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Alternativne tehnologije hidroenergetike

V času zavedanja okoljskih problemov glede emisij v okolje, predvsem ogljikovega dioksida in drugih toplogrednih plinov, je vse bolj očitno, da predvsem koriščenje obnovljivih energetskih virov vodi k zmanjšanju tega problema. Koriščenje hidroenergetskega potenciala rek je ena od bolj sprejemljivih možnosti koriščenja obnovljivih virov. V zadnjem času se zavedamo, da ima poseganje v reke, kot hidro-energetske vire, velik negativen vpliv na sam rečni habitat kakor tudi na okolje rek. Poznani so primeri, kjer zaradi nepravilne priprave rečnega korita anaerobno v vodi razpada biološki material, katerega produkti so metan, ogljikov dioksid, oziroma večina toplogrednih plinov. Prav tako klasične zajezitve rek zelo vplivajo na okolje, predvsem v smislu dviga podtalne vode, kar je na nekaterih področjih sicer zaželeno, večinoma pa ne. Da bi ohranili okolje, je potreben drugačen, alternativni, pristop izkoriščanja hidroenergije, ki praviloma omogoča nižji energetski izplen v primerjavi s klasičnim načinom koriščenja, vendar pa mnogo manj vpliva na okolje. Pri tem načinu praviloma koristimo samo dinamični del, torej tokovni ali kinetični del, energetskega potenciala. Za takšno izkoriščanje rečnega toka ne potrebujemo večjih zajezitev reke, s čimer je tudi vpliv na okolje bistveno manjši. Pri tako je poseganje v rečno korito in brežine manjše, saj potrebujemo le sidranje v rečni tok postavljenih turbin.

Reka Mura je edina večja slovenska reka, ki je v vseh teh letih ostala v naravni obliki in energetsko neizkoriščena. Neposredno okolje reke je občutljivo, saj je reka prodonosna, kar pomeni, da se dno in brežine reke spreminjajo. Žal so sosedje Avstrijci, reko večkrat zajezili in s tem prekinili naravni »dotok« proda iz Alpskega področja, kjer reka izvira. Dno reke se v slovenskem delu poglablja, ustvarjajo se mrtvi kanali, imenovani mrtvice, v katerih so se oblikovali edinstveni naravni biotopi. Žal poglabljanje reke vpliva tudi na upad gladine podtalne vode, ki je v nekaterih delih Prekmurja že zaskrbljujoč.

S podelitvijo državne koncesije Dravskim elektrarnam Maribor, za energetsko izkoriščanje reke Mure, se odpira možnost izgradnje verige hidroenergetskih central na reki Muri. V koncesiji je predvidenih 8 elektrarn od mejnega dela reke Mure z Avstrijo do Veržeja. V koncesiji ocenjeni energetski potencial znaša 84 MW, letna proizvodnja pa 445,8 GWh. Dolžina reke v slovenskem delu je okrog 98 km. Povprečna vodnatost reke Mure, oz. povprečni pretoki znašajo od 170 do 240 m^3/s. Glede na celotno porabo elektrike v Sloveniji, ki znaša približno 12,9 TWh z rastjo okoli 3% letno, bi energetsko koriščenje potenciala reke Mure pokrivalo okrog 3,5% slovenske porabe. Trenutno v Sloveniji s hidro viri pokrivamo 3,7 TWh, kar znaša približno 28,7% celotne porabe.

Civilna iniciativa, ki se je oblikovala zaradi ohranitve okolja in reke Mure, nasprotuje gradnji klasičnih zajeznih hidroelektrarn. Ocenjujejo, da bi bila izgradnja jezov in potrebnih zgradb pregrob poseg v okolje, ki bi trajno vplival na biotop reke Mure in njeno neposredno okolico.

Morda je prav alternativni pristop pri izkoriščanju hidro potencialov reke Mure priložnost za ohranjanje občutljivega okolja in samooskrbo regije z električno energijo.

Alternative hydro-energy technologies

Due to the awareness of environmental problems in the previous decade, mainly the emissions of carbon dioxide and other greenhouse gases, it is becoming evident that the increasing use of renewable energy sources leads to a reduction of this problem. The use of the hydro-energy potential of rivers is one of the acceptable possibilities for renewable sources. However, recently it has been confirmed that aggressive intervention on rivers for hydro-energy resources has a highly negative impact on the river habitat as well as on the wider environment of rivers. Cases of incorrect preparation of flood areas are known in which anaerobic decomposition of biological material produced methane, carbon dioxide, i.e., most greenhouse gases. The traditional river dams for hydro plants influence the environment severely, especially in terms of rising groundwater, which is desirable in some areas but mostly not. In order to preserve the environment, a different, alternative, approach is required to exploit the hydropower, which generally leads to lower energy gain compared to conventional method, but with less environmental impact. In this manner, only the dynamic part of the river, i.e., the flow or kinetic part, is used for energy. For such exploitation of river flow, we do not need a large "capture" of the river; consequently, there is less influence on the river environment. It does not demand major intervention on the banks and river bed; it requires only the anchoring of flow turbines.

The Mura River is the only Slovene river that remains in its natural form with its energy potential unused. The immediate environment of the river is sensitive, since the river transports earth material and consequently the bed and banks of the river changes over time. Unfortunately, in Austria, where the river begins, it has been dyked the several times, blocking and disrupting the natural flow of ground material from the spring alpine area. As a result, the bottom of the river in Slovenia is deepening and creating dead channels, called oxbow lakes, where unique natural habitats have developed. Unfortunately, the deepening of the river also lowers groundwater levels, which is in parts of the Prekmurje area is already alarming.

With the granting of government concessions to Dravske elektrarne Maribor (Drava Hydro-electrical Power Plants Company) for energy exploitation of the Mura, the possibility opens for the building of a chain of hydro power stations. In the concessions are eight power plants, from the Austrian border to Veržej. The energy potential is estimated to 84 MW, with annual production of 445.8 GWh. The length of the Slovenian part of the river is around 98 km. The average water capacity of the Mura River or average flow ranges from 170 to 240 m^3/s. With the overall consumption of electricity in the Slovenia, approximately 12.9 TWh with growth of 3% annually, the potential energy of the river Mura covers about 3.5% of Slovene electric power consumption. With its hydro resources, Slovenia currently covers 3.7 TWh, representing approximately 28.7% of total consumption.

Civil Initiative, locally formed to preserve the environment and the Mura, is opposed to the construction of classic hydroelectric plants. It is estimated that the construction of dams will be devastating for the biotope and its immediate surroundings.

Perhaps an alternative approach to the Mura River energy exploitation is an opportunity for preserving a sensitive environment accompanied with regional energy self-supply.

Krško, July 2010 Andrej PREDIN

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FUZZY APPROACH TO OPTIMISE ENERGY CAPACITIES FOR PERMANENT AND RELIABLE ELECTRICITY SUPPLY

MEHKI PRISTOP PRI OPTIMIRANJU ENERGIJSKE ZMOGLJIVOSTI ZA TRAJNO IN ZANESLJIVO OSKRBO Z ELEKTRIČNO ENERGIJO

Janez Usenik[ℜ]

Keywords: capacity, optimal price, energy, deterministic dynamic model, fuzzy logic, fuzzy model, estimation

Abstract

Planning optimal capacities and technologies for sustainable and reliable electricity supply with special attention to risk management is becoming increasingly important. Fabijan and Predin [1] dealt with this matter by estimating the power supply market in the near future and, based on this estimation, they built a deterministic quasi-dynamic model for forming the price of electricity supply.

The equation they have developed is correct and applicable. However, its weakness is in the usage of estimated values as explicit precise data.

In this paper, we will present a more current option of designing such a model, in which the fuzzy logic approach is applied. The application of fuzzy logic in this case is entirely reasonable, since all the values used in the model are only estimates, i.e. more or less reliable predictions. There are many options for building a fuzzy model, but in this paper only the most compatible with a given deterministic quasi-dynamic model will be shown. The direct comparison of numerical results is possible, which later enables building a knowledge base for the effective

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application of a neural network in the process of algorithm (built in the fuzzy system/model) learning.

Povzetek

Načrtovanje optimalnih kapacitet in tehnologij za trajno in zanesljivo oskrbo z električno energijo, pri čemer je posebno pozornost dana obvladovanju tveganj, je v sedanjih časih vse pomembnejše, Avtorja Fabijan, Predin, [1] se temu pomembnemu vprašanju posvetita s stališča ocenjevanja energetskega trga v kratkoročni bodočnosti in na tej podlagi izgradita deterministični kvazidinamični model oblikovanja cene električne energije. Formula, ki jo izpeljeta, je korektna in uporabna, njena šibkost je v tem, da z zgolj ocenjenimi vrednostmi operira kot z eksplicitnimi natančnimi podatki.
V tem članku je predstavljena bolj aktualna možnost, da pri oblikovanju takšnega modela k problemu pristopimo z uporabo mehke logike. Uporaba mehke logike je v tem primeru vsekakor smiselna, saj so vse vrednosti, s katerimi v modelu operiramo, zgolj ocene, torej bolj ali manj zanesljive napovedi. Različnih možnosti izgradnje mehkega modela je več, v članku je predstavljena tista, ki v strukturi algoritma najbolj sledi danemu determinističnemu kvazidinamičnemu modelu. Razlog za to je dvojni: možna je neposredna primerjava numeričnih rezultatov, kasneje pa je s tem omogočena izgradnja baze znanja za učinkovito uporabo nevronske mreže v postopek učenja algoritma, vgrajenega v mehki sistem/model.

1 INTRODUCTION

Following the paper Fabijan, Predin, [1], an optimal energy source structure for electricity production is treated by the needs for satisfying of some parameters, like

- long term reliable electricity energy supply,
- system suitability,
- suitability of production capability,
- suitability of electricity grid,
- market suitability,
- short-term and reliable supply.

From the point of view of the transmission system operator (TSO), the optimal structure of energy producing resources is treated by frequency control on the primary, secondary and tertiary (minute) control levels.

Energy companies are exposed to business risk, production risk and financial risk in general. Every kind of risk depends on many elements in the working of the energy system. The obligation of the decision makers is determining how to control this system, but the main challenge is that the efficiency of the system has to be as high as possible under all constraints in operating.

All these risks generate costs, depending on different technologies and sources of producing and selling electric energy. If we know these costs, we can calculate the price of electric energy in advance.

Risk is becoming an increasingly serious issue in all areas of society. The concept of risk generally implies an objective quantitative estimate of the probability of an event measured by

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its frequency. In industrial systems, unreliability is usually identified with the objective element in risk, Harris, [2].

2 DEFINING THE PROBLEM

In this article, we shall use the following notations:

$c_i(k_j)$ - price of one unit of electrical energy of source *i* at time point k_j,

$u_i(k_j)$ - quantity of production electrical energy in source *i* at time point k_j,

$w(k_j)$ - weight of rigidity of the sources structures in time point k_j,

$p(k_j)$ - interest rate in % at time point k_j,

$i(k_j)$ rate of the compound interest, where

$$i(k_j)=\frac{p(k_j)}{100} \tag{1.01}$$

$d(k_j)$ discount rate, where

$$d(k_j)=\frac{i(k_j)}{1+i(k_j)} \tag{1.02}$$

$\rho(k_j)$ - basis term for calculating discount present value, where

$$\rho(k_j)=1-d(k_j)=\frac{1}{1+i(k_j)} \tag{1.03}$$

k_j, $j\in J$, $J=\{1,2,3,\ldots,n\}$ - time distance in separate years (end of the time interval/year),

i = 1, 2, 3, …., m - set of sources

With respect to the minima of total costs, we obtain the formula for the calculated expected reference price of electric energy[1]

[1] In Fabijan, Predin, [1], the formula for calculating the expected reference price of electric energy exists in a similar form $c=\sum_{t}^{t\in\Gamma}\frac{w_t}{\sum_{\tau}^{\tau\in\Gamma}w_\tau}(1+d_t)^{l_t}\sum_{v}^{v\in\Psi}\frac{u_{t,v}}{\sum_{\upsilon}^{\upsilon\in\Psi}u_{t,\upsilon}}c_{t,v}$. The mining in accordance with (1.04) is the same.

$$c=\sum_{j\in J}\left[\frac{w(k_j)}{\sum_{j=1}^{j}w(k_j)}\left(1-d(k_j)\right)^{k_j}\left(\sum_{i=1}^{m}\frac{u_i(k_j)}{\sum_{i=1}^{m}u_i(k_j)}c_i(k_j)\right)\right] \tag{1.04}$$

In (1.04) expressions

$$\tilde{w}(k_j)=\frac{w(k_j)}{\sum_{j=1}^{n}w(k_j)}=\frac{w(k_j)}{w(k_1)+w(k_2)+\cdots+w(k_n)}\text{ , } j\in\{1,2,3,\ldots,n\} \tag{1.05}$$

and

$$\tilde{u}_i(k_j)=\frac{u_i(k_j)}{\sum_{i=1}^{m}u_i(k_j)}=\frac{u_i(k_j)}{u_1(k_j)+u_2(k_j)+\cdots+u_m(k_j)}\text{, } j\in\{1,2,3,\ldots,n\} \tag{1.06}$$

are normalized weights of every $w(k_j)$ and $u_i(k_j)$ for k_j, $j\in\{1,2,3,\ldots,n\}$ and $i=1,2,\ldots,m$, i.e.

$$\sum_{j\in J}\tilde{w}(k_j)=1, \qquad \sum_{i=1}^{m}\tilde{u}_i(k_j)=1.$$

Considering (1.03), (1.05) and (1.06), formula (1.04) has the simplest but applicable form

$$c=\sum_{j\in J}\left[\tilde{w}(k_j)\cdot\rho^{k_j}(k_j)\left(\sum_{i=1}^{m}\tilde{u}_i(k_j)\cdot c_i(k_j)\right)\right] \tag{1.07}$$

Formula (1.07) represents the *deterministic quasi-dynamic model*, depending on data not known in explicit, but only in estimated form.

This estimation contains expert knowledge, so the experts have to take an active part in the every part of decision process.

From this point of view, we can write the formula (1.07) in the form:

$$
\begin{aligned}
c = \sum_{j\in J}\left[\tilde{w}(k_j)\cdot\rho^{k_j}(k_j)\left(\sum_{i=1}^{m}\tilde{u}_i(k_j)\cdot c_i(k_j)\right)\right] = \\
= \tilde{w}(k_1)\cdot\rho^{k_1}(k_1)\left[\tilde{u}_1(k_1)\cdot c_1(k_1)+\tilde{u}_2(k_1)\cdot c_2(k_1)+\cdots+\tilde{u}_m(k_1)\cdot c_m(k_1)\right]+ \\
+\tilde{w}(k_2)\cdot\rho^{k_2}(k_2)\left[\tilde{u}_1(k_2)\cdot c_1(k_2)+\tilde{u}_2(k_2)\cdot c_2(k_2)+\cdots+\tilde{u}_m(k_2)\cdot c_m(k_2)\right]+ \\
+\cdots\cdots+ \\
+\cdots\cdots+ \\
+\tilde{w}(k_n)\cdot\rho^{k_n}(k_n)\left[\tilde{u}_1(k_n)\cdot c_1(k_n)+\tilde{u}_2(k_n)\cdot c_2(k_n)+\cdots+\tilde{u}_m(k_n)\cdot c_m(k_n)\right]= \\
= c_1(k_1)\rho^{k_1}(k_1)+c_2(k_2)\rho^{k_2}(k_2)+\cdots+c_n(k_n)\rho^{k_n}(k_n)
\end{aligned}
$$

A graphic representation is in Figure 1.

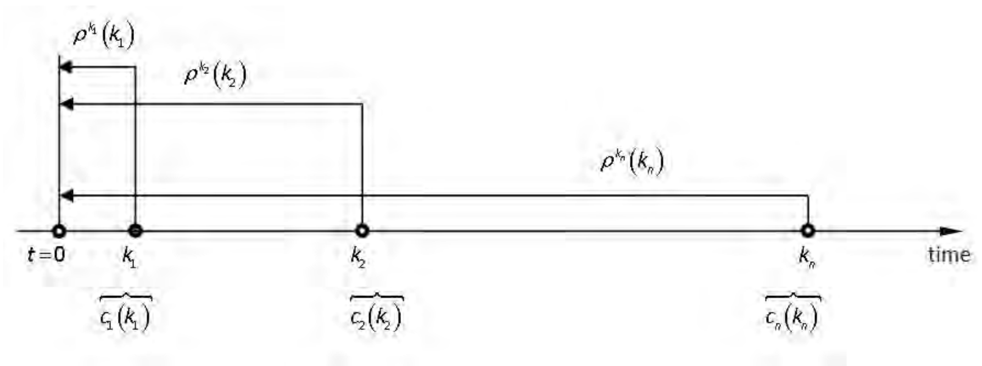

***Figure 1**: Dynamic process in formula (1.07)*

3 FUZZY MODEL

Every prediction of events and especially their future values is not precise; it depends on many circumstances, more or less known in advance. The quasi-dynamic deterministic model given by formula (1.07) is dependent on the precision of data. All numerical values in the future are not precise; they are only estimated. Of course, we do not know the price of electrical power ten years in the future. In this time of global recession, we do not know with certainty the price of electrical power for one year in future, to say nothing of five or more years. However, vagueness in prediction is appropriate for using fuzzy logic, Ross, [3]. We can a build fuzzy system to calculate (better: to predict) the price of energy power with regard to request for optimizing energy capacities with a permanent and reliable electricity supply.

Analysis of our problem has assumed that the consequences of decisions are known with certainty and are reversible. However, these assumptions are not factually correct for many problems. Resource-use decisions concern the future as well as present, and the future cannot be known with certainty, Perman and all, [4].

Resource stocks are subject to many stochastic effects. The methods of decision theory could be used to compute optimal management strategies in the presence of uncertainty. Dynamic decision theory, which is obviously required for resource decisions, is mathematically difficult. Numerical computation of optimal policies encounters the curse of dimensionality, Levin et al., [5].

In principle, every system can be modeled, analyzed and solved by means of fuzzy logic. Due to the complexity of the given problem and the subjective decisions of customers, which are better described with fuzzy reasoning, it is advisable to introduce a fuzzy approach. Some basic solutions of the control problems using fuzzy reasoning were presented in the paper Usenik, Bogataj, [6]. For some problems about the control of the power supply system, we propose fuzzy reasoning. It is obvious that decision makers, when solving everyday problems in control of systems, operate with fuzzy logic, Terano, [7].

Our proposed fuzzy model will be based on these assumptions, whereby the usual five steps have to be taken: fuzzification of the input and output variables, application of the fuzzy operator in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules, and defuzzification.

3.1 Fuzzy System Structure

The fuzzy system structure identifies the fuzzy logic inference flow from the input variables to the output variables. The fuzzification in the input interfaces translates analog inputs into fuzzy values. The fuzzy inference takes place in rule blocks which contain the linguistic control rules. The outputs of these rule blocks are also linguistic variables. The defuzzification in the output interfaces translates them into analog variables, Usenik, J. [8], FuzzyTech, [9].

The following figure shows the whole structure of this fuzzy system including input interfaces, rule blocks and output interfaces. The connecting lines symbolize the data flow.

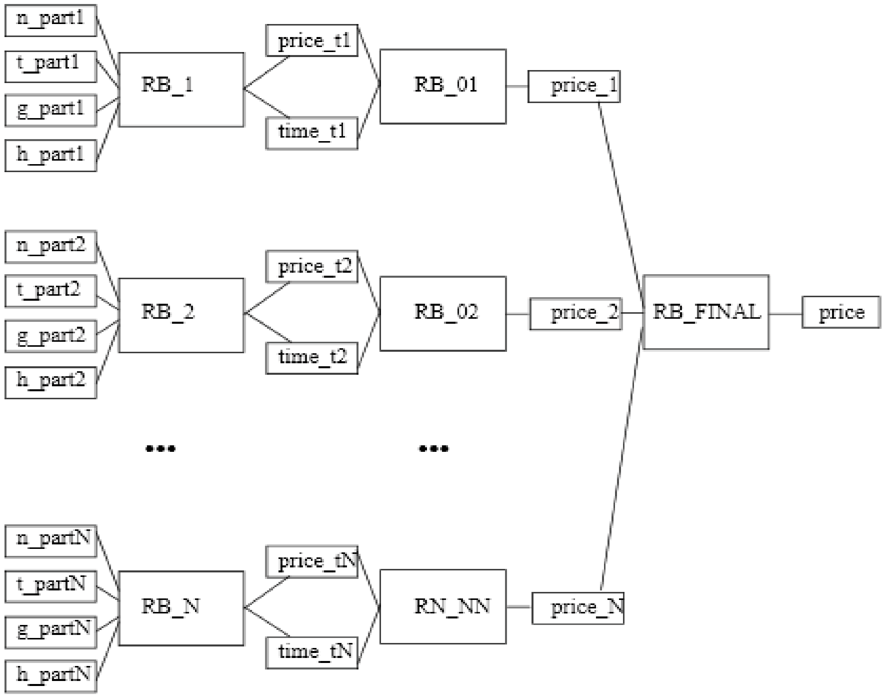

Figure 2: *Structure of the Fuzzy Logic System*

3.2 Fuzzification

In the fuzzification phase, we have to define fuzzy sets for all fuzzy variables (input and output) and define their membership functions. Linguistic variables are used to translate real values into linguistic values. The possible values of a linguistic variable are not numbers but so-called linguistic terms.

For every fuzzy set and for every fuzzy variable, we have to create membership functions. Linguistic variables have to be defined for all input, output and intermediate variables. The membership functions are defined using only a few definition points.

For the input fuzzy variable N_PART1, they could be as shown in Figure 3. On the x-axis, we measure the variable "nuclear part_1" given in percenteages (relative numbers) from 0 to 50%, depending on our data. On the y-axis, we measure membership for every possible "nuclear part_1" and for every fuzzy set LOW, MEDIUM and HIGH.

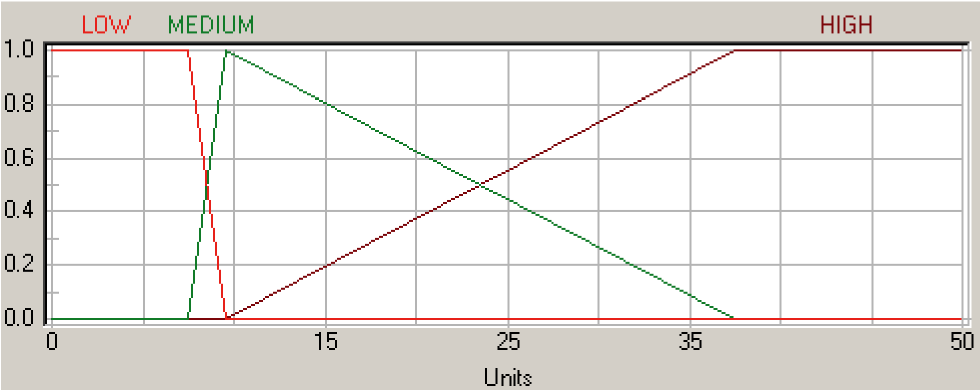

***Figure 3**: Input fuzzy variable N_PART1 and their membership functions*

The output of the fuzzy variable PRICE could be as shown in Figure 4. On the x-axis, we measure the variable "price" given in money units; in this example, euros from 0 to 60 EUR, depending on our data. On the y-axis, we measure membership for every possible "price" and for every fuzzy set LOW, MEDIUM and HIGH.

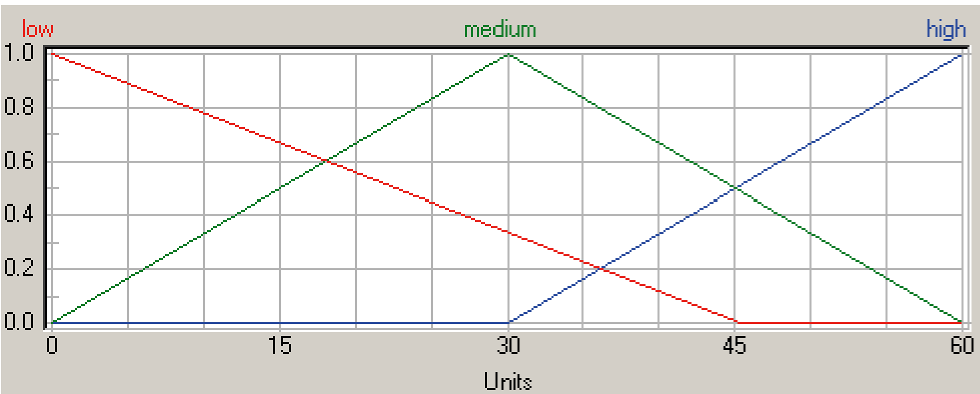

***Figure 4**: Output Fuzzy variable PRICE and their membership functions*

The output of the fuzzy process can be the logical union of two or more fuzzy membership functions defined in the universe of discourse of the output variable.

3.3 Rule Blocks

The rule blocks contain the control strategy of a fuzzy logic system. Each rule block confines all rules for the same context. A context is defined by the same input and output variables of the rules.

The "If" part of the rules describes the situation for which the rules are designed, while the "then" part describes the response of the fuzzy system in this situation. The degree of support (DoS) is used to weigh each rule according to its importance.

The processing of the rules starts with calculating the “if” part. The operator type of the rule block determines which method is used. The generalization of the Boolean “and” is the minimum operator and a generalization of the Boolean “or” is the maximum operator.

The computation of fuzzy rules is called fuzzy inference and consists of three steps: the application of the fuzzy operator (and/or) in the antecedent, the implication from the antecedent to the consequent and the aggregation of the consequents across the rules. The first step determines the degree to which the complete “if” part of the rule is satisfied. In this step, we usually use the operator OR for the minimum and the operator AND for the maximum. The second step makes use of the support of the precondition to calculate the support of the consequence. Finally, the aggregation step determines the maximum degree of support for each consequence.

In our work, we applied FuzzyTech software. In accordance of this software tool, the rules were automatically created.

For example in the rule block 03, we have six rules:

1. if PRICE_T3 is LOW and TIME3 is LOW, then PRICE 3 is LOW
2. if PRICE_T3 is LOW and TIME3 is HIGH, then PRICE 3 is MEDIUM
3. if PRICE_T3 is MEDIUM and TIME3 is LOW, then PRICE 3 is LOW
4. if PRICE_T3 is MEDIUM and TIME3 is HIGH, then PRICE 3 is HIGH
5. if PRICE_T3 is HIGH and TIME3 is LOW, then PRICE 3 is MEDIUM
6. if PRICE_T3 is HIGH and TIME3 is HIGH, then PRICE 3 is HIGH

3.4 Defuzzification

Defuzzification is the conversion of a given fuzzy quantity to a precise crisp quantity. In literature, at least seven methods, Usenik [10], are common for defuzzifying: max-membership principle, centroid method, weighted average method, mean-max membership, centre of sums, centre of the largest area, first (last) of maxima.

Different methods can be used for the defuzzification, resulting either into the most plausible result or the best compromise. The “best compromise” is produced by the methods CoM (Center of Maximum), CoA (Center of Area) and CoA BSUM, a version especially for efficient VLSI implementations. The “most plausible” result is produced by the methods MoM (Mean of Maximum) and MoM BSUM, a version especially for efficient VLSI implementations, Ruspini et all., [11], FuzzyTech, Users Manual, [9].

The result from the evaluation of fuzzy rules is fuzzy. Defuzzification is the conversion of a given fuzzy quantity to a precise crisp quantity. The most frequently method used in praxis is CoM defuzzification (the Center-of-Maximum). As more than one output term can be accepted as valid, the defuzzification method should be a compromise between different results. The CoM method does this by computing the crisp output as a weighted average of the term membership maxima, weighted by the inference results. CoM is a kind of compromise between the aggregated results of different terms *j* of a linguistic output variable and is based on the maximum *Yj* of each term *j*.

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4 NUMERICAL EXAMPLE

4.1 Numerical example using deterministic approach

As an example in Fabijan, Predin, [1], an estimate for reference price in Slovenia is done with regard to the next ten years. The controller calculates with three time points: the first is next year, the second is for the next three years and the third is for next ten years, i.e. $j=1,3,10$ k_j are k_1, k_3 and k_{10} .

Bank interest could be taken as fixed for all three time points:

$$p(k_1)=p(k_3)=p(k_{10})=4\%\,,$$

$$i(k_1)=i(k_3)=i(k_{10})=0{,}04\,,$$

$$d(k_1)=d(k_3)=d(k_{10})=\frac{0{,}04}{1{,}04}=0{,}03846 \quad \text{and}$$

$$\rho(k_1)=\rho(k_3)=\rho(k_{10})=0{,}96154\,.$$

Four types of electric power plants are considered: nuclear power plants, coal power plants, gas power plants and hydro power plants. For Europe, we can predict: a) for nuclear power plants the price of €35/MWh in the first time point, the price of €40/MWh in second time point and the price of €50/MWh in the third time point, b) for thermo power plants the price of €45/MWh in the first time point, the price of €50/MWh in second time point and the price of €70 /MWh in the third time point, c) for gas power plants the price of €60/MWh in the first time point, the price of €65/MWh in second time point and the price of €85/MWh in the third time point and d) for hydro power plants the price of €35/MWh in the first time point, the price of €40/MWh in second time point and the price of €60/MWh in the third time point. In our notations this means following data (in euros):

a) for nuclear power plants i=1: $c_1(k_1)=35$, $c_1(k_3)=40$ and $c_1(k_{10})=50$,
b) for thermo power plants i=2: $c_2(k_1)=45$, $c_2(k_3)=50$ and $c_2(k_{10})=70$,
c) for gas power plants i=3: $c_3(k_1)=60$, $c_3(k_3)=65$ and $c_3(k_{10})=85$,
d) for hydro power plants i=4: $c_4(k_1)=35$, $c_4(k_3)=40$ and $c_4(k_{10})=60$.

From the OEDC data, we assume that in the first time point the ratio between nuclear power plants versus thermal power plants versus gas power plants versus hydro power plants will be 23% : 39% : 25% : 13%. Following expression (1.05), this means $\tilde{u}_1(k_1)=0{,}23$, $\tilde{u}_2(k_1)=0{,}39$, $\tilde{u}_3(k_1)=0{,}25$ and $\tilde{u}_4(k_1)=0{,}13$. In the second time point, the ratio between nuclear power plants versus thermal power plants versus gas power plants versus hydro power plants will be 20% : 38% : 30% : 12%. Following expression (1.05), this means $\tilde{u}_1(k_3)=0{,}20$, $\tilde{u}_2(k_3)=0{,}38$, $\tilde{u}_3(k_3)=0{,}30$ and $\tilde{u}_4(k_3)=0{,}12$. In the third time point, the ratio between nuclear power plants

----

versus thermal power plants versus gas power plants versus hydro power plants will be 15% : 36% : 38% : 11%. Following expression (1.05), this means $\tilde{u}_1(k_{10})=0{,}15$, $\tilde{u}_2(k_{10})=0{,}36$, $\tilde{u}_3(k_{10})=0{,}38$ and $\tilde{u}_4(k_{10})=0{,}11$.

Of course, $\tilde{u}_1(k_1)+\tilde{u}_2(k_1)+\tilde{u}_3(k_1)+\tilde{u}_4(k_1)=1$, $\tilde{u}_1(k_3)+\tilde{u}_2(k_3)+\tilde{u}_3(k_3)+\tilde{u}_4(k_3)=1$ and $\tilde{u}_1(k_{10})+\tilde{u}_2(k_{10})+\tilde{u}_3(k_{10})+\tilde{u}_4(k_{10})=1$.

The source structure is changed slowly and therefore increases the influence of first year and decreases all later times in the ratio 50% : 30% : 20% in first, second and third time point, respectively. Following (1.04), we have $\tilde{w}(k_1)=0{,}5$, $\tilde{w}(k_3)=0{,}3$ and $\tilde{w}(k_{10})=0{,}2$; $\tilde{w}(k_1)+\tilde{w}(k_3)+\tilde{w}(k_{10})=1$.

YEAR	INTER. RATE	PRICE NUCL	PRICE COAL	PRICE GAS	PRICE HYDRO	WEIGHT NUCL	WEIGHT COAL	WEIGHT GAS	WEIGHT HYDRO	WEIGHT OF TIME
1	4	35	45	60	35	0.23	0.39	0.25	0.13	0.5
3	4	40	50	65	40	0.20	0.38	0.3	0.12	0.3
10	4	50	70	85	60	0.15	0.36	0.38	0.11	0.2
									$\sum$	1.0

***Table 1**: Data for numerical example*

From formula (1.07) we obtain:

$$
\begin{aligned}
c=&\sum_{j\in J}\left[\tilde{w}(k_j)\cdot\rho^{k_j}(k_j)\left(\sum_{i=1}^{m}\tilde{u}_i(k_j)\cdot c_i(k_j)\right)\right]=\\
&=\tilde{w}(k_1)\cdot\rho^{k_1}(k_1)\cdot\left[\tilde{u}_1(k_1)\cdot c_1(k_1)+\tilde{u}_2(k_1)\cdot c_2(k_1)+\tilde{u}_3(k_1)\cdot c_3(k_1)+\tilde{u}_4(k_1)\cdot c_4(k_1)\right]+\\
&+\tilde{w}(k_3)\cdot\rho^{k_3}(k_3)\cdot\left[\tilde{u}_1(k_3)\cdot c_1(k_3)+\tilde{u}_2(k_3)\cdot c_2(k_3)+\tilde{u}_3(k_3)\cdot c_3(k_3)+\tilde{u}_4(k_3)\cdot c_4(k_3)\right]+\\
&+\tilde{w}(k_{10})\cdot\rho^{k_{10}}(k_{10})\cdot\left[\tilde{u}_1(k_{10})\cdot c_1(k_{10})+\tilde{u}_2(k_{10})\cdot c_2(k_{10})+\tilde{u}_3(k_{10})\cdot c_3(k_{10})+\tilde{u}_4(k_{10})\cdot c_4(k_{10})\right]
\end{aligned}
$$

The numerical result is:

$$
\begin{aligned}
c=&0{,}5\cdot 1{,}04^{-1}\cdot(0{,}23\cdot 35+0{,}39\cdot 45+0{,}25\cdot 60+0{,}13\cdot 35)+\\
&+0{,}3\cdot 1{,}04^{-3}\cdot(0{,}20\cdot 40+0{,}38\cdot 50+0{,}30\cdot 65+0{,}12\cdot 40)+\\
&+0{,}2\cdot 1{,}04^{-10}\cdot(0{,}15\cdot 50+0{,}36\cdot 70+0{,}38\cdot 85+0{,}11\cdot 60)=45{,}06
\end{aligned}
$$

On the basis of all predictions data and formula (1.07) for the deterministic quasi-dynamic model, we obtained the estimated reference price of electric energy in this moment in the value of 45.06 €/MWh.

4.2 Numerical example using fuzzy approach

Using the fuzzy approach for this deterministic quasi-dynamic model, with equal data we get a final price of c=45.00 EUR. This result is very good and is based on the suitable form of membership functions in the fuzzy variables and on suitable rule blocks (if-then rules).

The error is small: just 0.13% for data from Table 1.

In Table 2, we can see the result in interactive debug mode of software FuzzyTech, ver. 3.55.

Inputs:		Outputs:	
A_N_PART1	8.0500	PRICE	45.0000
A_N_PART2	8.0000	PRICE_T1	38.1800
A_N_PART3	7.5000	PRICE_T2	45.7640
B_T_PART1	17.5500	PRICE_T3	45.3510
B_T_PART2	19.0000	PRICE1	25.0010
B_T_PART3	25.1000	PRICE2	27.5780
C_G_PART1	15.0000	PRICE3	27.2500
C_G_PART2	19.5000		
C_G_PART3	32.3000		
D_H_PART1	4.5500		
D_H_PART2	4.8000		
D_H_PART3	6.6000		
E_DISC1	4.0000		
E_DISC2	4.0000		
E_DISC3	4.0000		
TIME1	0.5000		
TIME2	0.3000		
TIME3	0.2000		

***Table 2**: Result of interactive debug mode*

5 CONCLUSION

The fuzzy approach is very successful with real problems, especially in cases of ambiguity and imprecise data. Predicting the prices of electrical energy for some years in advance is not explicit; this a very appropriate subject for fuzzy logic thinking. All predictions for the future are just estimates, more or less good, depending on the quantity of the relevant data, but very sensitive for every change of variable conditions in the prediction system. The electricity market, both in Europe and in Slovenia, depends on many variables; good and precise prediction of them is nearly impossible. A fuzzy system is, at its core, founded on vagueness, inaccuracy, approximation and with this suitable for description events in the future by the method of "common sense".

Requiring precision in engineering models and products translates to requiring high cost and long lead times in production and development. For other systems, expense is proportional to precision: more precision entails higher cost. When considering the use of fuzzy logic for a given problem, an engineer or scientist should ponder the need for exploiting the tolerance for imprecision, Ross, [3].

In the process of building the fuzzy system, we had to include some qualified experts and make an expert model. The expert system has separate domain-specific knowledge and problem solving methodology and includes the concepts of the knowledge base and the inference engine. The expert system should think the way the human expert does, Zimmermann, [12].

However, it can be said that fuzzy approach is highly efficient for the optimization of energy capacities with criterial function of permanent and reliable electricity supply. In Section 2, the developed fuzzy model for estimating the price of electrical energy for the coming years works quite well in the ambiguous conditions of the energy market. Building a fuzzy model is just one step in the creation of the relevant system; the robustness and the quality of algorithm depend on many examples. For this reason, the usage of neural learning is required; this is the next step in future research for making the relevant expert system.

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ISOLATED BI-DIRECTIONAL DC-DC CONVERTER

IZOLIRANI DVOSMERNI DC-DC PRETVORNIK

Franc Mihalič[ℜ] and Alenka Hren[1]

Keywords: *Switched mode power supply, Bi-directional DC-DC converter circuit, Pulse Width Modulation (PWM)*

Abstract

This paper presents principles of operation and safe start-up procedures for an isolated bi-directional DC-DC converter in buck and boost modes. This converter has been developed as a part of a multifunctional 4 kW power supply system that uses a high DC-link voltage (450 V). The isolated bi-directional DC-DC converter can charge 28 V batteries and supply auxiliary low voltage DC loads. Additionally, the isolated bi-directional converter can also draw power from the batteries or from a truck's driven alternator to maintain the high voltage DC-link. Modulation strategies and start-up procedures of this converter have been validated by using the Matlab SymPowerSystems Toolboxes and, finally, they have been also experimentally verified.

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Povzetek

V prispevku sta predstavljena princip delovanja in varen zagon izoliranega dvosmernega DC-DC pretvornika v delovnem režimu navzdol in navzgor. Ta pretvornik je bil razvit kot sestavni del več funkcionalnega napajalnega sistema moči do 4 kW z visoko napetostno enosmerno zbiralko (450 V). Izolirani dvosmerni pretvornik lahko polni 28 V baterije in napaja zunanje nizko napetostne enosmerne porabnike. Še več, ta pretvornik lahko črpa energijo iz zunanjih baterij ali iz alternatorja tovornega vozila in tako napaja visoko napetostno enosmerno zbiralko. Modulacijski principi in zagonske procedure pretvornika so bili najprej razviti in preverjeni s pomočjo računalniškega programa Matlab SymPowerSystems in nato eksperimentalno potrjeni.

1 INTRODUCTION

Isolated bi-directional DC-DC converters are commonly used in electronic equipment such as uninterruptible power supplies (UPS), electric vehicles and as front-end converters for distributed power-system applications, among others. In all applications, the key features are the safety of the system operation and operation at the highest possible efficiency. Now more than ever, we have to face the problems of energy supply, since the consumption of oil fuels is continually rising and their prices are unstable. Therefore, this must be the challenge for all RD centres throughout the world: to develop modern and new power supply systems operating at the highest possible efficiencies [1], [2].

A block diagram of the multifunctional power supply system (where the diesel engine supplying the DC link can be replaced with any alternative energy sources, e.g., solar, wind, fuel cells etc.) is shown in Figure 1.

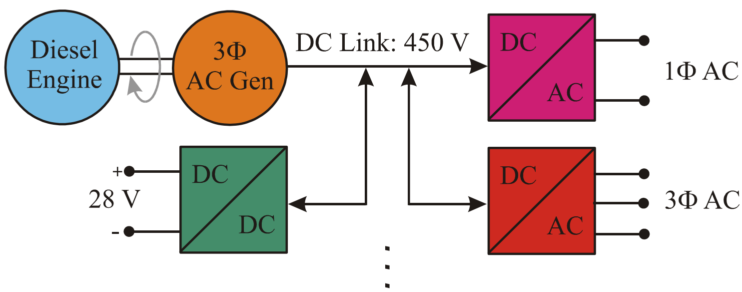

Figure 1: *Block diagram of the multifunctional power supply system.*

An isolated bi-directional DC-DC converter is the combined configuration of a battery-charging circuit and DC-DC converter circuit. It allows power flow in both directions, i.e., towards the battery and from the battery, and has a wide range of applications from uninterrupted power supplies, battery charging and discharging systems, aerospace applications to auxiliary power supplies for hybrid electrical vehicles. Possible implementations of bi-directional converters with full bridge topology using resonance [4], soft switching or hard switching [5] have been reported in literature. Each implementation has disadvantages, including higher component ratings, increased circuit complexity, loss of switching signals at light loads for soft-switch circuit etc. In this paper, the bi-directional full-bridge DC-DC converter topology (shown in Figure 2), using hard-switch PWM with emphasis on safe start-up procedures in boost- and buck-mode operation, will be discussed.

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2 ISOLATED BI-DIRECTIONAL CONVERTER DESCRIPTION

Bi-directional DC-DC converters are used to interconnect different DC voltage buses and to transfer energy between them. In most applications, in addition to the wide input and output voltage range operation, a high voltage transfer ratio is also required (e.g., switching frequency f_S = 25 kHz, DC-link voltage U_{DC} = 450 V, battery voltage U_{Bat} = 28 V and nominal output power P_o = 4 kW). In such a case, a direct bi-directional converter is not an appropriate option, since the converter would be operated with a small duty ratio in buck-mode operation or a large duty ratio in boost-mode operation. These requirements cause high current ripple; consequently, the components with higher ratings have to be chosen and the efficiency of the power system will be low, due to the increase in the switching losses. Therefore, for such an application, an isolated bi-directional converter has to be implemented. Galvanic isolation is also needed for safety concerns and electromagnetic compatibility reasons. The use of such isolated bi-directional DC-DC converters has the potential to improve the overall efficiency, fuel economy, reliability and safety of the multifunctional power supply system.

2.1 Isolated DC-DC Buck Converter

Like in a direct DC-DC buck converter (shown in Figure 2), the output voltage in an isolated buck converter is also controlled by the duty ratio $D = t_{on}/T_S = t_{on}.f_S$ (duty ratio is always in the range $0 < D < 1$) and transformer's turns ratio n as:

$$U_{Bat} = \frac{DU_{DC}}{n} \tag{1}$$

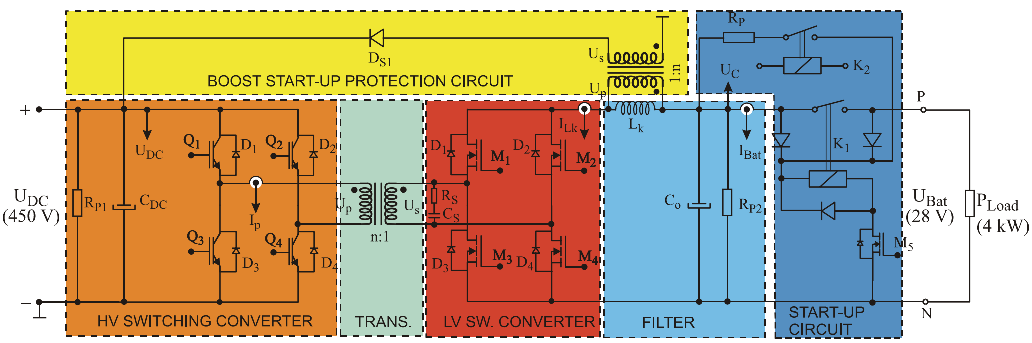
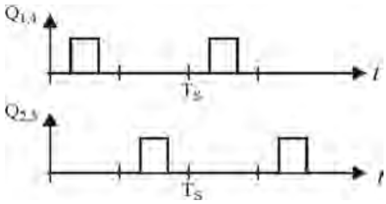
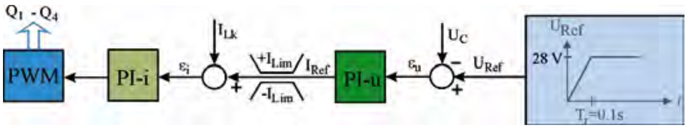


Figure 2: *Isolated bi-directional DC-DC converter.*

Full bridge converters are typically used in applications above 750 W, where IGBT power semiconductor switches are used in the high voltage applications and the MOSFET switches are required on the low voltage side. At the start-up of the converter in Figure 2, the output capacitor C_o is assumed to be empty. The PWM unit has to generate two driving pulses for each power transistor in leg at the primary side, where pulses in diagonals are equal to $Q_1 = Q_4$ and $Q_2 = Q_3$ (see Figure 3(a)). By raising the duty ratio D in (1) within the PWM unit, the output voltage U_{Bat} is increasing to the desired value. The whole system has a cascade control structure, i.e., an inner, current PI-controller for the inductor's current I_{Lk} and an outer, voltage PI-controller for the battery voltage (see Figure 3(b)) and is designed like all controlled power supply systems [6].



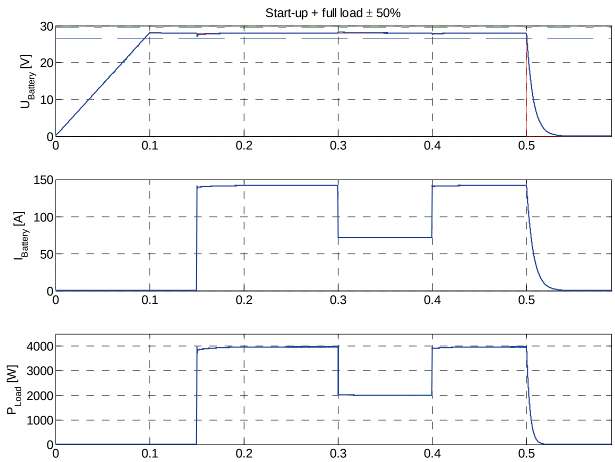
(a)



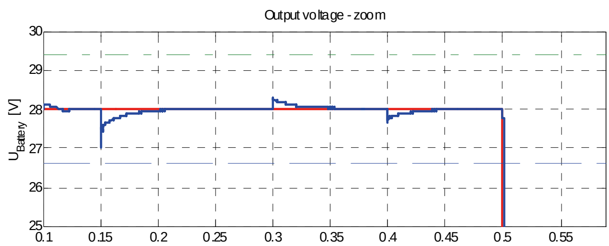
(b)

Figure 3: *(a) The driving signals in buck converter. (b) Block diagram of the control scheme for the buck mode of operation.*

The parameters of both PI-controllers have been designed by using Root Locus Method and small-signal CCM converter transfer functions [7]. The start-up of the isolated DC-DC buck converter with no-load and full- to half-load operation is shown in Figure 4(a).



(a)



(b)

Figure 4: *(a) Start-up, full- to half-load operation and shut-down of the isolated bi-directional DC-DC converter in buck mode: output voltage (top), output current (middle) and output power (bottom). (b) Output voltage is within the ± 5% limits.*

It is evident that with the chosen control scheme the output voltage remains within the ±5% of the 28 V even at the full-load operation at 0.15 s (see Figure 4(b)). At 50% load (from 0.3 s–

0.4 s), the results are even better, which confirms the efficiency of the cascade control structure. It is also evident that, when the shut-down of the converter's occurs at full-load, the output voltage decreases rapidly and without overvoltage spikes.

2.2 Isolated DC-DC Boost Converter

The same configuration (shown in Figure 2) can operate in the opposite direction, i.e., it can boost the battery voltage to a high DC-link voltage when the MOSFETs full-bridge converter is driven in the appropriate manner, depending on the duty ratio *D* and transformer's turns ratio *n* as:

$$U_{DC} = \frac{nU_{Bat}}{(1-D)} \qquad (2)$$

Like a direct boost converter, an isolated boost converter also has a start-up problem. At the beginning, the bulk input capacitors are empty (U_{Co} = 0 V and U_{DC} = 0 V); if we start the converter in boost mode, the control unit will put the maximum duty ratio to the MOSFETs switches to keep pumping energy into the inductor L_k. Since the output voltage is zero, the inductor cannot be discharged; as a result, the inductor will be saturated and the current will (theoretically) go to infinity. If over-load condition occurs (or immediate shut down), one cannot simply turn off all the switches, because the energy stored in the inductor cannot go anywhere, and it will generate high voltage spikes, which destroy the switches.

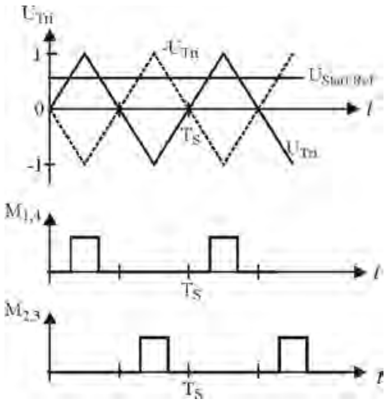
One possible (and low-cost) solution for solving problems at the start-up procedure is to use a charging resistor for the input capacitor C_o (R_P), as shown in Figure 2 (the same could also be applied to the bulk capacitor C_{DC} at the high voltage terminals through an adequate charging resistor). The charging currents are limited through the resistance, but when isolation is lost there are certain losses and the circuit is not protected against over load and shut down during the operation.

At high power levels, output rectifiers (in our case D_1 - D_4 and D_2 - D_3) in continuous-current-mode (CCM) boost converters have severe reverse-recovery problems due to the high rectifier forward current and the high output voltage. As a result, the active switches encounter huge turn-on current spikes, which are not only responsible for high turn-on loss but also cause severe electromagnetic interference (EMI) noise. To reduce the switching losses, the operating frequency of the CCM-boost converter must be reduced. However, reducing the operating frequency is not a good solution in terms of power density, cost and efficiency. An effective solution to alleviate rectifier reverse-recovery problems is proposed in [8]. By using only one additional rectifier and coupled winding on the boost inductor, the current through the original rectifier can be steered to a new branch. With proper design, the current through the original rectifier can be reduced to zero before the boost switch turns on.

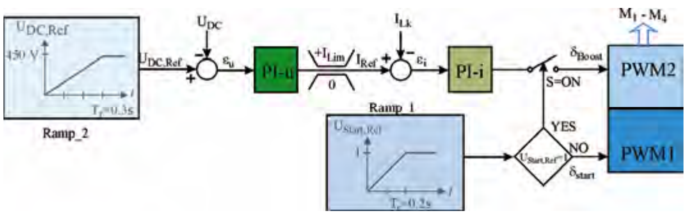
A similar solution for the aforementioned problems during the start-up procedure and shut-down protection, in isolated bi-directional DC-DC converter running in boost mode is shown in Figure 2, where a coupling winding is added to the inductor L_k and an additional diode D_{S1} is connected to the output terminal. First, input capacitor C_o must be charged through the charging resistor R_p (with auxiliary contactor K_2 on). When the input capacitor's voltage has reached the battery voltage $U_C = U_{Bat}$, the main contactor K_1 can be turned on. Now the start-up procedure can begin: the driving pulses for the MOSFETs are shown in Figure 5(a) with the duty ratio from 0 to 50% for both legs (when the starting reference voltage reaches $U_{Start,Ref} = 1$) and the output voltage is:

$$U_{DC} = \frac{U_{Bat}}{2nD} \tag{3}$$

With this scheme, the converter can operate in "fly-back" mode during start-up, and transfer the energy stored in the main inductor L_k to the bulk capacitor C_{DC} at the DC-link circuit. As in a buck converter, whole system has inner, current PI-controller for the primary current I_p and outer, voltage PI-controller for the DC-link voltage U_{DC}, as shown in Figure 5(b). The parameters of both PI controllers have been designed by using the Root Locus Method. The design of the PI-current controller parameters was performed using the transfer function that describes the relationship between the inductor current and the duty ratio.



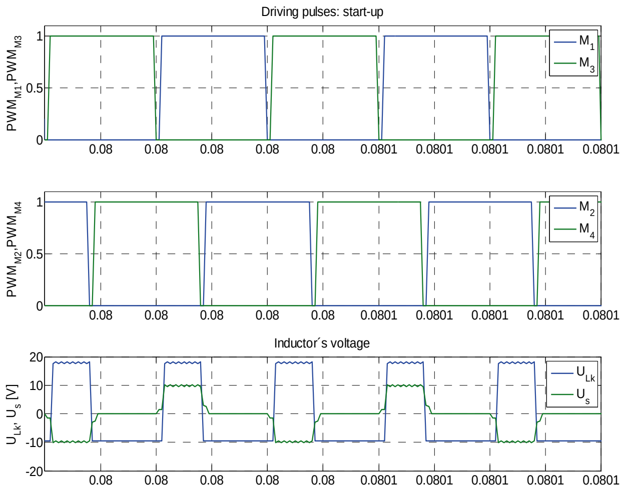
(a)



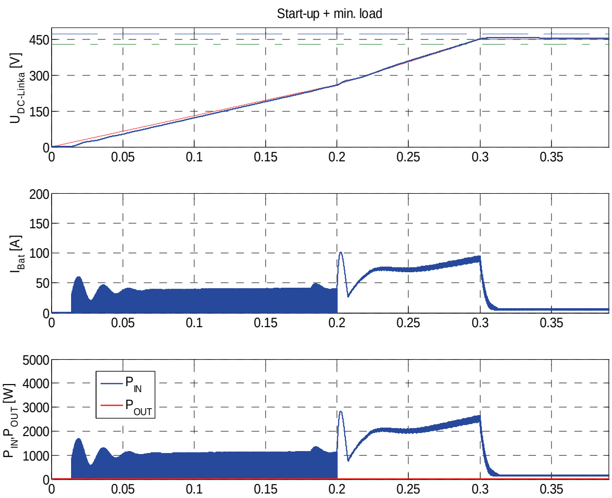
(b)

Figure 5: *(a) Start-up driving signals in boost converter. (b) Block diagram of the control scheme for boost mode of operation.*

Now, the entire system is ready for investigation: PWM driving pulses for each MOSFETs leg, inductor voltage and output voltage of the boost converter (i.e., secondary voltage of the transformer) are shown in Figure 6(a). It is evident that the inductor voltage is building up in a positive direction when M_1 and M_4 are conducting; this voltage is negative, when M_2 and M_3 are active. As seen in Figure 6(a), the output voltage of the DC-DC boost converter U_S (i.e. the secondary voltage of the transformer) is alternative; therefore, it can be transformed up to the high-voltage primary side, where it is rectified through the body diodes D_1 to D_4 of the IGBTs full-bridge converter.



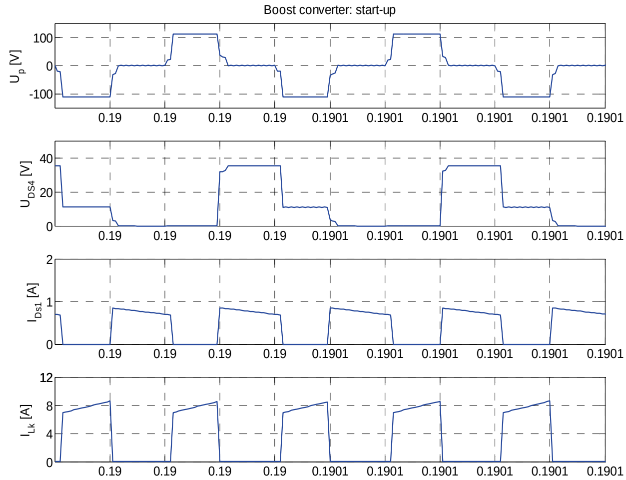
(a)



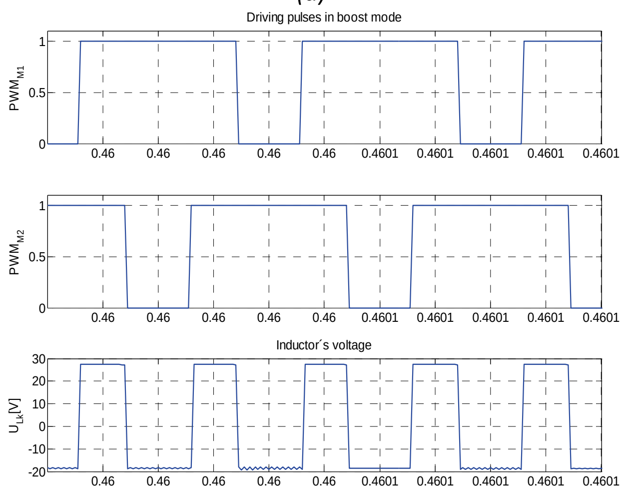
(b)

Figure 6: *(a) Start-up of the boost converter: driving pulses in each MOSFETs leg, inductor voltage and output voltage of the converter (U_S). (b) Start-up operation with minimal load: output voltage (top), input current (middle) and input- and output power (bottom).*

During the start-up (from 0 to 0.2 s), the HV DC-link voltage increases linearly (see Figure 6(b)), even though the input current I_{Lk} is discontinuous (as shown in Figure 7(a)). Notice that the boost converter works in fly-back mode only during the start-up procedure. The coupling winding and the protection diode D_{S1} do not operate during the normal boost mode. Therefore, the additional winding on the main inductor and applied protection diode can be small.



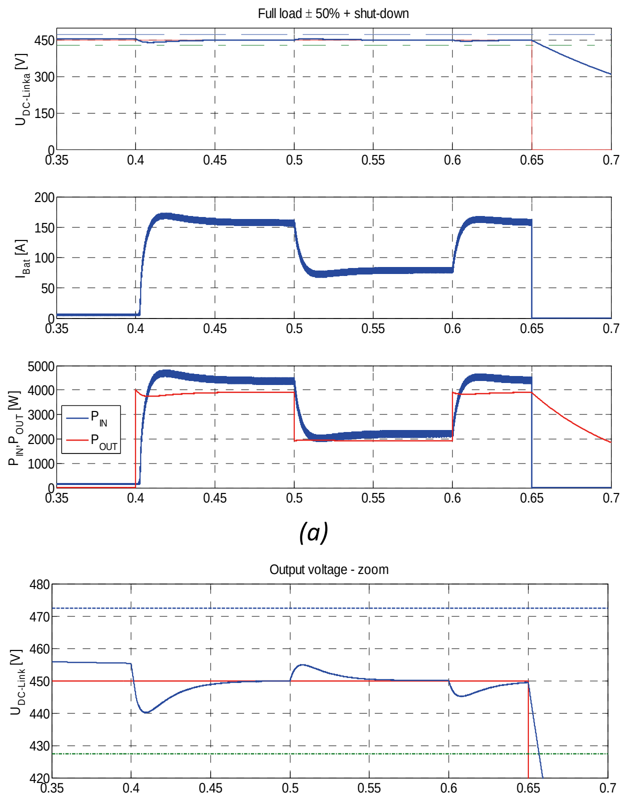
(a)



(b)

Figure 7: *(a) Start up of the isolated bi-directional DC-DC converter in boost mode: primary voltage, U_{DS} of the M_4, current through the protection diode D_{S1} and main inductor L_k. (b) Normal operation of the isolated bi-directional DC-DC converter in boost mode: driving signals and the inductor's voltage.*

The operation of the whole system in the boost-mode operation can be observed in Figure 7(b). During the normal boost operation, the inductor's voltage waveform is equal to the $U_{Lk} = U_{Bat}$ within the turn-on time and then equal to the $U_{Lk} = U_{Bat} - U_{DC}/n$ within the turn-off time. As predicted, the whole system is operating stably during the start-up with minimal load (i.e., for safety, there are always minimal load resistances R_{p1} and R_{p2} connected in parallel to the capacitors terminals; see Figure 2), as well with full-load (or half-load). Furthermore, immediate shut down is not dangerous (as shown in Figure 8(a) and with close examination of the output high voltage terminals in Figure 8(b)).



(a)

(b)

Figure 8: *(a) Steady-state operation with full/half load: output voltage (top), input current (middle) and input- and output power (bottom). (b) Output voltage is within the ± 5% limits.*

When over-voltage (or immediate shut-down) occurs, all of the MOSFET switches can be turned off because the energy stored in the main inductor can find its way through the protection diode D_{S1} to the output capacitor C_{DC} where it is used by the load, as confirmed in Figure 9(a) and (b), respectively.

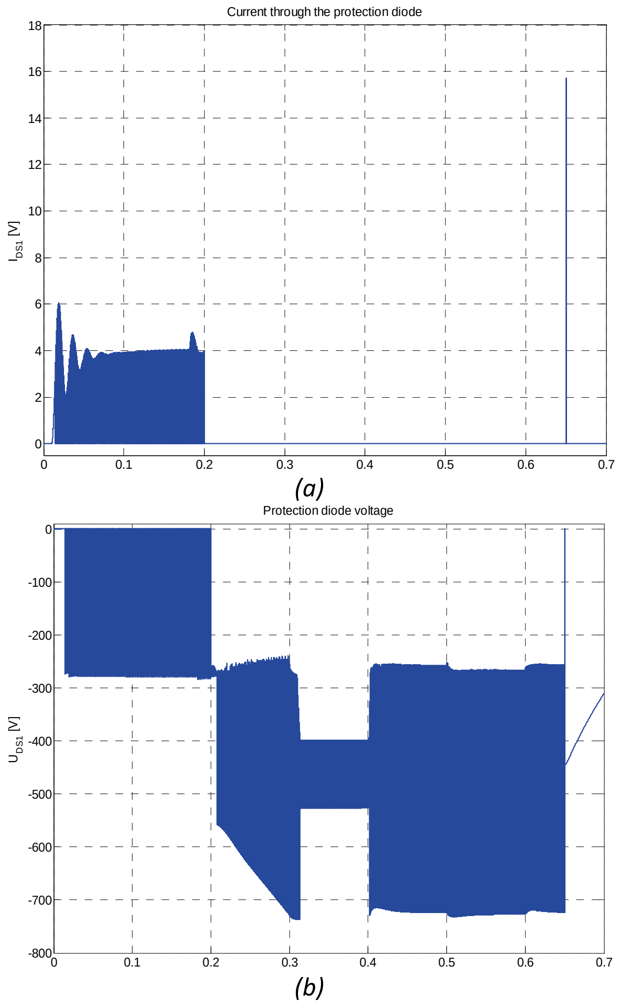


Figure 9: *(a) Current through the protection diode* D_{S1} *during start-up and at shut-down. (b) Voltage at protection diode* D_{S1} *during start-up and at shut-down.*

Based on the resulting waveforms in Figure 9(a),(b) the current and voltage rate of the protection diode D_{S1} can be chosen below 10 A and 1000 V, respectively. For other characteristics, the switching speed is very important, which leads to the decision that a Shottky diode should be used. The dissipation in this diode is limited, which means that no special cooling of the device is required.

3 EXPERIMENTAL SETUP AND RESULTS

In order to verify all the published theoretical background and the simulation results in the previous section, an experimental prototype of the bi-directional DC-DC power converter proposed in Figure 2 was built and is presented in Figure 10.

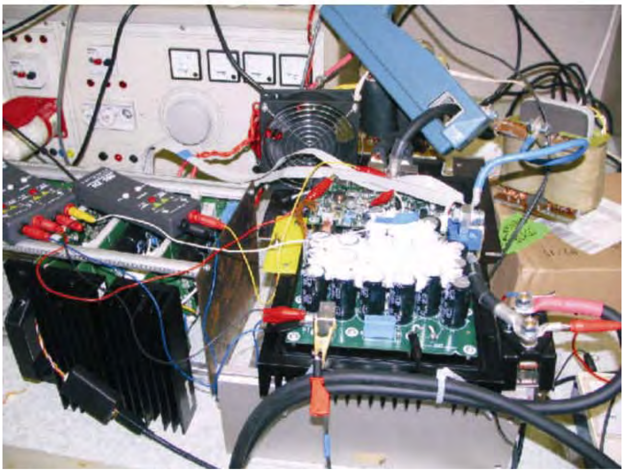


Figure 10: *Prototype of the bi-directional DC-DC converter.*

The simulation results, obtained by the exact model of the complete converter within the Matlab Simulink (shown in Figure 7(a)) and the experimental results (Figure 11) are in good agreement during the start up of the boost converter. The system was also tested under higher load conditions; results for U_{DC} = 450 V and P_o = 1000 W are shown in Figure 12. It is evident that the system is functioning stably and within the presumptions given at the beginning of this paper. Further investigations, measurements and optimizations are in progress.

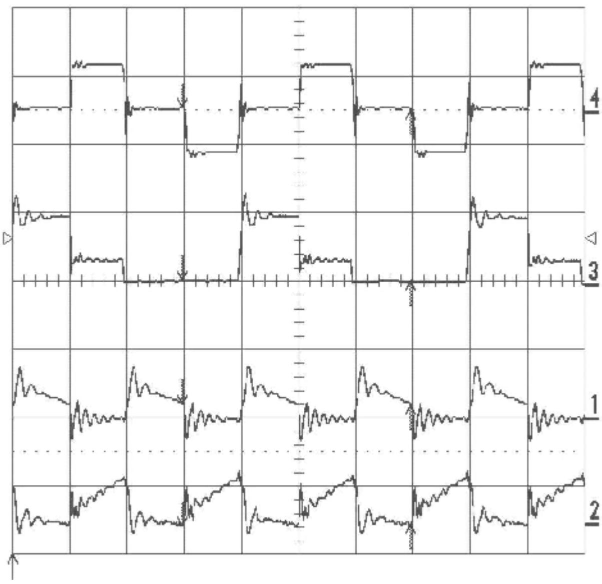


Figure 11: *Experimental results – start-up of the boost converter: CH1: I_{DS1} (1 A/div), CH2: I_{Lk} (10 A/div), CH3: U_{DS4} (40 V/div), CH4: U_p (200 V/div), time base (10 μs/div).*

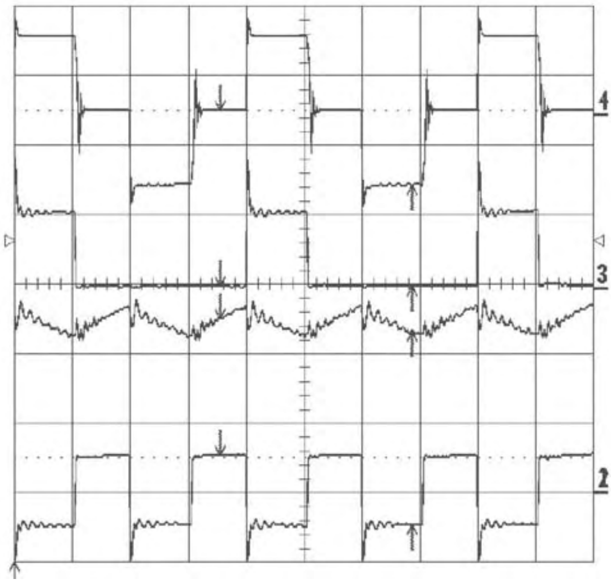


Figure 12: *Experimental results – steady-state of the boost converter: CH1: U_{Lk} (40 V/div), CH2: I_{Lk} (20 A/div), CH3: U_{DS4} (40 V/div), CH4: U_p (200 V/div), time base (10 μs/div).*

4 CONCLUSION

The new full-bridge topology of the isolated bi-directional DC-DC converter has been proposed and its safe operation has been discussed. The drawbacks of the conventional converter topologies during start up in buck- and boost-modes of operation have been presented, and solutions for safe start ups have been proposed. The solutions are based on the addition of coupling winding to the inductor and an extra diode connected to the output terminal. The operation of the proposed new topology has been verified by simulations and experimentally validated; the results are in good agreement. Based on this procedure, the building of the prototype was much easier with fewer unexpected obstacles and problems.

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Nomenclature

(Symbols)	(Symbol meaning)
D	duty ratio
f_S	switching frequency
n	transformer's turns ratio
t_{on}	turn-on time of the switch
T_S	switching period
U_{Bat}	battery voltage
U_{DC}	DC-link voltage

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CLEAN COAL TECHNOLOGIES AT VELENJE COAL MINE

ČISTE PREMOGOVNE TEHNOLOGIJE NA PREMOGOVNIKU VELENJE

Simon Zavšek[ℜ], Ludvik Golob, Janja Žula

Keywords: coal, best available technologies, energy efficiency, degasification, capture, transport and storage of CO_2, underground gasification of coal.

Abstract

The importance of coal is growing again after a rather long period in which it was not competitive against oil and natural gas as an energy resource.

There are important reasons for this: price per energy unit, the dispersion of global resources and the relation between global resources and consumption. The development of Clean Coal Technologies (CCT), friendlier to environment, keeps coal competitive.

The introduction and application of new and modern, best available technologies (BAT) enable keeping a substantial part of power supply in coal combustion irrespective of the increasing use of renewable resources and increased energy efficiency.

In future, new CCT will play a key role in assuring sufficient power production around the world and in the EU.

At the Velenje Coal Mine, we are aware of the problems occurring because of greenhouse gas emissions. Therefore, we launched a research project on CCT in 2007. This project is to apply the best available technologies that should contribute to more rational coal extraction, better safety at work and improved working conditions, as well as solving the environmental problems of coal gases.

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This paper presents the plans for the cleaner production, preparation and utilization of coal. In the framework of power generation, these plans enable the conditions for the transfer of knowledge, research results and technologies into working practice.

Regarding its definition, the concept of CCT is very wide; however, the research project at the Velenje Coal Mine consists of three main technologies: Lignite Degasification; the Capture, Transport and Storage of CO_2; and Underground Coal Gasification.

Accomplishing these, we intend to come closer to goals of Clean Coal Technologies, thereby improving the efficiency and environmental acceptability of lignite production, preparation and use.

Povzetek

Po dokaj dolgem obdobju, ko je bil premog kot energent v primerjavi z nafto in zemeljskim plinom nekonkurenčen in zaradi tega manj zanimiv, se njegov pomen v zadnjem času spet veča. Razlogov je več, in sicer: cena na enoto energije, različna razpršenost globalnih zalog in razmerje med svetovnimi zalogami in porabo. Prednost pred konkurentoma mu zagotavlja razvoj novih, ekološko bolj prijaznih tehnologij uporabe premoga, tako imenovanih čistih premogovnih tehnologij (Clean Coal Technologies). Zaradi uvajanja in uporabe novih modernih tehnologij (BAT) bo, kljub večji rabi obnovljivih virov in večji energetski učinkovitosti, mogoče še precej časa ohranjati znaten delež oskrbe z električno energijo iz premoga. Nove čiste premogovne tehnologije bodo v bodoče igrale ključno vlogo pri zagotavljanju zadostnih količin proizvedene električne energije tako po svetu kot tudi v EU in doma.

Ker se na Premogovniku Velenje zavedamo problemov, ki jih predstavljajo emisije toplogrednih plinov (TGP), smo že leta 2007 ustanovili razvojni projekt, ki je ciljno in razvojno naravnan v aplikacijo najboljših tehnologij, ki bodo prispevale k racionalizaciji procesa pridobivanja premoga, zagotavljanju večje varnosti in humanosti ter reševanju okoljskih problemov.

V prispevku so obravnavani in prikazani načrti za področje čiste proizvodnje, predelave in izrabe premoga, ki v okviru proizvodnje električne energije zagotavljajo pogoje za prenos znanj, rezultatov raziskav in tehnologij v prakso. Čeprav je pojem Čiste premogovne tehnologije glede na definicijo veliko širši, pa razvojni projekt na Premogovniku Velenje v tej fazi vsebuje tri pomembnejše sklope, in sicer: razplinjevanje lignita, zajem, transport in skladiščenje CO_2 in podzemno uplinjanje premoga. Z realizacijo navedenih sklopov se nameravamo približati ciljem, ki jih obsegajo Čiste premogovne tehnologije in so izboljšanje učinkovitosti in okoljske sprejemljivosti pridobivanja lignita, njegove predelave in izkoriščanja.

1 INTRODUCTION

Irrespective of growing use of renewable energy resources and better energy efficiency, oil, gas and coal will represent a substantial part in the power supply for the foreseeable future. The importance of coal is growing again after a rather long period in which it was not competitive against oil and natural gas as an energy resource. There are some important reasons for this: price per energy unit, the dispersion of global resources and the relation between global resources and consumption. Clean Coal Technologies are friendlier to environment and their development also enables the coal consumption for future power generation. Coal-based power generation represents more than 40% of global energy production, Kessels, [7]. The

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author cites many reasons for that. Among these, is the fact that the coal is often a state's own energy resource, thereby enabling energy security and independence. The next reason relates to global coal production and consumption (reaching 6 Gt), bearing in mind that, contrary to other primary energy resources, coal resources are abundant. Kessels notes that coal resources in Alaska reach over 5 Gt, i.e., more than 40% of coal resources in the USA.

Figure 1 shows the energy production forecast to 2030; it can be seen that the coal, in addition to nuclear power and renewable resources (together with energy efficiency), is playing a key role in assuring sufficient power production, Tanaka, [9]. Global power demand will rise by 45% until 2030, with the average annual rise is estimated at 1.6%. The share of coal is one third of the entire growth. This forecast was designed before the economic crisis and therefore does not reflect its effects.

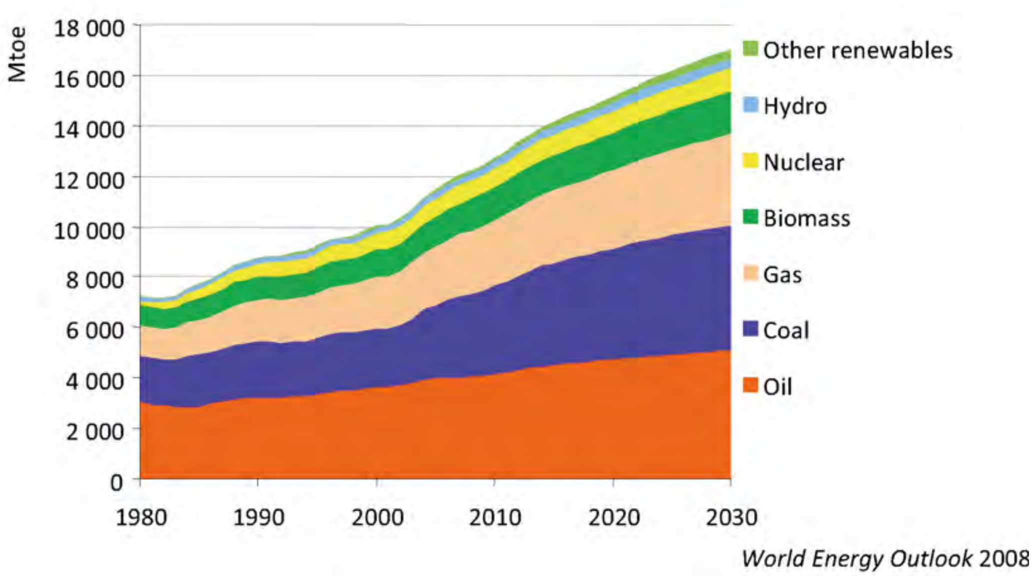

***Figure 1**: Energy production forecast till 2030 (reference scenario, IEA [6])*

2 CLEAN COAL TECHNOLOGIES

Clean Coal Technologies (CCT) are tied to technological progress leading to more efficient and environmentally friendly coal consumption. The plan and explanation of Clean Coal Technologies follow the DTI/IEA 1999 standard, DTI/IEA [2]. As seen in Fig. 2, the concept is very wide and includes:

a) Coal production, preparation, transport and coal yard;

b) Unconventional coal production through Underground Coal Gasification (UCG) or extracting methane from underground coal seams, i.e., Coal Bed Methane Extraction (CBME);

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c) Power generation through combustion of pulverised coal, i.e., Pulverised Fuel Combustion (PC);

d) Power generation through coal gasification, i.e., Integrated Gasification Combined Cycle (IGCC);

e) Other possible advanced technologies, such as hybrid combined cycles, heat engines, fuel cells;

f) Industrial and domestic use of coal in steel production, cement industry, heating plants;

g) Other technologies that turn coal into energy, such as liquefaction or briquetting;

h) Combustion remains use: fly ash, clinker, gasification remains, gas cleaning remains (gypsum);

i) other clean CCT possibilities including co-combustion of natural gas, biomass, co-generation and capture, transport and storage of CO_2, i.e., Carbon Capture and Storage (CCS).

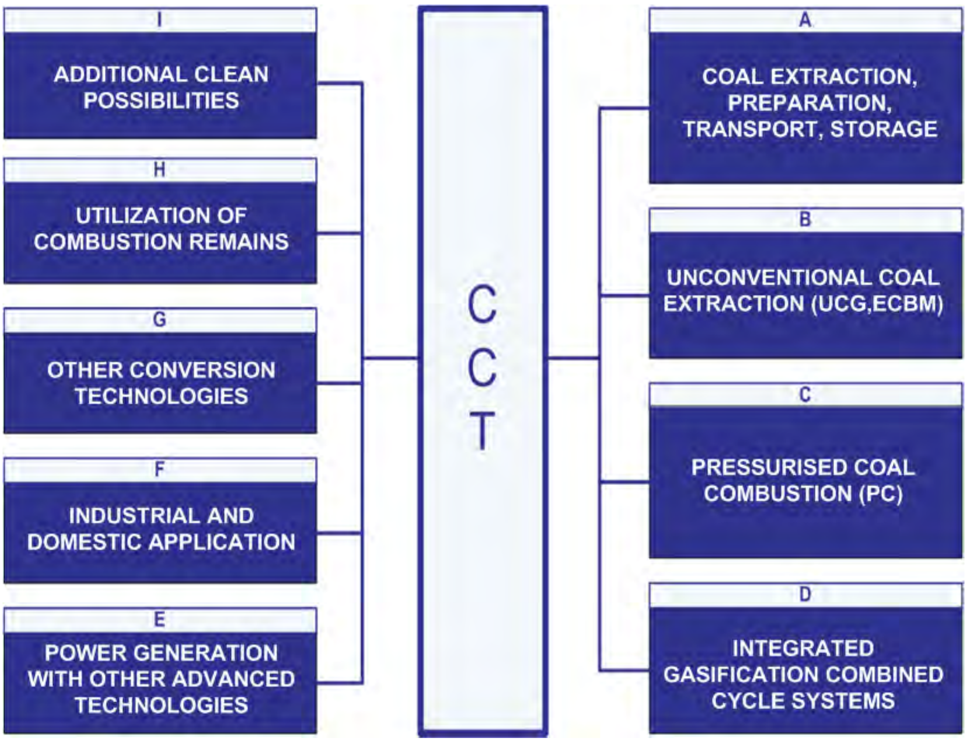

Figure 2*: Diagram of CCT (adapted after methodology of DTI/EIA 1999)*

The process of lignite production at the Velenje Coal Mine includes the activities of coal extraction, coal preparation, coal transport, coal yard (A), combustion remains use; in the nearby thermal power plant TE-Šoštanj the process of power generation with pulverized coal

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combustion is mastered (C). According to the Clean Coal Technologies Project, we are incorporating some other fields, including underground coal gasification possibilities and coal bed methane (B), power generation through coal gasification (D) additional clean possibilities (I).

3 DEVELOPMENT PROJECT CCT AT VELENJE COAL MINE

According to long-term production plan of lignite in Velenje Coal Mine, projected to 2045 and presently assuring a 30% share of Slovenia's power production, we decided to follow global trends and founded a project group to deal with these problems at the end of 2007. Fig. 3 shows the Clean Coal Technologies project's three sections: Lignite Degasification, Capture, Transport and Storage of CO_2 and Underground Coal Gasification.

3.1 Lignite degasification

Lignite degasification is obtaining methane in the process of lignite degasification. As the coal gas of the Velenje mine contains methane in addition to CO_2, we plan to capture both and therefore the part section of the project is referring also to activity I, i.e., other clean possibilities (CO_2 capture and storage). Regarding the fact that degasification of thin coal seams has long been an understood and practiced procedure, the Velenje Coal Mine will focus on the degasification development of a very thick coal seam. We plan to degasify the excavation pillars before coal excavation with the longwall method.

One of the goals of the degasification project should be the development of a statement on the development and application of the best technologies that contribute to the rationalization of the coal extraction process. Degasification diminishes the amount of gas at the active longwall face and positively affects production. Reduction of gas amounts in the excavation pillar contributes to better safety and working conditions, as the reduced gas concentrations allow reduced air volumes and, in consequence, ventilation that is more rational and has fewer problems with coal dust. The project is divided into the technological, and the research and development parts. In the technological part, the Slovenian project partners in a consortium. The development part of the project is constituted internationally and registered for co-funding with the RFCS (Research Found for Coal and Steel) fund. Both projects will last for three years, starting with the developmental part, followed by the project itself. Project activities will consist of a revision of basic coal seam and excavation data, field and laboratory research of important coal seam characteristics, *in situ* measurements and analysis of the longwall face advance on stresses, gas pressure, gas permeability and gas diffusion. The project foresees monitoring activities too. Common interpretation and numerical modelling of field and laboratory results for degasification planning and gas outburst control will follow. The project will conclude with a pilot test draining meant as a system for controlled degasification and control of gas outbursts at coal excavation of very thick coal seams.

Through the coordination of research projects such as gas component tracking, Velenje lignite petrography, and the structural model, and through doctoral study education, the research results of other projects are also incorporated into the project.

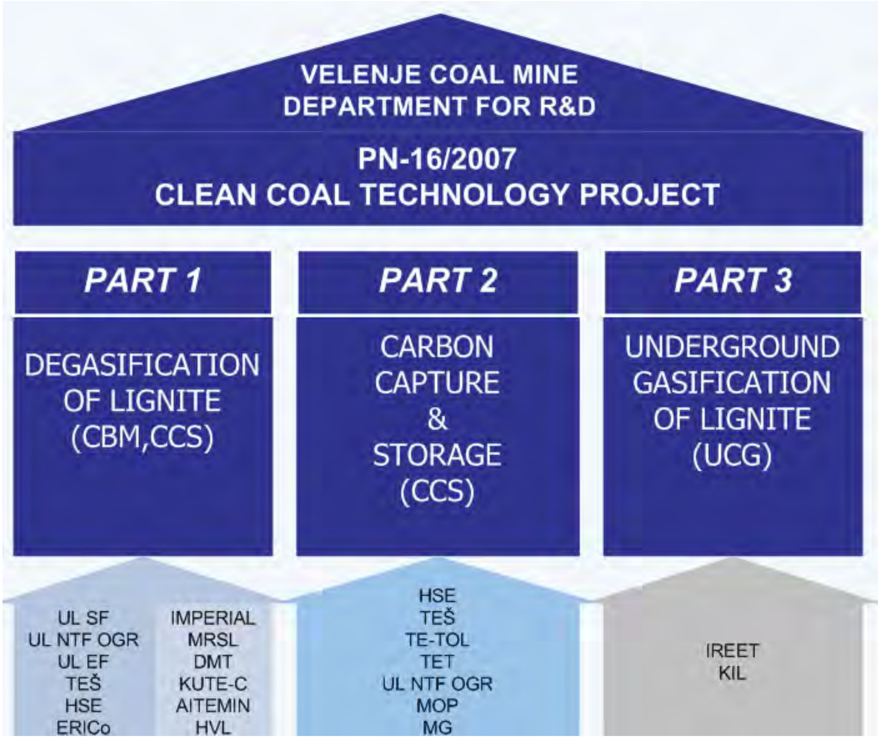

Figure 3: *Scheme of Clean Coal Technologies Project (Zavšek, [12])*

3.2 CO_2 capture, transport and storage (CCS)

In general, the CO_2 gas from power plants and industrial units must be captured, compressed and transported to the areas where sufficiently deep storage is possible. The CO_2 source is coal, gas, oil and biomass combustion. The major part of the CO_2 results from power and heat production, from chemical plants, steel and cement production. CCS technology represents the key to safe fossil fuel use, and therefore remains a real option for transitioning beyond the period of intensive fossil fuel use, Kessels, [7].

The known fossil fuel resources in the world contain a huge amount of carbon that will threaten the atmosphere. The described technology can help to realize plans for diminished increase of CO_2 in the atmosphere.

The situation considering the average efficiency and emissions per produced energy unit is as follows: world 28% (1110 gCO_2/kWh), EU 36% (880 gCO_2/kWh). Today, the reachable PC or IGCC TE technologies are nearing the efficiency of 42% and emissions of 740 gCO_2/kWh.

A very important short-term measure is to increase the efficiency. The goals for the further technological development until 2020 are heading towards 48% and 665 gCO_2/kWh, but the essential emissions decrease, which is expected after 2020, will require commercially affordable CCS technologies (Tanaka, [9], after VGB 2007: efficiency HHV.net, Topper, [10]).

In Europe, more specifically in Germany, the plans for pilot and demonstration CCS projects are ready and some of them are already running, Höll, [4].

Capture, transport and storage of CO_2 are at Velenje Coal Mine placed into the second part of the Clean Coal Technologies Project complex. Activities coordinated by HSE (Holding of Slovenian Power Plants) are a part of the project called Implementation of the Climate – Energy Package in Slovenian Thermal Energy (ZETe-PO) with the goal of reducing GHG emissions in the post Kyoto era (Fig. 4).

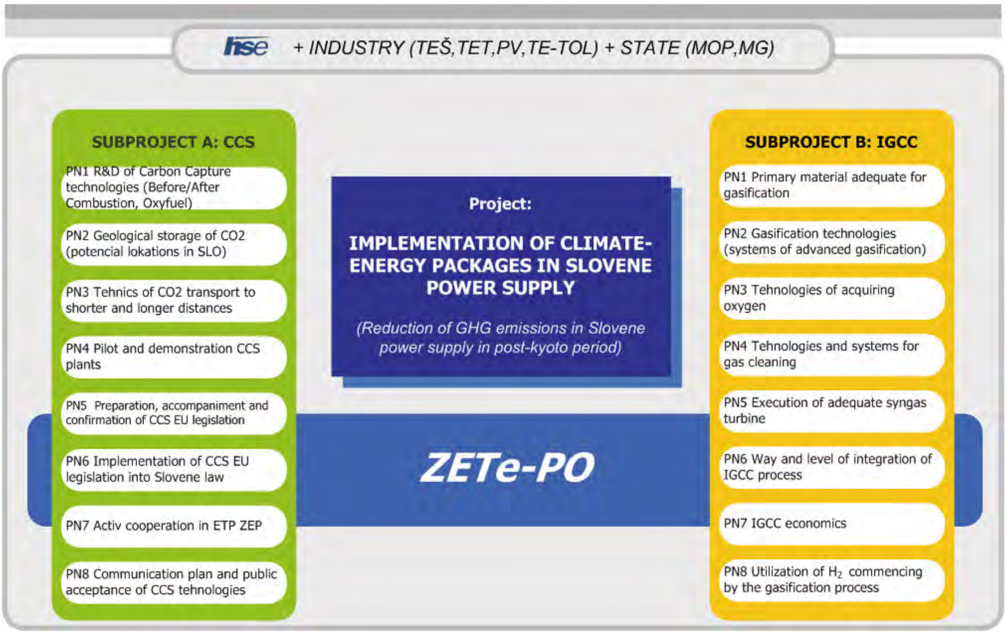

Figure 4*: Scheme of the ZETe-PO project*

Besides the coordinator and project leader HSE, the Slovenian thermo-energy companies and MOP (Ministry for Environment and Spatial Planning) and MG (Ministry for Economy) are involved. The ZETe-PO project is divided into two sub-projects: the first includes CCS (Carbon Capture and Storage) technologies and the second IGCC (Integrated Gasification Combined Cycle) technologies. The first sub-project is interesting for the Velenje Coal Mine because of geological CO_2 storage, implementation of EU legislation covering CCS, implementation of CCS legislation in Slovenia and active cooperation in the ETP ZEP. The project has been launched and is in the phase of collecting tenders for project tasks and application of co-funding of single projects in different EU programmes. In recent years, the Velenje Coal Mine funded and cooperated in CO_2 storage research where the possibilities of storage in geological formations and primarily the coal seam were studied, Orešnik et al., [8].

3.3 Underground coal gasification

The underground coal gasification, representing the third part of our project, is an unconventional type of coal utilization. In general, the procedure is quite simple, as only two boreholes (or two wells) are needed (Fig. 5). Through the injection well, air and steam are brought under pressure into the coal seam where the combustion begins. The production well is used to obtain the gas, called "synthetic gas" or "syngas". The main components of syngas are hydrogen and carbon monoxide. The underground coal gasification (UCG) technology is very complex and demanding as the most successful tests in the world have shown. UCG needs a multidisciplinary approach of geology, hydrogeology, chemical engineering, chemistry and thermodynamics.

The most interesting advantage of the UCG will be economic, because minor operative and investment costs are foreseen. The next advantage should be the flexible use of syngas. Even the environmental view is considered advantageous, as most combustion products remain underground, including heavy metals SOx, and NOx, Couch, [1]. The costs for CO_2 separation are minor; there may be possibilities for carbon storage in the cavities or adjacent rocks. The disadvantages of the UCG are the operational risks due to the lack of tested large-scale UCG trials and the frequent problems that have occurred during tests in the USA and Europe. The process can be uncertain considering environmental impacts and public acceptability. The possible disadvantages may be the ground water pollution (contamination) and surface subsidence. The UCG product can be used in different ways: co-generation, gas turbine, from coal to liquids etc.

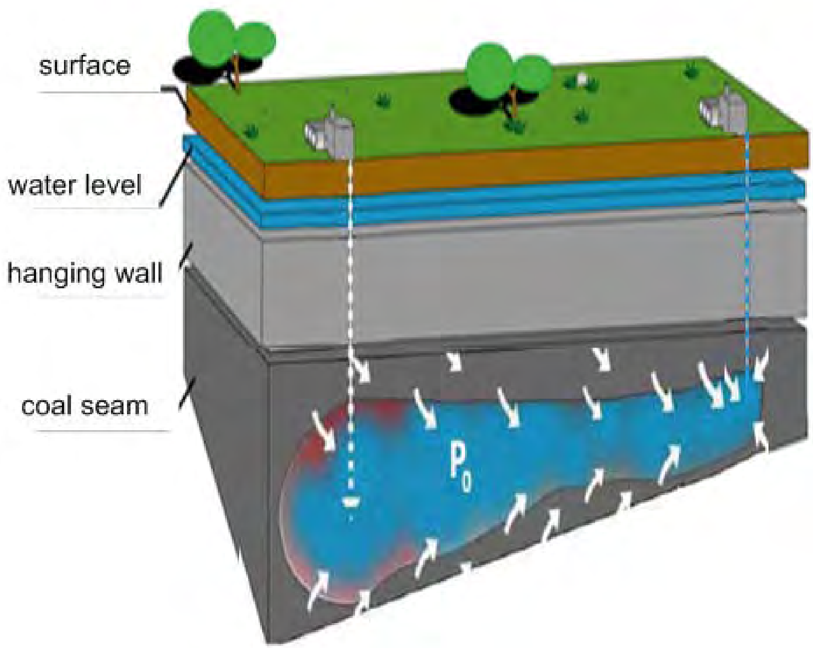

***Figure 5**: Sketch of the underground coal gasification procedure (UCG)*

Regarding UCG, the Velenje Coal Mine has a longer history. In the late 1950s, a study on UCG possibilities in the lignite deposits of former Yugoslavia was completed at the Chemical Institute in Ljubljana (Kemijski inštitutu Borisa Kidriča) In the 1980s, some laboratory testing was done on smaller samples as well as bigger samples of Velenje lignite, Eberl, [3]. In 2002, a feasibility study of UCG in Velenje Coal Mine was not entirely completed, but the finished component parts comprise the preliminary deposit evaluation, deposit evaluation with analysis of existent data (general data, geology, hydrogeology), additional resource characterization, technological difficulties of the process, and technological difficulties of deposit preparation. The study did not examine the issues of process product use, environmental susceptibility, economy and final evaluation.

Through the third section of the Clean Coal Technologies Project at Velenje Coal Mine, the task force has been revived and the feasibility study continued with the missing parts. Important factors are discussed include process product use (quantity and quality of the product, product quality oscillation, size of the energetic structure, and energetic use of the product), economy and final evaluation. In continuation the activities will run to prepare the proposal of project task for pilot UCG test in Velenje, to gain the concession for research of coal in Goričko (Slovenia) and to prepare a proposal of project task for pilot UCG test in Goričko, Zavšek, [12].

3.4 Conclusion

Through realization of the goals of the Clean Coal Technologies Project, the way to development and application of best available technologies is paved. This will contribute to more rational coal extraction, better safety at work, better working place condition and solving the environmental problems regarding coal gases.

In the fields of coal production and conventional or unconventional coal utilization, the Clean Coal Technologies Project brings conditions for transfer of knowledge, research results and technologies into practical work. Based on the realization of the research and development phases of the technologies discussed, we can continue to follow innovation; the task force's work is aimed at the acquisition of national and European research funds and the opening of market possibilities.

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ENERGY POLICY FOR PRODUCTION RESOURCES

ENERGETSKA POLITIKA ZA PROIZVODNE VIRE

Drago Papler, Štefan Bojnec[ℜ]

Keywords: competitiveness, efficiency, renewable sources of energy, energy policy, education, sustainable development, factor analysis

Abstract

The Republic of Slovenia's most recent energy policy, with the adoption of the climate-energy package and obligations of the European Union, gives greater importance to alternative sources of energy and to climate change. How realistic it is to set an obligation for a 20% share of renewable sources of energy in the primary structure of energy by 2020 or the even higher 25% share set in Slovenia?

Surveys, using a written questionnaire, were conducted among the managers in the energy sector, focusing on competitiveness in supply, efficient use of energy and sources of energy. With this research, we have analysed the opinions among experts on these questions, and we compare the results with the other surveyed groups from the social sciences, natural sciences, and electrical energy education. The methods of the analysis used are descriptive statistics with calculations of mean values, correlation analysis and multivariate factor analysis, which are based on the survey data. In the research, we find associations between different factors and their impacts within the identified common factors. The comparisons of the results provide opportunities to derive implications on similarities and differences in the opinions between different professional groups and user structures. The average age of the managers in the sample in the energy sector was 39.4 years. The education structure is rather normally distributed; the average amount of completed education per manager is 16.0 years.

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The multivariate factor analysis confirmed three common factors for competitiveness in energy supply. The first one has the highest weights in the factors of energy in the economy, costs and CO_2 emissions, which are termed “energy costs in the economy”. The second common factor has the highest weights in research and development, alternative sources of energy, ecology, prices of energy, competitiveness and knowledge, which jointly represent “sustainable development of knowledge for competitive energy supply”. The third common factor has the highest weights in the factors safe use of energy and ecology, which gives the common factor of “efficient use of clean energy”.
The highest opinion marks are given to knowledge, savings with energy, research and development as well as to alternative sources of energy. The lowest opinion marks are given to costs, prices, and competitiveness.
The research of opinions on sources of energy confirmed three common factors. The first one has the highest weights in the factors of perception, awareness, subsidies, promotion, fuel cells, biomass, chemical means, food for energy (orientation of agriculture from production of food also to production for needs of energy is balanced), geothermal energy, intensity in agriculture, ecological conditions, and co-production, which is termed “energy policy, awareness, supports, and promotion of renewable sources of energy”. The second common factor has the highest weights in factors wind energy, solar energy, energy from agriculture, feasibility of adopted obligations, small hydroelectricity plants, hydroelectricity plants, food for energy, geothermal energy, and biomass; these are termed “natural potentials of renewable sources of energy”. Nuclear power energy is evaluated differently. The third common factor has the highest weights in factors chemical means, nuclear power energy, fossil fuels, education, and self-sufficiency, which gives the common factor of “self-sufficiency of conventional energy sources”.
The highest mean values of opinion marks are given to efficient use of energy in transport, alternative sources of energy such as solar energy and wind energy, education, and hydroelectricity plants. The lowest mean values of opinion marks are given to subsidies, fuel cells, and perception on energy use. Beliefs on the feasibility of a 25% share of renewable sources of energy by 2020 are evaluated with the average mark of 3.20.

Povzetek

Najnovejša slovenska energetska politika s sprejetjem podnebno-energetskega paketa in zavez EU daje alternativnim energijam in klimatskim spremembam večji pomen. Ali bo zahteva 20 % deleža obnovljivih virov energije v primarni strukturi leta 2020, oziroma še višja 25 % slovenska zaveza uresničljiva? Med energetskimi menedžerji in intelektualci je bila izvedena raziskava o konkurenčnosti in učinkoviti rabi energije ter virih energije. Z njo smo ugotavljali kakšno mnenje imajo strokovnjaki o teh vprašanjih in rezultate primerjali z drugimi značilnimi anketiranimi skupinami iz družboslovja, naravoslovja in izobraževanja na področju električne energije. Kot metode analize so bile uporabljene opisne statistike z izračunom srednjih vrednosti, korelacijska analiza in multivariatna faktorska analiza na anketnih podatkih. V raziskavi smo ugotovili medsebojno povezanost posameznih dejavnikov in njihov vpliv znotraj ugotovljenih skupnih faktorjev. Rezultati nam dajejo podobna mnenja in različne poglede med poklicnimi skupinami in uporabniškimi strukturami. Anketiranci v skupini energetski management so imeli povprečno starost 39,4 let in dokaj enakomerne porazdelitve glede na izobrazbo; njihovo povprečno število dokončanih let izobraževanja je bilo 16,0.

Pri raziskavi o konkurenčni dobavi energije so se potrdili trije skupni faktorji. Prvi skupni faktor ima največjo težo v dejavnikih energija v gospodarstvu, stroški in toplogredni plini, zato ga

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poimenujemo energetski stroški gospodarstva. Drugi skupni faktor ima največjo težo v dejavnikih raziskave in razvoj, alternativni viri energije, ekologija, cene energentov, konkurenčnost in znanje, to je trajnostni razvoj znanja za konkurenčno oskrbo z energijo. Tretji skupni faktor ima največjo težo v dejavnikih varčna raba energije in ekologija, kar daje skupni imenovalec v učinkoviti rabi čiste energije.
Najvišje srednje ocene so anketiranci namenili znanju, varčevanju z energijo, raziskavam in razvoju ter alternativnim virom energije. Najnižje ocene pa stroškom, cenam in konkurenčnosti.
Pri raziskavi o virih energije so bili izraziti trije skupni faktorji. Prvi skupni faktor ima največjo težo v dejavnikih zavest, ozaveščanje, subvencije, promocija, gorivne celice, biomasa, kemijska sredstva, hrana za energijo (usmeritev kmetijstva iz proizvodnje hrane tudi na proizvodnjo za potrebe energije je uravnotežena), geotermalna energija, intenziteta kmetijstva, okoljski pogoji in soproizvodnja, zato ga poimenujemo energetske politike, ozaveščanje, podpore in promocija za obnovljive vire energije. Drugi skupni faktor ima največjo težo v dejavnikih vetrna energija, sončna energija, energija iz kmetijstva, uresničljivost sprejetih zavez, male hidroelektrarne, hidroelektrarne, hrana za energijo, geotermalna energija in biomasa, nasprotno usmerjena pa je jedrska energija, to je naravnih potencialov obnovljivih virov energije. Tretji skupni faktor ima največjo težo v dejavnikih kemijska sredstva, jedrska energija, fosilna goriva, izobraževanje in zadostnost, kar daje skupni imenovalec v zadostnosti konvencionalnih energetskih virov.
Najvišje srednje ocene so anketiranci namenili učinkoviti rabi energije v transportu, alternativnim virom energije kot sta sončna energija in vetrna energija, izobraževanju in hidroelektrarnam. Najnižje ocene pa subvencioniranju, gorivnim celicam in zavesti. S povprečno oceno 3,20 od maksimilno možno 5 anketiranci verjamejo v uresničljivost 25 % deleža obnovljivih virov energije do leta 2020.

1 INTRODUCTION

The questions of managing the global common resources and the economics of global climate change have raised the awareness of linking energy, environment, economy, and equity [1], [2] and [3]. Efficient energy use and the use of renewable sources of energy are among the important strategic energy objectives in Slovenia. The Slovenian presidency of the European Union (EU) in the first half of the 2008 presented the climate-energy package, which was accepted by the EU Commission. This implies the importance of sustainable energy management in Slovenia as well as in the EU.
The Ministry of Environment and Spatial Planning of Slovenia has promoted projects on renewable sources of energy by 2020. Studies have been completing on the focusing of competitive energy supply, efficient energy use, and renewable sources of energy [4], [5], [6], [7] and [8]. Therefore, this paper aims to present some findings from the in-depth analysis on the suppliers' and users' opinions regarding these questions, in order to promote education and policies that increase awareness towards more efficient supply and use of energy as well as for a greater investments and the use of the renewable sources of energy.
We first present the methodology and data based on the in-depth surveys. The body of the paper deals with the findings of the research on the importance of efficient energy use and on renewable sources of energy, focusing on the production of electrical energy on the current status and opportunities to achieve the objective of 20% of renewable sources of energy by 2020. We have found that among the important determinants to achieve this objective are the education and promotion activities that contribute to raising awareness and improving public opinion for promotion of more efficient energy use and for the increasing role of the renewable

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sources of energy (hydro-electricity, solar and wind energy, biogas, biomass and similar) in sustainable energy and economic development in Slovenia.

2 METHODOLOGY AND DATA

2.1 Methods of analyses

For the methods of the analyses, we employ correlation and multivariate factor analyses using the unique in-depth survey data. The absolute value of the correlation coefficient indicates the degree of linear association between the pairs of the analysed variables. The multivariate factor analysis will show the main common factors that are important for the explanation of the analysed question with the importance of the weights for the included variables [9].

2.2 The survey's questionnaire

The in-depth surveys were conducted in June 2008 by using a written questionnaire. We received 516 completed questionnaires for four target professional groups: social sciences (Faculty of Management Koper), natural sciences (Naklo Biotechnical Centre), electrical energy (Education Centre of the Energy System of Ljubljana) and energy management (the magazine EGES with focuses on energy, the economy and ecology). Our focus is on the energy management group

2.3 Structure of the surveyed persons

Among the surveyed persons in the energy management group, over two thirds are men (68.4%). The average age is 39.4 years. The average duration of the education is 16 years; the most frequent single separate group is with the university education (34.2%), then higher vocational education (17.9%), Master of Science (16.2%), specialist (8.5%), higher education (6.8%), secondary education (6%), doctor of science (5.1%), Bologna I (4.3%) and Bologna II (0.9%).

3 COMPETITIVE ENERGY SUPPLY

3.1 Summary statistics

In the empirical analysis, 13 variables that are important for competitive supply in the electro-energy system are included: progress, costs, energy in the economy, electricity in households, price of electrical energy in households, price of energy, competitiveness, reducing energy use (i.e., economical energy use), ecology, emissions of CO_2, alternative sources of energy, knowledge and research and development. The opinions were evaluated by the use of a Likert scale from 1 (not important) to 5 (very important). The highest mean values are found for: knowledge (4.6), saving energy use (4.5), research and development (4.4), alternative sources of energy (4.4), ecology (4.34), and emissions of CO_2 (4.32).
For competitive supply and efficient use of energy, the empirical results show high expectations regarding the research and development of new solutions and technologies that will contribute to the environmentally friendly supply of energy and thus contribute to sustainable environmental development. The surveyed persons are aware of the importance that energy

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use has for environment and regarding measures for saving energy use. The suppliers of electrical energy are less recognised on the market, and they do not experience significantly different prices for the alternative supply of electrical energy. They call for more competitive supply of electrical energy and energy in general.

3.2 Correlation matrix

The correlation matrix shows the direction and intensity of association between the analysed variables. The Pearson correlation coefficients show relatively modest intensity of the associations between the analysed variables. The highest partial correlation coefficient is found between the variables for costs and energy in the economy (0.531), saving use of energy and ecology (0.528), and alternative sources of energy and research and development (0.513).

3.3 Multivariate factor analysis

We perform the factor model in two steps: first, we estimate the share of the explained variance of the analysed variables with the common factors with the principal axis factoring and with the maximum likelihood method. Second, we estimate factor weights with the use of the rotations with the Oblimin-Kaiser normalisation and with the Varimax-Kaiser normalisation (Table 1). The scree plot indicates the break point at the third factor. The factor model with the three common factors cumulatively explain 46.5% of the variance of the analysed variables: the first common factor at 24.6%, the second common factor at 11.3% and the third common factor 10.6%.

3.3.1 Principal axis factoring method

The principal axis factoring method confirms three common factors. The first common factor is efficient energy use, which has the highest weights in variables for research and development, energy in the households, ecology, costs, alternative sources of energy, saving energy use, electricity in households, emissions of CO_2, knowledge, competitiveness, and progress. The second common factor is sustainable knowledge development for the competitive supply of energy, which has the highest weight in the variable for an efficient energy use. The third common factor is knowledge for the management of energy costs, which has the highest weights in the variables for knowledge, the price of electricity in households, and electricity in the economy.

3.3.2 Maximum likelihood method

The maximum likelihood method, without rotation of factors, indicates that within the first common factor (the energy costs for the economy) the variables for energy in the economy, saving energy use, ecology, emissions of CO_2, and costs have the highest weights. The second common factor (efficient energy use) has the highest weights in the variables for saving energy use, energy in the economy, and costs. The third common factor (sustainable knowledge development for competitive energy supply) has the highest weights in the variables for research and development, alternative sources of energy, ecology, price of energy, competitiveness, costs, and progress.

3.3.3 Maximum likelihood method – Oblimin with Kaiser normalisation

The Oblimin with Kaiser normalisation maximum likelihood method strengthened the impact of the individual factors, and confirmed the stability of the estimations. In the first common factor (the energy costs of the economy), the highest weights are in the variables for energy in the economy, costs, emissions of $CO_{2,}$ and research and development. The second common factor (the efficient use of energy) has the highest weights in the variables for saving energy use and ecology. The third common factor (the sustainable knowledge development for competitive energy supply) has the highest weights in the variables for research and development, alternative sources of energy, ecology, costs, competitiveness, price of energy, progress, electricity in households, and knowledge.

3.3.4 Maximum likelihood method – Varimax with Kaiser normalisation

The Varimax with Kaiser normalisation maximum likelihood method reinforces the previous findings. The first common factor (energy costs for the economy) has the highest weights in the variables for energy in the economy, costs, and emissions of CO_2. The second common factor (the sustainable knowledge development for competitive energy supply) has the highest weights in the variables for research and development, alternative sources of energy, price of energy, competitiveness, progress, and knowledge. The third common factor (efficient energy use) has the highest weights in the variables for saving energy use and ecology.

	Principal axis factoring method[a]			Maximum likelihood method[b]			Maximum likelihood method – Oblimin with Kaiser normalisation[c]			Maximum likelihood method – Oblimin with Kaiser normalization			Maximum likelihood method – Varimax with Kaiser normalisation[d]		
	Factor Matrix			Factor Matrix			Pattern Matrix			Structure Matrix			Rotated Factor Matrix		
Factors	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Progress	.299	.085	.031	.130	.023	.272	.043	-.036	.272	.142	-.128	.296	.089	.279	.074
Costs	.537	.149	-.212	.431	.314	.240	.492	.047	.218	.549	-.162	.364	.508	.286	.046
Energy in the economy	.561	.129	-.101	.762	.647	-.001	1.047	.134	-.061	.988	-.157	.241	.996	.089	.000
Electricity in households	.446	.132	.335	.278	.051	.230	.181	-.100	.207	.277	-.214	.294	.223	.247	.147
Price of electricity for households	-.025	.112	.360	-.080	.077	-.019	.007	.114	.000	-.026	.112	-.031	-.009	-.016	-.111
Price of energy	.164	.240	.061	-.037	-.006	.330	-.114	.040	.357	-.010	-.030	.308	-.062	.326	-.010
Competitiveness	.348	-.123	-.260	.204	-.117	.294	-.018	-.202	.271	.130	-.276	.324	.053	.294	.229
Saving energy use	.502	-.704	.142	.761	-.649	-.001	.042	-1.025	-.179	.286	-.986	.133	.161	-.013	.986
Ecology	.538	-.293	.133	.463	-.272	.346	.034	-.489	.272	.267	-.578	.425	.146	.346	.516
Emissions of CO2	.422	-.104	-.048	.453	.141	.010	.431	-.138	-.048	.457	-.252	.133	.435	.044	.186
Alternative sources of energy	.536	.194	-.286	.261	.153	.547	.169	.024	.557	.343	-.188	.605	.248	.570	.068
Knowledge	.404	.241	.530	.230	.060	.223	.155	-.064	.208	.242	-.171	.277	.193	.239	.109
Research and development	.613	.202	-.135	.302	.161	.703	.165	.018	.718	.394	-.240	.766	.270	.728	.092

Table 1: *Competitiveness, ecology and energy (matrices of five different extraction methods with three components extracted)*

Cronbach's Alpha measures accuracy of measurement: Cronbach's ά factor 1 = 0.662, N=3 (energy in the economy, costs, and emissions of CO_2). Cronbach's ά factor 2 = 0.537, N=6 (research and development, alternative sources of energy, price of energy, competitiveness, progress, and knowledge). Cronbach's ά factor 3 = 0.686, N=2 (saving energy use, and ecology). [a] 25 iterations, [b] 19 iterations, [c] 6 iterations, [d] 4 iterations.

4 SOURCES OF ENERGY

4.1 Summary statistics

Twenty-three variables on sources of energy, development supports and knowledge are investigated: fossil fuels, feasibility 25%, sufficiency 25%, nuclear energy, transport, ecological conditions, wind energy, hydroelectricity plants (HE), small hydroelectricity plants (SHE), solar energy, co-production, intensity in agriculture, chemical means, energy from agriculture, food for energy, biomass, geothermal energy, fuel cells, subsidies, awareness, consciousness, promotion and education. The Likert scale from 1 (not important) to 5 (very important) is used. The highest opinions are for transport (4.55), solar energy (4.24), wind energy (4.03), education (3.89), hydroelectricity plants (3.79), and small hydroelectricity plants (3.78).

4.2 Correlation matrix

The Pearson correlation matrix indicates significant associations between consciousness and promotion (0.635), awareness and subsidies (0.628), food for energy and chemical means (0.618), consciousness and subsidies (0.607), awareness and promotion (0.579), consciousness and awareness (0.561), biomass and geothermal energy (0.553), hydroelectricity and small hydroelectricity plants (0.545), consciousness and biomass (0.535), awareness and fuel cells (0.521).

4.3 Multivariate factor analysis

The multivariate factor analysis confirms three common factors, which explain 44.3% of the variance of the analysed variables: the first explains 26.7% of variance, the second an additional 10.6% of variance and the third an additional 7.0% of variance.

4.3.1 Principal axis factoring method

The principal axis factoring method reveals three common factors. The first common factor on energy policy, awareness, government support and promotion for renewable sources of energy has the highest weights in the variables for consciousness, food for energy, promotion, subsidies, chemical means, awareness, biomass, geothermal energy, intensity in agriculture, fuel cells, energy from agriculture, small hydroelectricity plants, ecological conditions, co-production of energy, sufficiency at 25% of renewables, and hydroelectricity plants. The second common factor on the natural potential of renewable sources of energy has the highest weights in the variables for wind energy, solar energy, small hydroelectricity plants and feasibility at 25% of renewables. The third common factor on conventional energy sources has the highest weights in the variables for fossil fuels, nuclear energy, and intensity of agriculture.

4.3.2 Maximum likelihood method

The maximum likelihood method without rotations of factors confirms that within the first common factor (energy policy), awareness, government supports and promotion for renewable sources of energy have the highest weights in the variables for consciousness, awareness, promotion, subsidies, food for energy, chemical means, biomass, fuel cells, geothermal energy, intensity of agriculture, energy from agriculture, ecological conditions, co-production of energy, and sufficiency of 25%. The second common factor (the natural potentials of renewable sources of energy has the highest weights) in the variables for wind energy, solar energy, feasibility of 25%, small hydroelectricity plants, and energy from agriculture. The third common factor (the sufficiency of conventional energy sources) has the highest weights in the variables for chemical means, intensity of agriculture, fossil fuels, and nuclear energy.

4.3.3 Maximum likelihood method – Oblimin with Kaiser normalisation

The Oblimin with Kaiser normalisation maximum likelihood method reinforces the findings. The structure matrix for the first common factor (energy policy, awareness, government support and promotion for renewable energy sources) has the highest weights in the variables for consciousness, awareness, subsidies, promotion, fuels cells, chemical means, food for energy, biomass, geothermal energy, intensity of agriculture, ecological conditions, and education. The second common factor (natural potential of renewable sources of energy) has the highest weights in the variables for wind energy, energy from agriculture, small hydroelectricity plants, solar energy, food for energy, feasibility of 25%, hydroelectricity energy, and geothermal energy. The third common factor (sufficiency of conventional energy sources) has the weights in the variables for chemical sources, intensity of agriculture, food for energy, nuclear energy, sufficiency of 25%, and fossil fuels.

4.3.4 Maximum likelihood method – Varimax with Kaiser normalisation

The Varimax with Kaiser normalisation maximum likelihood method confirms three common factors. The first common factor (energy policy, awareness, government supports and promotion for renewable sources of energy) has the highest weights in the variables for consciousness, promotion, subsidies, fuel cells, biomass, chemical means, food for energy, geothermal energy, intensity of agriculture, ecological conditions and co-production of energy. The second common factor (natural potential of renewable sources of energy) has the highest weights in the variables for wind energy, solar energy, energy from agriculture, feasibility of 25%, small hydroelectricity plants, hydroelectricity, food for energy, geothermal energy and biomass. The third common factor (sufficiency of conventional sources of energy) has the highest weights in the variables for chemical means, nuclear energy, fossil fuels, education, and sufficiency of 25%.

	Principal axis factoring method[a]			Maximum likelihood method[b]			Maximum likelihood method – Oblimin with Kaiser normalisation[c]			Maximum likelihood method – Oblimin with Kaiser normalization			Maximum likelihood method – Varimax with Kaiser normalisation[d]		
	Factor Matrix			Factor Matrix			Pattern Matrix			Structure Matrix			Rotated Factor Matrix		
Factors	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Fossil fuels	-.036	-.037	.427	-.059	-.012	.348	-.172	-.019	.336	-.122	-.037	.306	-.146	-.035	.319
Feasibility 25%	.358	.395	.138	.284	.450	.153	-.058	.538	.143	.125	.535	.186	.034	.526	.170
Sufficiency 25%	.402	.054	.264	.373	.084	.239	.179	.194	.291	.284	.276	.340	.228	.226	.317
Nuclear energy	-.036	-.391	.359	.007	-.395	.343	.089	-.389	.393	.039	-.323	.369	.060	-.360	.376
Transport	.141	.207	.107	.101	.214	.051	-.048	.246	.041	.031	.235	.057	-.008	.237	.051
Ecological conditions	.417	.011	-.072	.428	.069	-.033	.334	.188	.032	.394	.289	.106	.359	.234	.072
Wind energy	.345	.536	-.006	.265	.560	-.024	-.066	.639	-.051	.114	.614	.002	.026	.620	-.018
Hydro energy	.394	.285	.045	.334	.347	.043	.079	.444	.056	.220	.473	.113	.149	.452	.089
Small hydro energy	.442	.432	-.197	.368	.447	-.194	.142	.548	-.187	.273	.571	-.109	.208	.556	-.141
Solar energy	.350	.464	.004	.281	.490	-.021	-.017	.572	-.035	.146	.564	.019	.066	.561	-.002
Co-production	.409	.027	-.116	.391	.110	-.104	.307	.216	-.050	.363	.302	.022	.332	.257	-.011
Intensity in agriculture	.536	-.126	.372	.525	-.012	.364	.310	.142	.453	.428	.279	.519	.362	.198	.487
Chemical means	.649	-.144	.242	.655	-.019	.382	.416	.172	.495	.549	.344	.581	.474	.244	.540
Energy from agriculture	.473	.337	.001	.431	.425	-.030	.146	.547	-.011	.306	.589	.068	.225	.561	.035
Food for energy	.701	.068	.219	.689	.189	.279	.373	.388	.372	.549	.536	.472	.454	.448	.426
Biomass	.580	.003	.022	.584	.095	-.031	.449	.256	.058	.535	.395	.158	.486	.320	.112
Geothermal energy	.554	.100	.050	.534	.190	.044	.330	.341	.111	.449	.450	.200	.385	.388	.160
Fuel cells	.530	-.240	-.262	.553	-.183	-.140	.611	-.036	-.020	.597	.143	.078	.596	.052	.031
Subsidies	.651	-.308	-.058	.702	-.221	-.014	.710	-.030	.135	.724	.193	.251	.706	.077	.194
Awareness	.642	-.554	-.044	.711	-.465	.010	.838	-.273	.192	.789	-.007	.305	.800	-.143	.247
Consciousness	.784	-.137	-.318	.811	-.026	-.307	.806	.190	-.162	.835	.412	-.009	.810	.299	-.080
Promotion	.685	-.177	-.058	.709	-.093	-.097	.678	.100	.038	.714	.304	.161	.686	.198	.103
Education	.279	-.233	-.189	.307	-.217	-.208	.449	-.140	-.126	.387	-.020	-.065	-.146	-.035	.319

Table 2: *Sources of energy (matrices of five different extraction methods with three components extracted)*

Cronbach's Alpha (ά) measures the accuracy of measurement by the individual common factors: Cronbach's ά factor 1 = 0.855, N=12 (awareness, consciousness, subsidies, fuel cells, biomass, chemical means, food for energy, geothermal energy, intensity in agriculture, ecological conditions, and co-production of energy). Cronbach's ά factor 2 = 0.790, N=9 (wind energy, solar energy, energy from agriculture, feasibility 25%, small hydroelectricity plants, hydroelectricity plants, food for energy, geothermal energy, and biomass). Cronbach's ά factor 3 = 0.352, N=5 (chemical means, nuclear energy, fossil energy, education, and sufficiency 25%).
[a] 6 iterations, [b] 7 iterations, [c] 11 iterations, [d] 4 iterations.

5 ENERGY POLICY

5.1 Energy policy in EU and in Slovenia

The EU has not yet developed a common energy policy, but a common energy strategy is emerging through ecological policy in the single European market. The objectives of the energy policy in Slovenia are consistent with the country's broader development objectives, with the objectives of the EU for energy policy and with the international obligations within the Green Book for National Energy Programme for in-depth debate on key strategic development questions of the energy sector and for preparation of the National Energy Programme for Development vision by 2030. Strategic guidelines and derived mechanisms are in the areas of efficient energy use, market and entry of new technologies, development of local energy systems, efficient management of market activities, development of activity for the supply of electrical energy, tax and price policy and financing.

5.2 Energy policy and competitiveness

Table 3 presents relevant policies for three common factors identified for the energy costs of economy, sustainable development of knowledge for competitive supply of energy, and efficient use of energy.

1. ENERGY COSTS OF ECONOMY	2. SUSTAINABLE DEVELOPMENT OF KNOWLEDGE FOR COMPETITIVE SUPPLY OF ENERGY	3. EFFICIENT USE OF ENERGY
- Policy for reduction of emissions of CO_2 for encouraging cost-efficient energy sector. - Policy oriented towards development of entrepreneurship and wider choices of technologies with job creation and economic growth as well as networking with research programmes and	- Policy of sustainable supply of energy with establishing a competitive market for electrical energy, which will contribute to a more competitive economy. - Policy to support sustainable development of advanced alternative sources of energy and transfer of knowledge with pilot and demonstration	- Policy to support energy restructuring and renovation of buildings with implementation of measures for efficient use of energy and introduction of new concepts of integrated programming of energy-saving sustainable construction (location, construction of buildings, energy-saving heating,

programmes for technological development.	projects. - Policy for efficient market mechanism with opportunities for consumer choices of supply of different energy products and services. - Policy for a greater transparency of the energy market for public energy stock exchange Borzen with measures that will provide incentives for producers to trade electrical energy in the stock exchange.	renewable sources of energy) - Policy of energy supply and use of waste in public-private partnerships. - Policy of efficient management of energy in the public sector (schools, hospitals, nursery schools, houses for elderly people, municipality buildings etc.), support of measures for energy efficiency, implementation of monitoring of energy uses and energy accountancy.

***Table 3**: Energy policy and competitiveness*

5.3 Energy policy and sources of energy

Table 4 presents relevant energy policies regarding three common factors identified for energy policy, awareness, government supports and promotion for renewable sources of energy; natural potentials of renewable sources of energy; and for the sufficiency of conventional energy sources.

1. ENERGY POLICY, AWARENESS, GOVERNMENT SUPPORTS AND PROMOTION FOR RENEWABLE SOURCES OF ENERGY	2. NATURAL POTENTIALS OF RENEWABLE SOURCES OF ENERGY	3. SUFFICIENCY OF CONVENTIONAL ENERGY SOURCES
- Policy of awareness, education, promotion of renewable sources of energy, supports for exchanges of good practices and experiences, providing expert supports, studies and demonstration projects. - Policy and measures for supports of renewable sources of energy with investment supports, subsidised interest rates for investments, guaranteed prices for renewable sources of energy and efficient energy use. - Taxation policy favouring renewable sources of energy.	- Policy for introduction of natural potentials in production of electrical energy from renewable sources of energy: wind energy, solar energy, water energy, geothermal energy and wood biomass in facilities for co-production of heat and electrical energy with high efficiency. - Policy for providing conditions for continuation of investment cycle for use of hydro-potentials in large facilities in upper and middle part of Sava River, opportunities on Idrijca and Mura Rivers with concessions	- Policy for use of nuclear energy. - Policy for substitution of updated and ecologically unacceptable thermal production units with new technologies at existing locations with investments into human capital and infrastructure. - Long-term policy towards coal mining in Šaleška valley due to diversification of energy sources. - Policy towards future energy development of fossil fuels, particularly gas.

- Policy for improvements of ecological conditions for investors. - Policy of supports in agriculture and policies towards waste in agriculture. - Policy of research and development of new technologies for fuel cells, geothermal potentials, bio fuels and electrical energy for transport.	for smaller hydroelectricity plants on other water resources. - Policy for more intensive investments into construction of systems of heating on wood biomass and biogas.	

***Table 4**: Energy policy and energy sources*

6 CONCLUSION

The competitive energy supply has impacts on the economy, environment, and energy use. With the multivariate factor analysis, we have confirmed three common factors: (1) energy costs of the economy (energy in economy, costs and emissions of CO_2), (2) sustainable development of knowledge for competitive supply of energy (research and development, alternative sources of energy, prices of energy, competitiveness, progress and knowledge), and (3) efficient use of energy (saving energy use and ecology). The empirical results and the findings on the opinions are biased to the interviewed professional/consumer groups. The energy managers emphasised the importance of the energy costs in the economy, sustainable knowledge development for the competitive supply of energy and efficient energy use. The prices of electricity in households, prices of energy, and price competitive supply of energy were found to be critical issues.

The sources of energy are found to be associated with three common factors: (1) energy policy, awareness, government supports, and promotion of a greater role of renewable sources of energy (consciousness, awareness, subsidies, fuel cells, biomass, chemical means, food for energy, geothermal energy, intensity of agriculture, ecological conditions, and co-production of energy), (2) natural potentials of renewable sources of energy (wind energy, solar energy, energy from agriculture, feasibility of 25% of renewable sources of energy, small hydroelectricity plants, hydroelectricity plants, food for energy, geothermal energy, and biomass), and (3) sufficiency of conventional energy sources (chemical means, nuclear energy, fossil fuels, education, and sufficiency of 25%). Awareness, chemical means, government subsidies, fuel cells, and consciousness of citizens are found to be critical issues. This calls for a more critical debate on the government's energy policy and for a greater role of educational and promotional activities for a greater supply and use of renewable sources of energy as well as for more environmentally friendly use of energy.

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EXPERIMENTAL ANALYSIS OF THERMO-DYNAMICAL SURGE AT WATER PUMP INLET

EKSPERIMENTALNA ANALIZA TERMODINAMIČNIH FLUKTUACIJ TOKA NA VSTOPU V VODNO ČRPALKO

Ignacijo Biluš, Andrej Predin[ℜ]

Keywords: cavitation, centrifugal pump, thermal imaging camera

Abstract

This paper is concerned with an experimental analysis of a cavitation operating regime in a centrifugal water pump, in which the thermodynamic process is controlled with a hydrodynamic flow pattern.

Experimental results are obtained via thermal imaging system visualisation and flow variable measurement results. Both experimental methods clarify the mechanism of thermo-dynamical surge generation, cavitation propagation and confirm the theory.

Povzetek

Pričujoči prispevek predstavlja ekperimantalno analizo prehodnega kavitacijskega obratovalnega režima v centrifugalni črpalki pri katerem tokovni režim vzbuja termodinamične fluktuacije toka.

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Predstavljena eksperimentalna analiza je bila izvedena z meritvijo tokovnih veličin in s pomočjo sistema za vizualizacijo obratovalnega režima s termovizijsko kamero. Kombinacija obeh metod omogoča vpogled v mehanizem termodinamičnih fluktuacij in razširjanje kavitacije v obravnavanem kavitacijskem režimu, rezultati pa potrjujejo teoretična izhodišča.

1 INTRODUCTION

The trend toward higher speed and power in order to achieve high performance characteristics has inevitably increased the potential for operating instabilities in modern pumps. Even in the absence of cavitation and its complications, these phenomena can lead to performance loss and, in the worst case, to structural failure.

One of the major sources of instability in a centrifugal pump is, as mentioned, cavitation. Cavitation of a centrifugal pump is the result of insufficient net positive suction head and can occur within the entire range of operating conditions.

Longer pump operation at the lowest flowrates and insufficient pressure levels at the inlet can cause the transient cavitation phenomenon called thermo-dynamical surging. During the thermo-dynamical surging process in a pump, the transient phenomenon can result in extremely strong pressure rise. The pressure rise can lead to the destruction of the system. Accordingly, it is very important to avoid this operating regime. This paper introduces a fast and cost-effective method for pump-operating regime diagnosis.

2 THERMO DYNAMICALLY INDUCED CAVITATION SURGING

In the case of cavitating flow regimes; three distinct operating possibilities are known (Figure 1). The stable regime [1], in which the majority of cavitating centrifugal pumps operate; the unstable regime, described as hydro-dynamically induced cavitation surging; and the transient regime, described as thermo-dynamically induced surging [2].

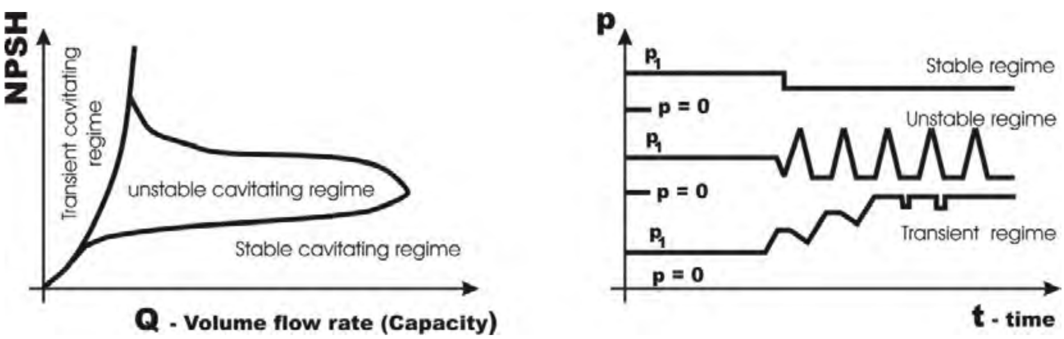

***Figure 1**: Cavitating regimes*

Thermo-dynamically induced cavitation surging results from deficiencies in plant design that permit pump operation at zero or near zero flowrate conditions. At zero flowrate, the cavities

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are an ever-growing, time-dependent phenomenon. At near zero flowrate, heating magnifies the hydro-dynamic surging taking place within the pump.

Normally, centrifugal pumps generate the head to match the system resistance over a range of flowrates which, for economic operation, should be near to the best efficiency flowrate. During such an operation, power in the form of hydraulic losses is dispersed mainly as heat to the liquid passing through machine. This is evidenced by a temperature rise of the pumped liquid, which is independent of time, until wear increases internal clearances and affects hydraulic performance. This transient, progressive build-up of temperature can magnify the effect of the hydro-dynamically induced surging described in [3]. An explosive growth in the total volume of the cavities within the impeller may occur. Where the rate of heat input is large and the design of plant restricts the expansion of the pumped liquid, very high inlet pipe pressures can result.

2.1 Experimental analysis

Despite fast computational simulations, experimental results still play a crucial role in the validation of mathematical and numerical models for a variety of basic and applied thermal transport problems [4].

For experimental test purposes, a commercial radial water pump with design speed 2900 rpm, maximal capacity $Q_{\max} = 0.027\,\mathrm{m^3/s}$ and maximal head $H_{\max} = 25\,\mathrm{m}$ was used. The operating characteristics of the pump are shown in Figure 2.

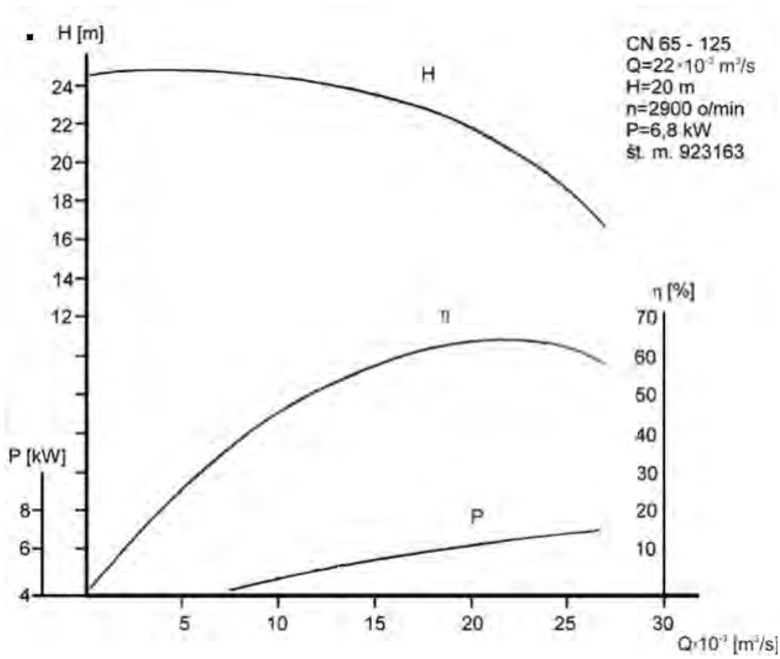

***Figure 2**: Operating characteristics of tested pump*

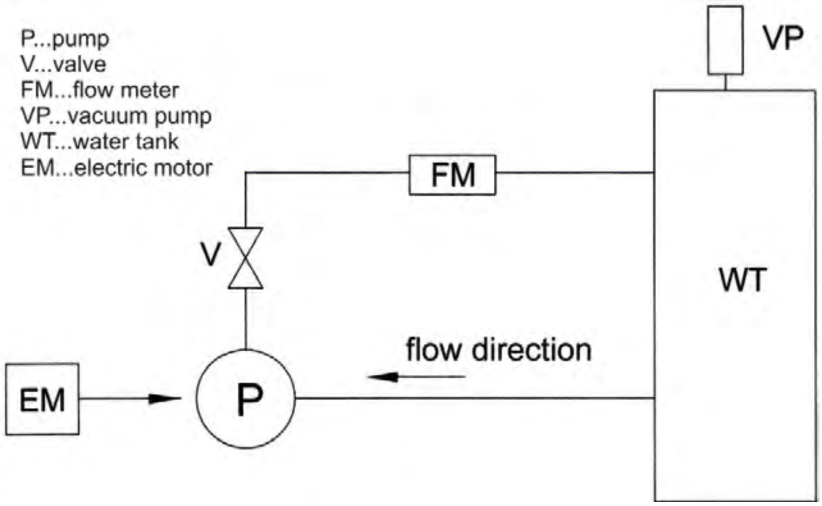

***Figure 3**: Cavitation test system*

The pump was connected to the closed loop test rig as shown in Figure 3. The system was designed for testing of pump cavitation regimes.

For the purpose of the present analysis, the FLIR Systems thermal imaging camera was used (Figure 4). The pump casing temperature was measured with a ThermaCam E65 camera (range between -20°C to +250°C). Before use, the ThermaCam was calibrated (Figure 5) with a general purpose K-type thermocouple (positive Chromel wire and negative Alumel wire) at reference conditions defined by a Hart Scientific 6102 Micro-Bath.

***Figure 4**: Thermal Imaging Camera*

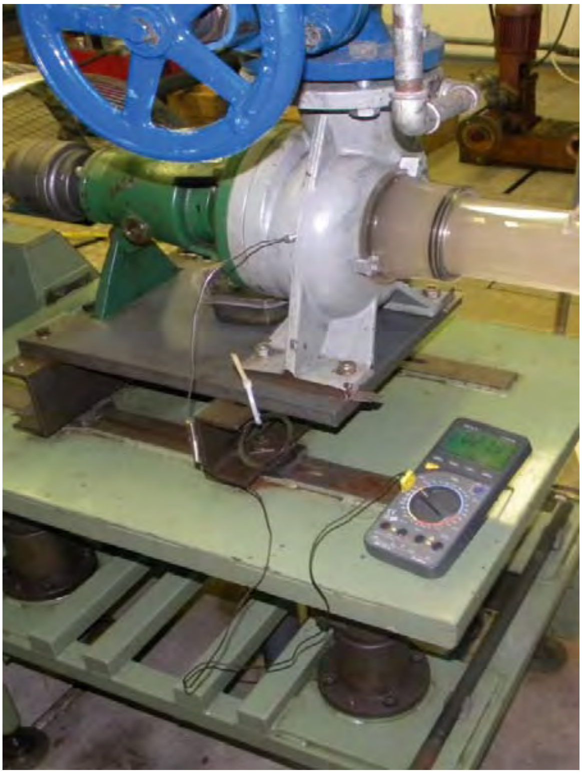

***Figure 5**: Calibration*

2.2 Results analysis

2.2.1. Temperature rise

The experimental analysis results show that the temperature rises to the value depending on system geometry. The stabilized temperatures in the system presented seem to be lower than values reported by other authors [5]. The reason for this could be in the closed-loop test rig, without a non-return valve, which allows the fluid to expand in the direction of the suction pipe. The temperature in the near zero flowrate region (flowrates between 0 [l/s] and 1 [l/s]) stabilized between 51.3°C and 48.1°C after approximately 15 minutes (Figures 6, 7). The value is independent of the reference pressure in the system set by vacuum pump. The flowrates higher than 1 [l/s] do not cause the temperature rise, owing to sufficient cooling liquid.

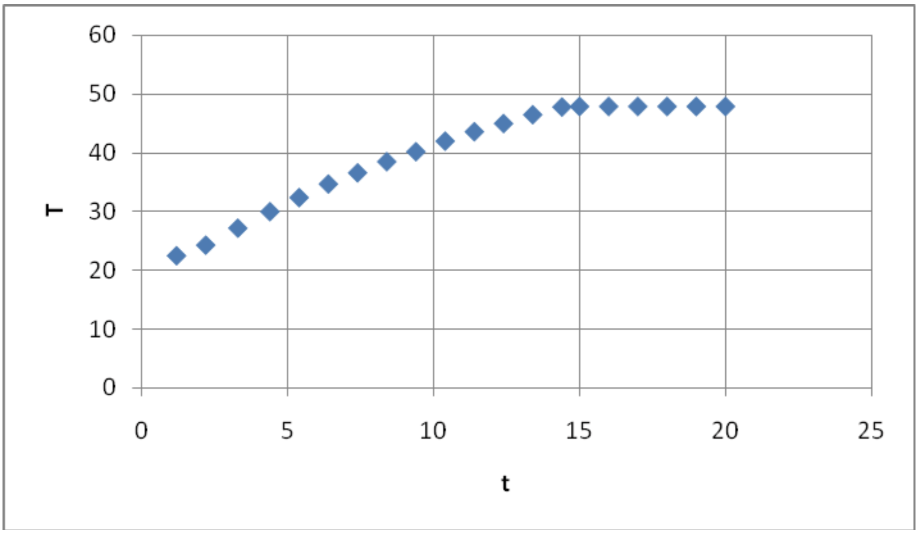

Figure 6: *Temperature rise at the control point*

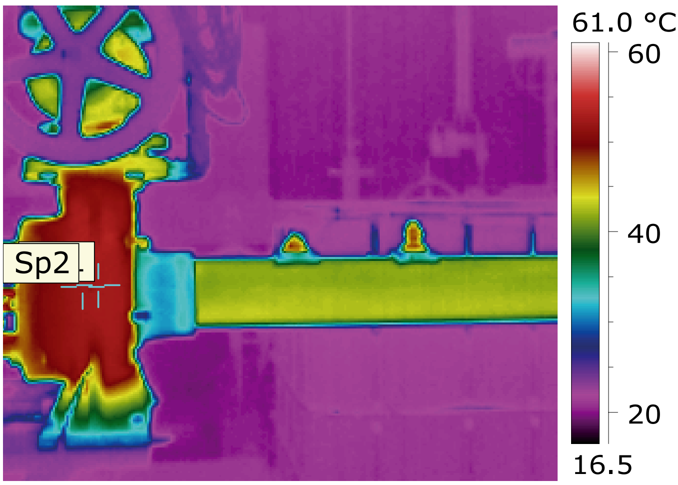

Figure 7: *Stabilized temperature*

The temperature field during the pump's operation in a transient cavitation regime is shown in Figure 8. It is evident that temperature rises in impeller channels, and that heat transfers from water to the system according to the thermal conductivity of the material (steel casing and Plexiglas inlet pipe).

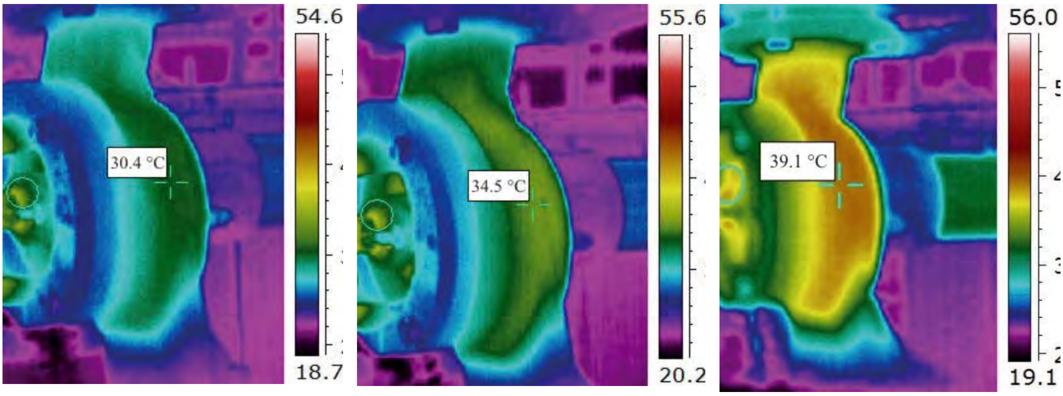

***Figure 8**: Temperature rise measurement (Δt=150 s)*

2.2.2. Temperature drop

If the flowrate through the system is increased, the temperature drops instantly at the region filled with fresh water. In the region of pump housing where heat transfer is dominated by diffusion, the temperature drops slowly, as shown at Figure 9.

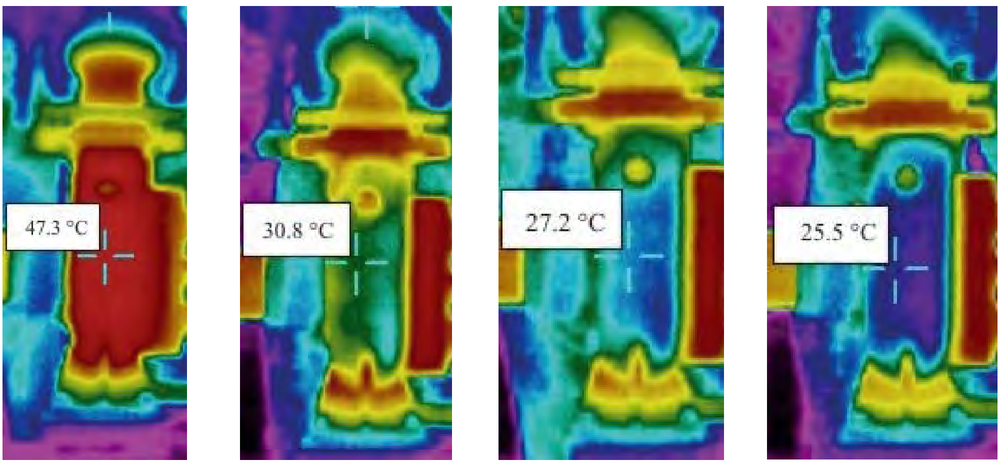

***Figure 9:** Temperature drop measurement (Δt=25 s)*

3 CONCLUSION

The thermo-dynamical induced surge is a system instability that involves not just the pump characteristics but those of the complete piping system in a complicated transient operating regime.

The stabilized temperature is independent of the reference pressure in the system, set by vacuum pump.

A thermal imaging camera can be used for the visualisation of the heat transfer mechanism and an instant view of temperature distribution in a hydraulic system.

The presented approach can be used for fast and effective diagnosis of system and possible problems connected to near zero flowrate operation of pump.

For detailed quantitative analysis of heat transfer and thermal stresses in the turbo-machinery, the influence of thermal boundary resistance between dissimilar materials should be included.

The presented thermal imaging approach is capable of offering satisfactory results in the process of operating failure analysis, but owing to the transient nature of the complicated swirling turbulent two-phase flow regime in the system analysed, both numerical and experimental research methods should be used for detailed studies.

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