptable and could even be dangerous; therefore, the results of each test can only be treated as specific to its own conditions. All the tests were small scale ones, and not one resulted in a commercially acceptable technology that would meet all environmental requirements (Couch 2009). The amount of all the gasified coal is insignificant: between 15 and 20 Mt. Many tests were realised in shallow deposits (less than 100 m deep), which is not the target depth for commercial UCG development. The pressure that can be reached in the reactor and the possibility of gas migration (escape) limits these processes in shallow deposits.

Table 1: *Amount of the gasified coal and estimated UCG test costs.*

Former Soviet Union	More than 15 Mt after 1950 and 10 x 10^9 USD of estimated costs
USA	50,000 ton since 1970 and 300 M USD of estimated costs
Europe	Less than 10,000 tons since 1950 and 100 M USD of estimated costs
Australia	More than 32,000 tons between 2000 and 2002 and 5 M USD of estimated costs

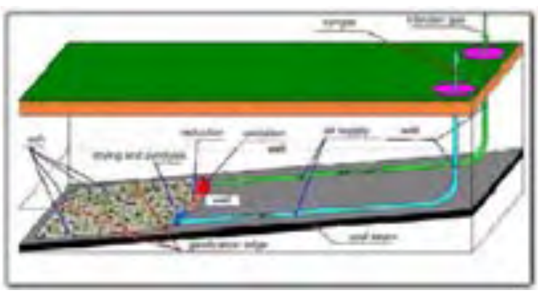
For UCG, four main methods are known; these methods are a foundation for further development (Couch, 2009, Courtney, 2008, Green, 2008) – Fig. 3.

- The Soviet method now includes an ERGO Exergy method and is based on vertical wells using hydraulic fracturisation combined with retractable ignition to restore the connection between injection and production wells. Currently, this method is used in Majuba, South Africa and Chinchilla, Australia.
- The parallel method uses several parallel vertical wells, which are connected by in-seam boreholes.
- The CRIP (controlled retraction injection point) method also connects the in-seam borehole with vertical wells but the essential element is burner retraction through an injection borehole in the entry direction.
- The Chinese method of long underground passages is especially adapted for abandoned mines.

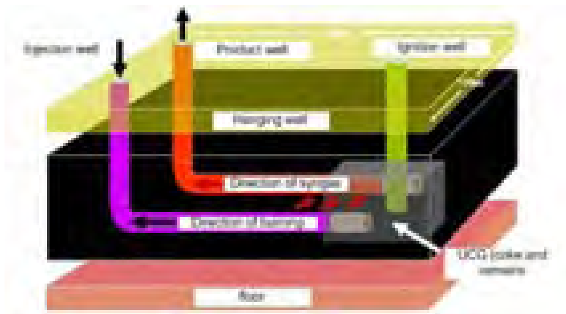


Parallel wells method (εUCG)

CRIP



Chinese long channel method



Configuration used in EU trials

Figure 3: *Main UCG methods*

The test results can be summarised into some general statements (Couch, 2009):

- Substantial gas losses occur with tests in shallow depths.
- Underground water pollution possibilities are major with tests in shallow depths.
- Coals of lower rank (lignite, sub-bituminous) are more permeable and reactive as the higher rank coals (anthracite, bituminous) affect the borehole connection.
- Coals of lower rank are softer, which affects the borehole stability.
- Coal deposit depth is the key factor that affects the operating pressure in the reaction chamber, especially if the whole process requires this pressure to be slightly lower than the hydrostatic pressure, so the water can come in the reaction chamber and not into aquifers.
- Introduction of the oxygen into the reaction chamber can raise the calorific value of the synthetic gas.
- The procedure of gasifier closure has also been introduced. The reactor chamber is cleaned or washed with water after the extinction of burning, just to avoid the precipitation of some contaminants.

The UCG technology is still not commercially viable in spite of many statements, methodologies, suggestions, monitoring techniques etc. Commercial viability should be reached in next 5 to 10 years as many tests are currently running worldwide (South Africa, Australia, India, USA, China etc.). The most promising results come from Chinchilla, Queensland, Australia, where Linc Energy Ltd. is has been running its third UCG test (March, 2009, Green Car Congress). According to reports, the results are very encouraging. It is important to mention that they are connecting the UCG process to CTL (coal to liquid) process for commercial reasons.

3.1 Findings from some UCG tests

In the former Soviet Union, some UCG tests were described as commercially viable but (according to reports) several problems emerged, including gas loss, low gas calorific value, underground water pollution. Many tests were economically unsuccessful. Some bituminous coals were successfully gasified, but some swelled during heating and this reduced the connection between boreholes.

In the deeper deposits, higher ranking coals usually occur. In such deposits, coal seams are usually thinner and therefore the connection between wells is made by in-seam guided drilling. This technology is expensive and the drilling costs are thus higher. In deeper deposits, the pressure is higher but – at the same time – the possibilities for potential aquifer interactions and consecutive contamination of the underground water are minor. The composition of the synthetic gas changes at higher pressures; this increases the calorific value of the synthetic gas. The majority of European tests were done at depths of more than 500 m.

The calorific value of gasification products from shallow deposits, gasified with addition of air, reached from 4 MJ/m^3 to 6 MJ/m^3. Synthetic gas from deeper deposits reached from 12 MJ/m^3 to 14 MJ/m^3 (Couch, 2009). The UCG process is highly suitable for the coals with higher ash content, because the ash remains underground and needs no further treatment. Very few tests were done on lignite and none in thick seams where the underground gasifier control would be difficult.

Due to the realisation of UCG tests in different coal types, the test results are too diffuse to be suitable for reliable conclusions. While it can be said that it is possible to gasify all coal types, some specific conditions require a specific UCG method.

4 CO_2 TREATMENT

The commercial use of CCS technologies (carbon capture and storage) or the price of emission coupons will essentially affect the competitive position of energy producers in EU as in Slovenia. As may be foreseen, locations with cheaper CCS will gain long term advantages. Therefore, a very important challenge for the UCG process is to make use of the extinct cavities, left after gasification, for CO_2 storage.

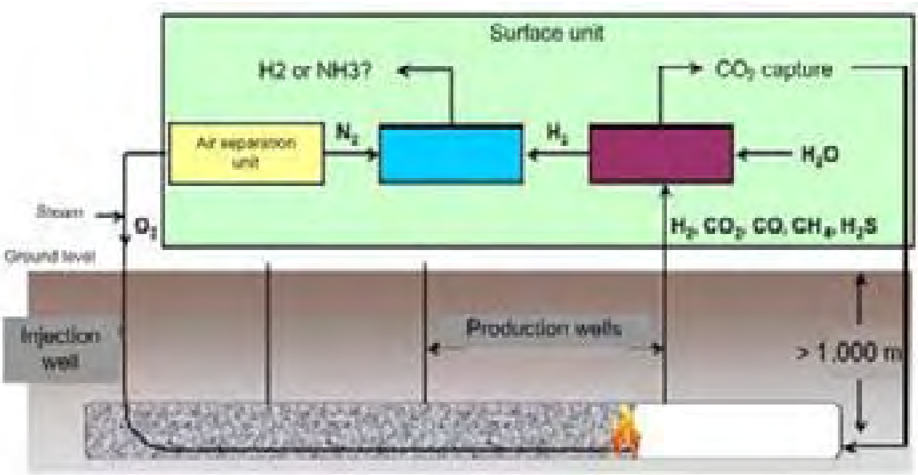


***Figure 4**: UCG and CCS*

CO_2 is also a component part of the synthetic gas, but well-known technologies enable its separation. In cases where only oxygen or oxygen/steam mixture is introduced into the gasifier, the CO_2 separation is much simpler, as there is no gas diluting nitrogen present in the synthetic gas. First, the sulphur compounds and solid particles are removed and then the CO_2 is captured. The CO_2 is then transported and stored under pressure (usually under supercritical conditions) for hundreds or even thousands of years. Storage possibilities include deep aquifers, oil deposits, depleted natural gas and coal deposits, and oceans. Some research has been done on the suitability of extinct cavities left behind after UCG process, but this has yet to be proved practical from the commercial point of view.

Considering the legislative background of UCG and CCS, the present knowledge of legislative requirements for the implementation of these technologies on a large scale is insufficient. The right move in this direction would be a directive on geological CO_2 storage, but the majority of work on this still has to be done.

Shallow UCG processes (less than 500 m) require greater rock volume between the gasifier and storage cavity to prevent mass transfer as seen in Figure 5.

***Figure 5**: CCS at shallow UCG*

The possibility of CO_2 storage should form a vital part of the evaluation and selection of UCG locations since the same research is important for both: geophysics, drill core analyses, borehole depth etc. The advantages and disadvantages of CO_2 storage in extinct cavities are discussed in continuation.

The first advantage is the known capacity; with UCG, a rather big cavity occurs (5 m to 8 m diameter) between wells. Coal gasification between wells at 300 m distance would form a cavity of 6,000 m^3 to 15,000 m^3. If only 50% of the cavity would be accessible (because of roof or wall collapse) at a supposed depth of 1,000 m (standard geothermal grade 30°C/km) it could host between 1,700 t and 4,500 t of CO_2 (Burton et al., 2006).

The next advantage is the physical properties of the coal. The CO_2 gas is absorbed into the porous coal structure and the coal swells. Coal swelling means relatively quick pore and fracture sealing and therefore a reduced possibility of CO_2 migration (escape). At the same time, there are remains of coal, coke and ash in the cavity, representing a vast specific surface appropriate for CO_2 adsorption (Upadhye et al., 2007). An impermeable roof stratum of the cavity is also a very favourable characteristic as the potential CO_2 migration (escape) is neutralised.

The third advantage is the existent equipment at the site (wells, gas separation unit etc.) diminishing CCS costs.

As a disadvantage, the cavity stability is compromised because of various impacts: heating, watering, roof or wall collapse etc; all of which are almost impossible to evaluate or even measure before the CO_2 storage begins.

The next disadvantage is a reaction of CO_2 with water in which a weak carbon acid results and then reacts with coal, coke or ash and forms sulphuric acid. These acids can precipitate into adjacent rocks, leaching metals and other dangerous chemicals into underground water. Volatile organic components (VOC), e.g. benzene, dissolve in CO_2 and enter the environment. Such processes increase the danger of underground water contamination.

As injecting CO_2 into the coal seam causes vast changes in temperature, pressure, pH value, concentration of separate components, coal permeability, porosity and reaction kinetics, these

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changes should be carefully studied and their environmental impact well known, controlled and monitored (Burton et al., 2006).

5 UCG IN SLOVENIA SO FAR

In the late 1950s and early 1960s, a study on UCG possibilities in lignite deposits of the former Yugoslavia was completed at the Chemical Institute in Ljubljana (Kemijski inštitut Borisa Kidriča). For gasification experiments, the pressurised Luirgi procedure was adopted, using a copy of a gasifier by the Birmingham Station of the Gas Council. The gasifier capacity reached 50 bar and 900°C. Oxygen and CO_2 or their mixture was the gas reagent. Lignite samples were previously partly dried or semi-coked or activated with a $ZnCl_2$ solution. The calorific value of the synthetic gas reached round 16 MJ/m3 in spite of high moisture content and high ash value (Eberl, 1983). In continuation the study by Chemical Institute, in 1960 the Bureau of Industry discussed the integral role of lignite from the Velenje deposit in the power supply of Slovenia and the possibility of lignite gasification and gas production as a substitution for lower quality generator gas for industrial needs, bigger cities and local markets. The commercial part of the study included an argument for technological alternation from thermal power plant to more efficient and cleaner gasification procedures.

In the 1960s, the technological program for lignite refining included procedures of raw lignite drying and gasification for transportable gas production. One part of the dried lignite should be semi-coked. In 1967, widespread investment was suspended, but the debt settlement lasted for many years (Repe, 1994).

6 FIRST LABORATORY TESTS

For the first laboratory gasification tests in the 1980s, both, minor sample quantities (5 kg – Levec, Berčič, 1984) and a larger diameter (50 cm) coal block (composed of five pieces) were treated. As the contact surfaces were not even, a gypsum layer filled the gap (Berčič, Levec, 1985). The findings of these tests show that a uniform coal lump is necessary for the study of the influence of single UCG parameters on cavity growth and gas composition.

For the next test at the Chemical Institute, in 1986, bigger blocks were prepared from pressed lignite debris (average grain size 1 cm). The cylindrical coal block measured 80 cm with a 50-cm diameter. For the experiment, a constant molar rate, with steam:oxygen = 1:1 was chosen; the experiment lasted for 250 minutes. Combustible gases concentrations were simulated: high hydrogen content (circa 50 mol%), high carbon monoxide content (between 12 mol% and 15 mol%), relatively low but constant methane concentration (2 mol%). The average calorific value of the synthetic gas reached 11.5 MJ/m^3 (Berčič, Levec, 1986). In the UCG process, the cavity growth and its shape is very important. It is impossible to monitor the cavity growth during the process but observation can be made afterwards. One layer after another was carefully removed and single stages photographed and measured. The vertically formed walls were smooth and the boundary between the slag and pyrolised coal was very sharp. The slag filled almost the whole cavity; only a small part under the top was partly empty (Berčič, Levec, 1986).

In 1987, more gasification experiments of pressed lignite were done, using 110 cm long cylinders with 50 cm diameter and various oxygen:steam ratios. A borehole with a 1.2 cm diameter served as a connection to establish the gasification circuit. A specially constructed feeding and ignition unit introduced the mixture of propane and butane gas and oxygen into the borehole and provoked the ignition. The reliable sign of successful ignition was the temperature rise in the thermo elements reaching the borehole. Hot gases from the gasifier were led first through the water-cooled heat exchanger and then into chromatographic loops of successively bound gas chromatographs. Temperature development in the gasifier was monitored by more thermo elements with a measuring range from 0°C to 1,350°C. With the combustion of the organic matter in the coal, the cavity grows and with that the available reaction surface. According to cavity growth, the total flow of steam/oxygen mixture also had to be increased.

As indicated by former tests (Levec, Berčič, 1984), the effect of air used as the reactant at gasification was a high percentage of nitrogen in the synthetic gas. Nitrogen reduces the calorific value and cannot be easily removed from the synthetic gas. In the case of oxygen used as the reactant at gasification, the calorific value of the synthetic gas was higher. The calorific value increased with the steam:oxygen ratio and decreased with pressure. Higher airflow velocity also increased the calorific value. The presence of steam decreases the temperatures in the borehole and gases also contain hydrogen and methane in addition to oxidation products. At H_2O:O_2 ratios higher than 2:1, the results were not applicable. Coal moisture content affects the initial phase of the gasification process much more than after longer times when the ratio between surface and volume (S/V) in the cavity is smaller. As this ratio, (S/V) is still high; the major contribution to calorific value of the gas comes from carbon monoxide (CO) and hydrogen (H_2) while the needed water (H_2O) comes from the coal drying (Rečnik, 1987). Reduction of S/V ratio is shown in hydrogen (H_2) and methane (CH_4) rising, because of carbon monoxide (CO). The CO:H_2 ratio is therefore an indicator of cavity growth in the system:

$$CO/H_2 = \text{function (S/V)}$$

Reduction of S/V ratio also reduces the CO/ H_2 ratio.

In the next table, the results of Velenje lignite gasification are shown at various steam/oxygen ratios. According to the results, the most appropriate steam/oxygen ratio is 1:1.

***Table 2**: Results of the Velenje lignite gasification*

H_2O:O_2 ratio	H_2 (%)	CO (%)	CH_4 (%)	CO_2 (%)	Calorific value (MJ/m^3)
1:1	28.7	15.1	2.8	53.4	6.69
2:1	19.4	9.6	2.1	68.9	4.53
1.5:1	22.5	12.8	3.4	61.3	5.84

7 UCG FEASIBILITY STUDY IN VELENJE

In 2002, a feasibility study of UCG in the Velenje Lignite Mine was made to substantiate the possibility of UCG in the coal seam of the Velenje depression. The following working phases were foreseen:

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1. preliminary deposit evaluation with analysis of existent data (general data, geology, hydrogeology);
2. additional resource characterisation;
3. technological parameters of the process;
4. technological parameters of the deposit;
5. products of the process and products use;
6. environmental susceptibility;
7. economic evaluation;
8. final evaluation.

The following parameters formed the characterisation of single potential site:

1. Geometrical parameters
    - coal seam outline
    - drilling possibility (subsidence area, subsidence lakes, settlements, active mining)
    - safety pillars
    - areas where the ratio between coal thickness and seam depth is equal or less than 10:1
    - variation in coal seam thickness, coal seam inclination, tectonics
2. Coal reserves – at least 15 Mt.
3. Physical and chemical coal parameters (carbon value, ash value, moisture content, volatile matter, sulphur, calorific value etc.).
4. Hydro-geological parameters.

Based on these criteria, two possible locations were chosen as described in detail in the geological part of UCG feasibility study (Veber, 2002):

1. Tičnica
2. Ležen – the north-western part of the deposit

Both possible locations for UCG tests are presented on Fig. 6. Samples for additional resource characterisation were taken from the seam in the north-western part of the deposit and the numerous existent data from Tičnica area were evaluated.

***Figure 6**: Possible locations for UCG tests*

8 PLANS FOR THE FUTURE

Some vital parts of this feasibility study are still missing, because the research work was discontinued. The missing parts are: evaluation of process product use, size of the energy structure, economic evaluation and final evaluation.

In 2010, we intend to complete the study, especially with the economic part, and to confirm the possibility of UCG in the coal seam of the Velenje depression. We will continue research in that direction to prepare and determine the tasks needed to execute the pilot UCG test in Velenje. We are taking action to get the concession for researching coal sources in the north-east part of Slovenia, called Goričko.

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