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## *Plinovodna projekta Nabucco in Južni tok, konkurenta ali se dopolnjujeta?*

Navidezno se zdi, da se bije bitka med plinovodnim projektom *Nabucco*, katerega zagovornik je Evropska unija, ki bi s tem projektom rada zagotovila nekakšen energetski obvod mimo ruskega ozemlja in si s tem zmanjšala veliko energetsko odvisnost Evrope od Ruskega plina ter plinovodnim projektom *Južni tok*, s katerim si želi Rusija še povečati svoj vpliv na energetskem trgu Evrope. Projekt Nabucco naj bi Evropi zagotavljal 31 milijard kubičnih metrov plina na leto iz nahajališč Azerbajdžana, konkretno iz najdišča v Šah Deniz, preostali del kvote pa iz Turkmenije in Iraka. Prav zagotovitev omenjene kvote Nabucca že poraja dvome o možnostih zagotovitve željenih (predvidenih) količin in izvedljivosti celotnega projekta. Dvom temelji na dejstvu, da sta Turčija in Azerbajdžan konec lanskega leta podpisala sporazum o gradnji Transanatolskega plinovoda, po katerem naj bi steklo 16 milijard kubičnih metrov plina prav iz nahajališča v Šah Deniz-u; od tega 10 milijard proti Evropi. Tako se zdi, da Južni tok pridobiva na pomenu. Žal bo projekt Nabucco Slovenijo obšel in se končal v Avstriji v mestu Baumgarten. Na drugi strani, pa se južni tok z enim krakom prav tako konča v prej omenjenem avstrijskem mestu, medtem ko z drugim krakom, ki se deli v hrvaški Subotici, prehaja slovensko ozemlje in se konča nekje na južnem avstrijskem. Za Slovenijo je še kako zanimiv prav projekt Južni tok, ki bo proti Evropi ponesel skoraj dvakrat večje količine zemeljskega plina kot Nabucco, konkretno 63 milijard kubičnih metrov na leto. Za Rusijo pa je Južni tok pomemben predvsem zato, ker se z njim želijo izogniti transportnim potem preko tranzitno nestabilne Ukrajine, hkrati pa seveda zagotoviti še večji delež prodaje v Evropi. Rusi zaradi ogromnih zalog zemeljskega plina nimajo težav z zagotavljanjem zadostnih količin plina.

Turčija kot ključna »vozliščna« država, preko katere so speljane vse poti plinovodov naprej proti severni Evropi, postaja energetsko vse bolj pomembna, kar se konec koncev odraža tudi na njihovi veliki gospodarski rasti. Še enkrat se potrjuje dejstvo, da je energetika in z njo povezano gospodarstvo pravi motor razvoja. Turčija se seveda tega vsekakor zaveda, zato »ogroženemu« projektu Nabucco ponuja tudi alternative, saj vedo, da bodo potrebe po energentih v Evropi v prihodnjih letih samo še naraščale. Za Evropo sta predvsem zanimiva projekta ITGI (Turško-grško-italijanski plinovodi), ki bi naj že leta 2015 čez Turčijo in Grčijo zagotavljal plin iz Azarbejdžanskih nahajališč in Transanatolski plinovod (TAP), ki naj bi Evropi zagotavljal plin iz Iraka. Kljub vsemu, se v Turčiji zavedajo dejstva, da kratkoročno in srednjeročno ne bo šlo brez jedrske energije, zato je Turčija že pred dvema letoma z Rusijo podpisala sporazum o gradnji svoje prve jedrske elektrarne v Akkuyu. Ta naj bi bila dokončana še pred koncem tega desetletja. Gradnjo svoje druge jedrske elektrarne pa bodo najverjetneje zaupali Japonski. Locirana bo v Sinopu na črnomorski obali. Z izgradnjo obeh jedrskih elektrarn si Turčija prizadeva doseči čim večjo energetsko neodvisnost, ne glede na to, da je že danes največja, energetsko tranzitna država. Zavedajo se pomembnosti energetske neodvisnosti, kljub temu, da vse plinsko/naftne poti proti Evropi potekajo čez njihovo ozemlje.

Upam, da se Slovenija zaveda vseh prednosti Južnega toka ter da bo ponujeno priložnost izkoristila v čim večjem obsegu, tudi kot motor za izhod iz sedanje gospodarske krize, kot tudi krize vrednot, ki smo ji danes priča v Sloveniji.

## *The Nabucco and South Stream pipeline projects: do they compete with or do they complete each other?*

It seems as if the Nabucco and South Stream pipeline projects are fighting a battle. The Nabucco project is supported by the European Union, which would like to ensure a sort of bypass of Russian territory, thereby reducing the EU's dependency on Russian gas. The South Stream project is supported by Russia, which would like to increase its influence on EU gas market.

The Nabucco project would provide Europe with 31 billion cubic meters of gas per year from deposits in Azerbaijan, specifically from the deposits in Shah Deniz, and the remaining part from Turkmenistan and Iraq. The quest to ensuring these quotas via the Nabucco project is already casting doubts on the ability to provide the desired (planned) volumes and on the overall feasibility of the project.

The doubt is based on the fact that Turkey and Azerbaijan signed an agreement to build the Trans-Anatolian pipeline at the end of last year, according to which it would provide 16 billion cubic meters of gas from the deposits in Shah Deniz; 10 billion cubic meters of which would go to Europe. Thus, it appears that South Stream is becoming more important. Unfortunately, the Nabucco project will bypass Slovenia and end in Baumgarten, Austria.

In contrast, one of the South Stream branches ends in the abovementioned Austrian town, while the other branch, which is divided in Subotica, Croatia, crosses Slovenian territory and ends somewhere in southern Austria.

For Slovenia; the South Stream project is very interesting: it could deliver almost double the quantity of natural gas to Europe compared to Nabucco: about 63 billion cubic meters per year.

For Russia, South Stream is very significant because they want to avoid transport via Ukraine, which is politically unstable, but also provide a bigger share of sales in Europe. Russia has no problem supplying sufficient quantities of gas, because of its enormous reserves.

Turkey, with its crucial geographic position as a key "node" state through which all the pipelines pass on their way to northern Europe, is increasingly becoming important regarding energy, which is ultimately reflected in their strong economic growth.

Again, the fact is confirmed that the energy field and its related economic effects are the real engine of societal development. Turkey is well aware of that, so besides the "threatened" Nabucco project, they also offer alternatives, because they know that the need for energy in Europe will continue to increase in the coming years.

For Europe, the following projects are particularly interesting: ITGI (Turkey-Greece-Italy gas pipeline), which is supposed to provide gas from Azerbaijan deposits through Turkey and Greece by 2015, and the Trans-Anatolian pipeline (TAP) that would provide gas to Europe from Iraq. Nevertheless, Turkey is aware of the fact that nuclear energy is vital in the short and medium term, so they signed an agreement with Russia two years ago for the construction of their first nuclear power plant, in Akkuyu. It is to be completed before the end of this decade. Construction of a second nuclear power plant is likely to be entrusted to the Japanese. It will be located in Sinopu on the Black Sea coast.

With construction of two nuclear power plants, Turkey is committed to maximizing its energy independence, irrespective to the fact that they are presently the largest energy transit country.

They are aware of the importance of energy independence, regardless of the fact that all gas/oil routes to Europe are crossing their territory.

I hope that Slovenia is aware of the benefits of South Stream, and that it will take the opportunity to exploit them to the fullest extent, as well as use them to overcome the current economic crisis and the crisis of values that we are witnessing today in Slovenia.

Krško, May, 2012

Andrej PREDIN

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# 'FORKLIFT TO GRID' – HOW TO SYNERGISE THE ELECTRICITY AND LOGISTICS SECTORS

# 'VILIČAR NA OMREŽJE' – KAKO SINERGIJSKO POVEZATI ELEKTRIČNO OMREŽJE Z LOGISTIČNIM SEKTORJEM

Matjaž Knez[ℜ], Andrej Predin[1], Bojan Rosi[2],

**Keywords:** logistics, electric vehicle, electric forklift, Vehicle to Grid', a new technological concept – 'Forklift to Grid.'

## Abstract

Interruptions of electricity supply at the national level are due to a lack of production capacity as well as a lack of transmission capacity, and have an immediate and significant impact on industry, households and other sectors. It is therefore necessary to constantly seek new ways of storing electrical energy and thus have a positive effect on the coverage of energy and peak power system stabilization. This paper deals with the possibility of the integration of environmentally friendly renewable energy sources with modern technologies into the energy management of logistics processes, which is very important in global business and helps to increase both the efficiency and effectiveness of business systems.

This paper shows the study of the current research findings on the 'Vehicle to Grid' innovative concept and a proposed theoretical model of F2G integration into energy management of a

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warehouse. Analyses of data, calculations of the economic value and of the profitability of the proposed business model yielded positive results that fully confirm the thesis that the integration of environmentally friendly renewable energy sources and new technologies into the logistic processes can improve logistics management while minimizing the negative impact of business on the environment.

## Povzetek

Prekinitve dobave električne energije na nivoju celotnega sistema so posledica tako nezadostnih proizvodnih kot tudi nezadostnih prenosnih zmogljivosti, ter imajo takojšen in pomemben vpliv na industrijo, gospodinjstva in ostalo široko rabo. Zato je treba nenehno iskati nove načine shranjevanja električne energije in s tem vplivati na pokrivanje energetskih konic in stabilizacije energetskega sistema. Članek obravnava aktualno problematiko možnosti integracije okolju prijaznih obnovljivih virov energije s sodobnimi tehnologijami v energetski management logističnih procesov. Slednji je namreč v globalnem poslovanju izredno pomemben in pripomore tako k večji učinkovitosti, kot tudi uspešnosti poslovnih sistemov.

V članku so predstavljena obstoječa raziskovalna spoznanja, ki se navezujejo na inovativni koncept V2G in predstavljen teoretični poslovni model integracije F2G v energetski management skladišča.

Analize zbranih podatkov, izračuni ekonomske vrednosti in donosnosti predlaganega modela so podali pozitivne rezultate, kar v celoti potrjuje tezo, da integracija okolju prijaznih obnovljivih virov energije in nove sodobne tehnologije v logistične procese lahko izboljšajo energetski management podjetja, hkrati pa se zmanjšajo negativni vplivi delovanja podjetja na okolje.

## 1 INTRODUCTION

Fierce competition between companies, shorter product life cycles, and recent economic crisis-related events all call for the adjustment of all supply chain participants. Therefore, costs will also play a decisive role in business competitiveness[3] on the global market, and are among the advantages that distinguish a given organization from other suppliers in the market.

The aim of every system, including logistics systems, is to optimally provide production with needed materials and energy, and to optimally provide users with products in the desired quantities, with the desired qualities, and at the right time. The aim is to achieve an optimal level of supply service, Ogorelc, [1].

For this reason, companies are seeking ways to optimize their processes in order to reduce costs and become more flexible. One potential new innovative solution in logistics management is the concept called 'Vehicle to Grid' (V2G), designed by the leading researcher and innovator, Professor Willett Kempton from the University of Delaware, USA, Knez & Bajor, [2].

The V2G concept is an attractive idea on how to synergize the electricity and the logistics transportation sectors. Pure electric and hybrid-electric vehicles (which are capable of

[3] Competitive advantage results from innovative combination of knowledge, special skills, technology, information and unique business methods that enable the supply of products and services that the buyers appreciate and want to buy, Greaver, [13].

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connecting to the grid and loading/unloading electrical energy) could help to better manage electricity resources. Moreover, the concept enables vehicle owners to earn money by selling power back to the grid when parked, depending on the current fuel- and electricity-prices. On average, vehicles in the US spend only 4–5% of the day on the road and at least 90% of personal vehicles remain unused (in parking lots or garages) even during peak traffic hours, Tomić & Kempton, [3].

Within the United States alone, Rydzewski, [4], there are currently some 230 million gasoline-powered cars, sport utility vehicles (SUVs) and light trucks, which, if converted to or replaced with a combination of plug-in hybrids and all-electric vehicles, could have increased the power capacity of all electricity generation in the country by 20-fold. This large potential power source has great value. When a V2G-enabled vehicle is tied into the electric grid via a power connection, the vehicle's instantly-responsive electric storage system can be directed by a wireless communication device to deliver power services to the region. These power services help to stabilize the electric grid, significantly enhance the capabilities of renewable wind and solar generation, and provide many other value-added services to the community.

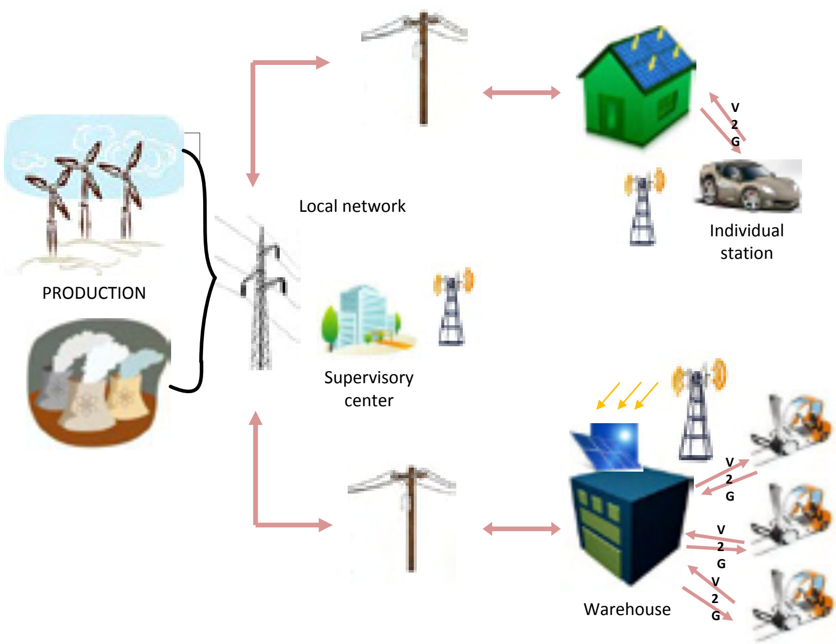


***Figure 1:** V2G concept in national electrical grid*

V2G further provides an opportunity to improve the reliability of the electric grid. The vehicles are typically parked where people use power, i.e. at home and at work. The placement of the vehicles on the grid in this manner makes the power supply a 'distributed generation tool' for localized storage and use. When the grid fails, the cars are ready to back up the power supply.

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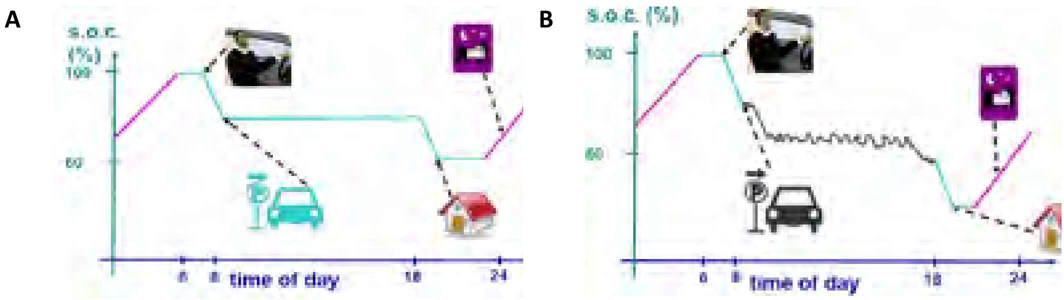


***Figure 2:*** *The conventional view on the use of electric vehicles (A) and a new perspective on the use of electric vehicles with V2G concept (B)*
*Source: (Kempton et al., [5])*

Moreover, V2G creates an opportunity for vehicles to become revenue-producing assets, as opposed to liabilities that lose value year after year. The V2G-equipped vehicles participate in specific power markets in return for a fee. Several variables affect the income potential, including the size of the battery pack, the type of power service, the hours-per-day the car is parked and plugged in, and the market rate, or value of the service. Combine the above opportunities with a cleaner environment and reduced dependence on imported petroleum-based fuels, and V2G is a win-win for everyone, Rydzewski, [4].

The V2G concept is a way to use electric vehicles (battery, fuel cell or hybrid vehicle) to provide electricity for various purposes while electric vehicles are parked. Each vehicle must meet three requirements, Kempton & Tomić, [6]:

- the vehicle must be plugged in;
- it must have a system (or communication unit) for communication with the electrical network (distributors);
- an electricity consumption meter must be installed in the vehicle.

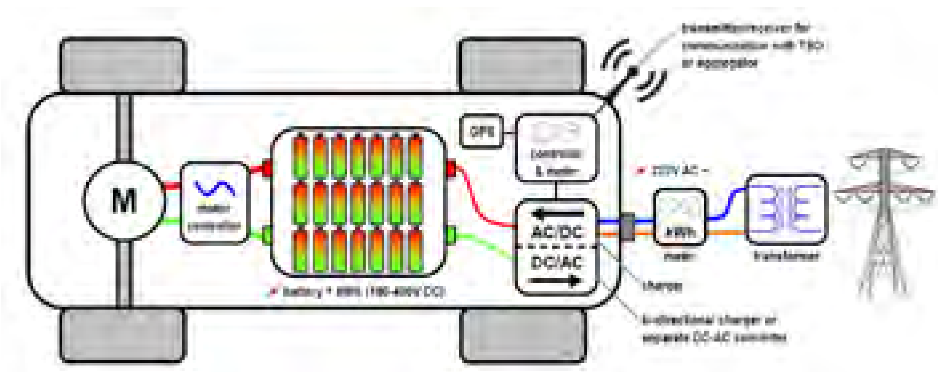


***Figure 3:*** *Vehicle communication with electric power network via V2G concept*
*Source: Spinnovation, [7]*

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The basic idea behind the concept of V2G is to 'buy electricity when it is cheap and sell when it is expensive', which means that the vehicle battery charges when the electricity price is low (in low tariff) and sells the energy to the grid when the electricity price is high (in high tariff), Kempton et al., [5].

Henceforth, in this study we will use the term 'F2G', since the object of study is the electric forklift and a new innovative technological concept which is derived from the original V2G concept and the type of electric vehicle.

## 2 METHODOLOGY OF RESEARCH

Theoretical research was performed on a central warehouse with mixed goods owned by the largest Slovenian retailer, Mercator d.d. The warehouse is located in the centre of Ljubljana (the capital of Slovenia) and has three storage areas. The possibilities of building a photovoltaic electric power plant were calculated for the flat roof of the warehouse with a size of 600 $m^2$. Calculations were made regarding solar energy use.

Mercator uses 128 electric forklifts with an average battery capacity of 17.2 kWh per vehicle. The forklifts are used for moving goods and other warehouse operations from 6.00 till 22.00, five days per week. During weekends and public holidays (114 days a year), vehicles are parked at the chargers. Each vehicle has its own schedule of operations.

Forklifts can now use lithium ion batteries to get F2G plug-ins, either as original equipment or as supplementary aftermarket power modules. Lightweight lithium ion batteries have greater power density and are capable of thousands of charge cycles, making them suitable for the grid's fluctuating need for power, Morrison, [8].

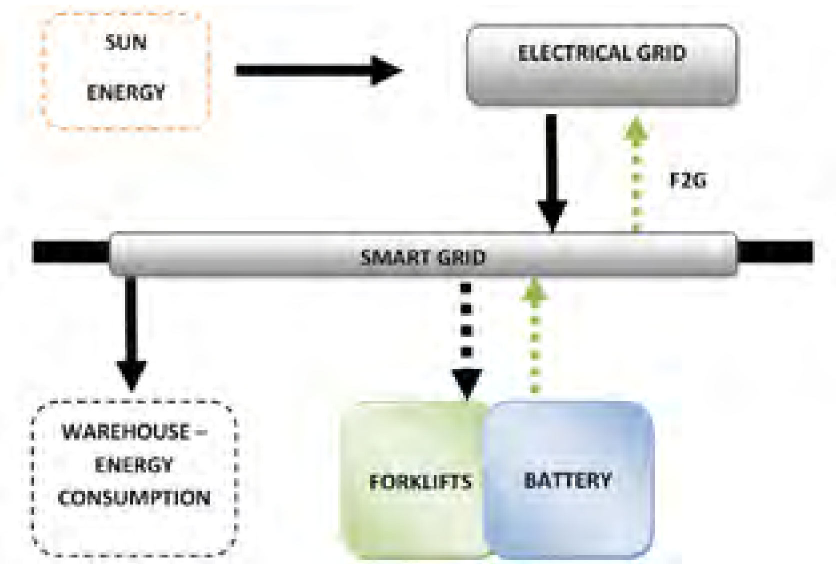


***Figure 4:*** *Business model of F2G integration into warehouse energy management*

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The photovoltaic (PV) roof system could feed the grid directly or charge the vehicle batteries. The vehicles could make money selling power into the grid during high-load conditions by responding to market price signals. The system (smart grid) could monitor vehicle battery charge, solar output and local electric system demand.

With a real-time controller, the system can respond to price signals from the electric grid spot market. When the grid calls for more power, the system would feed in the available surplus from the forklift batteries and the PV charging system, thus helping to reduce spot prices and satisfy the system's need for power. A key aspect of achieving the promise of F2G systems and a renewable electric grid is the ability to implement smart control between the electric grid, user devices, and power sources such as F2G batteries and distributed generation such as PV.

There are more possible scenarios, Knez & Bajor, [9], but only one (Figure 4) is described in this paper, in which all energy produced by the PV roof is sold to the grid directly and the forklifts are charged from the grid and sell energy back when there is a need for it.

The first section of research contains the calculation of the energy produced by the PV and the second section shows the calculation and value of the proposed model.

## 2.1 Energy from the sun

The data was acquired from the Ministry of the Environment and Spatial Planning and the Environmental Agency of the Republic of Slovenia for the period from 2003 to 2009. The measuring spot lies very close to the warehouse. The location is significant due to the specific features in this part of the city, e.g. fog and smog. The degree of solar radiation that reaches the Earth depends on solar activities, latitude, weather (cloudiness, humidity) and altitude as well as on the shape of the surface, Enecon, [10]. Slovenia is at the latitude of 46˚ north, which influences the angle of solar rays, depending on the season, taking into account the axis of the earth of 23.5˚. The latitude of 46˚ reaches the maximum angle on 21 June, which is 67.5˚ (90 - (46.0-23.5˚) = 67.5˚. In December, when the days are the shortest, the angle is the smallest. Therefore, the sun reaches the lowest energy values of radiation, which means that the angle of rays is the smallest on 21 December at noon, when it is only 21.5˚, Lead, [11]. Regardless of the optimal direction of solar cells that alters throughout the year, the data in this study refers to the horizontal surface. With the optimal direction of solar cells, which also takes into account the current latitude (based on the horizontal surface) and the direction of the sun, the expected efficiency increases by at least 10 percent.

Slovenia mainly has continental weather and distinct seasons. Therefore, the total volume of solar energy is smaller than, for example, in tropical areas and is also unequally distributed throughout the year (Figure 5). In Germany, the irradiation is around 1000 kWh/m$^2$ and in subtropical areas it is around 2000 or 2500 kWh/m$^2$, Lead, [11]. Slovenia has an advantage over Germany, with around 1250 kW/m$^2$.

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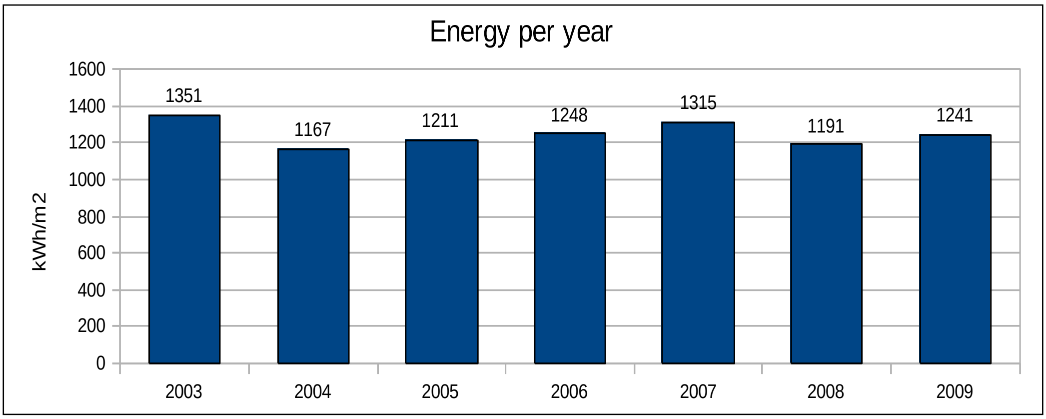


***Figure 5:*** *Summary of energy per year in kW/m² on a horizontal surface*
*Source: Jereb & Knez, [12].*

The research further aims to calculate solar energy and thus focus on limit values of solar irradiation (minimum and maximum) throughout the entire year. The focus was on the year 2009. Moreover, the study further took into account the data for December as the weakest month and July as the strongest month regarding the distribution of solar energy. Mercator has a flat roof of 600m², where we collected that data shown in Figure 6.

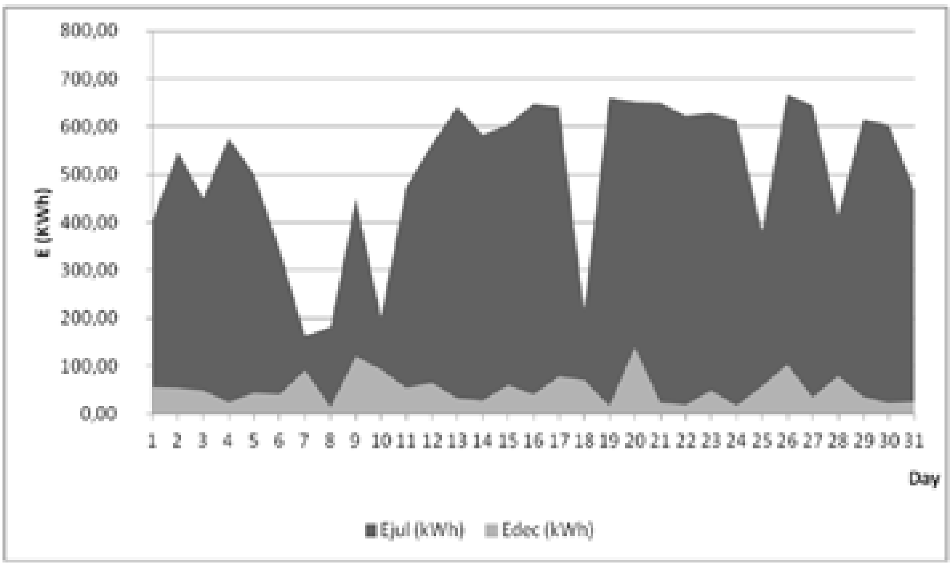


***Figure 6:*** *Energy distribution (per day/roof) in July and December 2009*
*Source: Jereb, Knez, [12].*

Figure 6 shows values of produced energy multiplied by the efficiency of the chosen solar cells (semi-crystal silicon photovoltaic modules produced by the company Bisol d.o.o. from Slovenia, where the average efficiency of cell transformations (at temperatures of 25˚C and 44˚C) is 14%).

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Figure 7 also shows that the average production of solar energy per day in July was 510 kWh and the average solar energy produced in December was 53kWh, which shows that if the system would use this energy for warehouse energy needs, the amount of energy produced in July would cover 5% of the daily energy demand and merely 0.6% in December. However, due to the policy of the electrical energy system in Slovenia, it is better to sell all the produced energy to the local grid, because the prices are subsidized by the government.

## 2.2 Energy consumption of warehouse

The data of energy consumption was acquired from the Slovenian retail company Mercator d.d. Data analysed are presented in Figures 7a and 7b. Monthly consumption and the amount of electricity consumed do not coincide with the seasons, as is expected in comparison to residential complexes and office buildings.

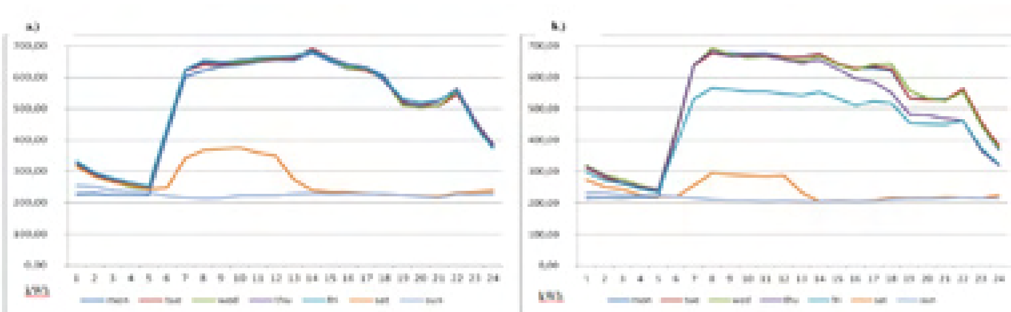

***Figure 7:*** *Daily consumption of electricity in July (a.) and December (b.) 2009*

In the warehouse, we also measured the power consumption of electric forklifts. We wanted to know when they are usually filled and what the consumption of electricity is (Figure 8a).

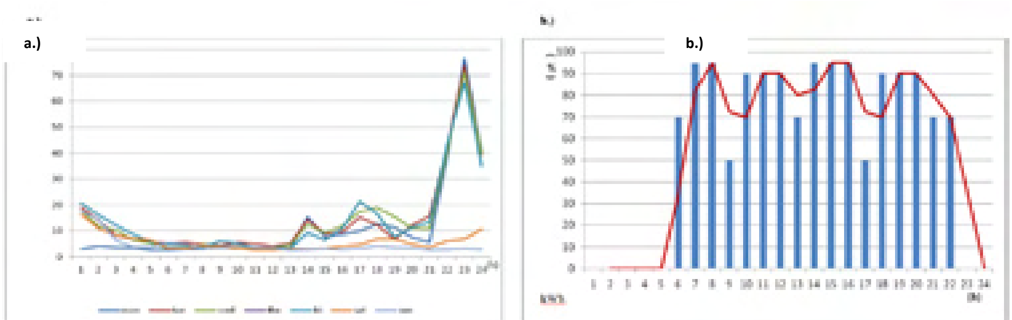


***Figure 8:*** *Daily consumption of electricity at the filling point of electric forklifts (a.) and daily activity of electric forklifts (b.)*

Figure 8a shows that energy consumption is highest during the night. In this relatively short time (3 hours and 40 minutes) electric forklifts bear 50% of the total daily consumption of active

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energy. Measurements have also shown that the consumption of electricity (EV) per hour Mondays to Fridays, when the store is open, does not change significantly.

## 2.3 Value of F2G integration in warehouse system

The economic viability of F2G critically depends on the cost; the forklift owner has to produce F2G power [14]. The cost for regulation down is zero because regulation down is the same as charging the battery, thus it is 'free charging' at times when the vehicle is providing regulation down. The yearly cost for regulation up is, Tomić & Kempton, [3]:

$$C_{reg-up} = (C_{en} P t_{plu} g R_{d-c}) + a_c \tag{2.1}$$

where $c_{Reg\text{-}up}$ represents the total cost of regulation up, $c_{en}$ the cost per energy unit in €/kWh and includes the cost of electricity, losses, plus battery degradation costs, and $c_{ac}$ is the annualized capital cost for additional equipment needed for F2G.

(Eq. 2.2) is used to calculate the per kWh cost to the battery of forklift owner for providing power to the grid and (Eq. 2.3) is used to calculate the cost of battery degradation.

$$c_{en} = \frac{c_{pe}}{\eta_{conv}} + c_d \tag{2.2}$$

$$c_d = \frac{c_{bat}}{L_{ET}} = \frac{(E_s c_b) + (c_1 t_1)}{L_c E_s DoD} \tag{2.3}$$

where $c_{pe}$ is the cost of purchased electricity for recharging in €/KWh; $c_d$ is the cost of battery degradation in €/KWh calculated as shown in (Eq. 2.3); $\eta_{conv}$ the conversion efficiency of fuel or electricity (in this case it is the two way electrical efficiency (electricity to battery storage and back to the electricity)), which is 0.73 for a battery with above average efficiency; $c_{bat}$ the battery replacement cost in euros (capital and labour costs); *LET* the battery lifetime energy throughput for a participant cycling regime in kWh; $E_s$ the total energy storage of the battery in kWh, $c_b$ the cost of battery replacement in €/kWh; $c_1$ is the cost of labour in €/h; $t_1$ labour time required for battery replacement, and $L_c$ the battery lifetime in cycles.

The other cost component of delivering F2G power is the fixed cost, expressed as annualized capital cost $c_{ac}$ for additional equipment required for F2G (Eq, 2.4) [14].

$$c_{ac} = c_c \times CFR = c_c \times \frac{d}{1-(1+d)^{-n}} \tag{2.4}$$

where $c_c$ is the capital cost (the one time investment) in euros, *d* the discount rate and *n* is the time during which the investment is amortized in years. AC Propulsion, Inc. (2007) designed a power electronics system that allows charging from and discharging to the grid, whose fixed cost is around €284 ($c_{pes}$). Further requirements are an on-board meter of electrical flow for billing purposes, which costs around €35 ($c_{ms}$) and a wireless system installed in production scale, which is estimated at around €71 ($c_{ws}$). The total capital cost ( $c_c = c_{pes} + c_{ms} + c_{ws}$ ) is €390. According to (Eq. 2.4), the capital annualized cost using a discount rate of 10% over a period of 10 years is approximately €39 per year, per forklift.

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The electrical power capacity available for V2G is determined by two factors (Tomić, Kempton, 2007): (a) the limitation of the electrical circuit where the forklift is connected and (b) the stored energy in the battery divided by the time it is used.

The electrical circuit limit is computed from the circuit's ampere capacity (A), multiplied by the circuit's voltage (V). This is the power capacity of the line or $P_{line}$ (Eq.2.5).

$$P_{line} = I \times U = 50A \times 220V = 11kW \qquad (2.5)$$

Based on the practical limits of typical home and commercial circuits, the study uses 15 kW as the $P_{line}$ limit. The limit imposed on the electrical power capacity for F2G by the forklift ($P_{forklift}$) is a function of the energy stored on board (i.e. in the batteries), the dispatch time needed, and the driver's requirement for driving range. The formula for calculating $P_{forklift}$ for battery EDVs is shown in (Eq. 2.6):

$$P_{forklift} = \frac{(E_s DoD - d_d + d_{rb} / \eta_{forklift}t)\eta_{inv}}{t_{disp}} \qquad (2.6)$$

where $P_{veh}$ is power capacity in kW, $E_s$ the stored energy available in kWh, *DoD* the maximum depth of discharge of the battery, usually 80% for NiMH and 100% for Li-Ion batteries, $d_d$ the distance driven in kilometres since the battery was full, $\eta_{forklift}$ the forklift driving efficiency in km/kWh, $\eta_{inv}$ the efficiency of the inverter and other power electronics (dimensionless) with a value of 0.93 [14], and $t_{disp}$ is the dispatch time in h. The dispatch time will be a fraction of the plugged-in time. The electrical power capacity for regulation is determined by the limits imposed by $P_{line}$ rather than the $P_{veh}$. When F2G is used for regulation, $P_{veh}$ is a much higher value than $P_{line}$ due to the short instantaneous dispatch time (usually on the order of 1–4 min).

When the vehicle is providing regulation down only (power flowing from grid to vehicle), the power capacity will be defined by wiring and the electronics ($P_{line}$), but the storage capacity of the battery and DoD will determine how long the vehicle will be plugged-in ($t_{plug}$) before the battery is full. Referring to Tomić and Kempton's [3] calculations and equations rearranging the theoretical research, we arrive at $t_{plug}$ (Eq. 2.7)

$$t_{plug} = \frac{E_s DoD \eta_{charger}}{P_{line} R_{d-c}} \qquad (2.7)$$

where $\eta_{charger}$ is the efficiency of the charger, or efficiency of line AC to charge batteries, with a value of 0.93. In regulation-down-only mode, theoretical research assumes that DoD is 50% at the start, so after the battery is fully charged, the vehicle will not be available to provide regulation down.

Using (Eqs. 2.2–2.4) and the cost of purchased electricity at €0.066/kWh, theoretical research calculates the cost of energy for regulation ($c_{en}$), which is €0.235/kWh.

Theoretical research calculates that each forklift of the fleet would be plugged in for 8.43 hours ($t_{plug}$) and DoD would be 80%, which means that each forklift could miss out on 20% of the energy stored in the battery. Based on that research we can calculate the annual revenue of each forklift using (Eq. 2.8):

$$r_{Reg-up} = (p_{cap} P t_{plug}) + (p_{el} P t_{plug} R_{d-c}) \qquad (2.8)$$

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where the $p_{cap}$ is the capacity price in €/kWh, $t_{plug}$ the amount of time in hours the forklift is plugged in, $p_{el}$ the market (selling) price of electricity (€/kWh) and P is the power of the forklift in kW.

The term ($R_{d-c}$) is the dispatch to contract ratio, which in combination with $t_{plug}$ defines the dispatch of F2G power, Tomić & Kempton, [3]. The $R_{d-c}$ is defined by (Eq. 2.9):

$$R_{d-c} = \frac{E_{disp}}{P_{cont} t_{cont}} = \frac{E_{disp}}{P t_{plug}} \tag{2.9}$$

where $E_{disp}$ is the energy of the battery in kWh, P is the power of the forklift motor in kW and $t_{plug}$ is the time in hours that forklift is plugged in.

# 3 DISCUSSION

If integration of the business model (Figure 4) is split into two parts and we first examine the economic viability of solar energy integration in the energy storage management, we find that the investment in solar power is very profitable and would amount to €192,000 in the phase of operation. The net present value would be positive (at a 6% discount rate, calculated based on a time period of ten years), and the return on investment is expected in nine years. It follows that the integration of solar power project in the energy storage management is certainly economical.

The second part of the business model represents the integration of the F2G concept, where a single, initial investment into the upgrade of electric forklifts was €49,920. When calculating the net present value, the discount rate was increased in comparison to solar power and was 10% in our case, mainly due to the fact that it is a research project with a correspondingly higher risk. The net present value, which we calculated for the time period of ten years, would be positive and return on investment would be achieved after the first year of forklift operation based on the F2G concept. From that, as with solar power, it follows that the integrating the F2G concept into energy management and storage is economically strongly feasible.

If we look at the overall profitability of the business model (we are talking about the optimistic scenario) with a total investment of €241,920, then we find that the net present value, calculated for the time period of ten (10) years, was also positive and that the investment would already be repaid in third year of operation of the business model.

For comparison and the credibility of the proposed model, we selected different prices of electricity, which we sell to the grid and even at lower purchase prices the investment in our model would still be reimbursed in less than ten years.

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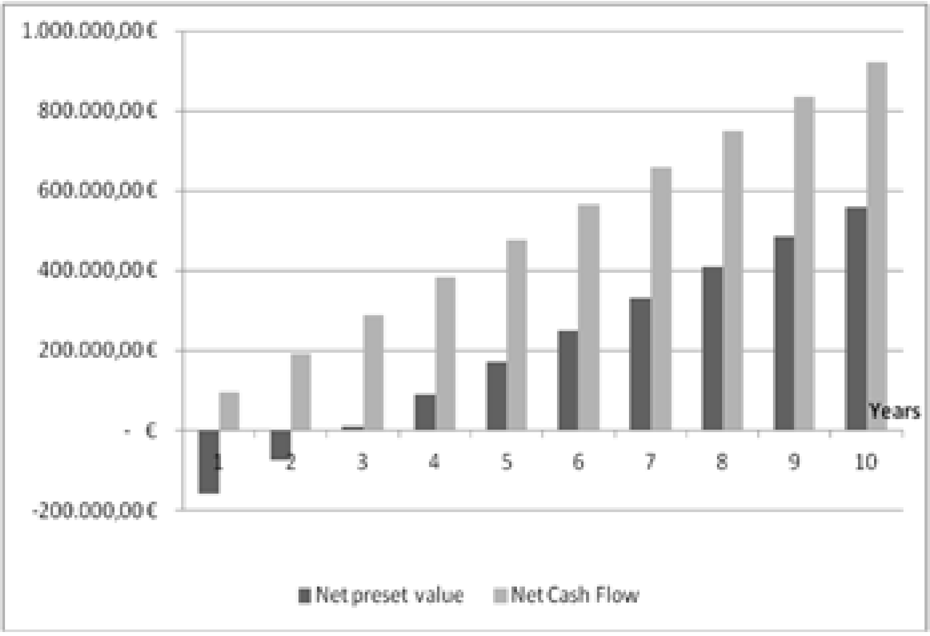


***Figure 9:*** *NPV and NCF of our proposed business model*

With the implementation of our innovative business model, according to the net cash flow, the average cost of electricity, calculated for a period of ten years, decreased by approximately 43%, as shown in Figure 10.

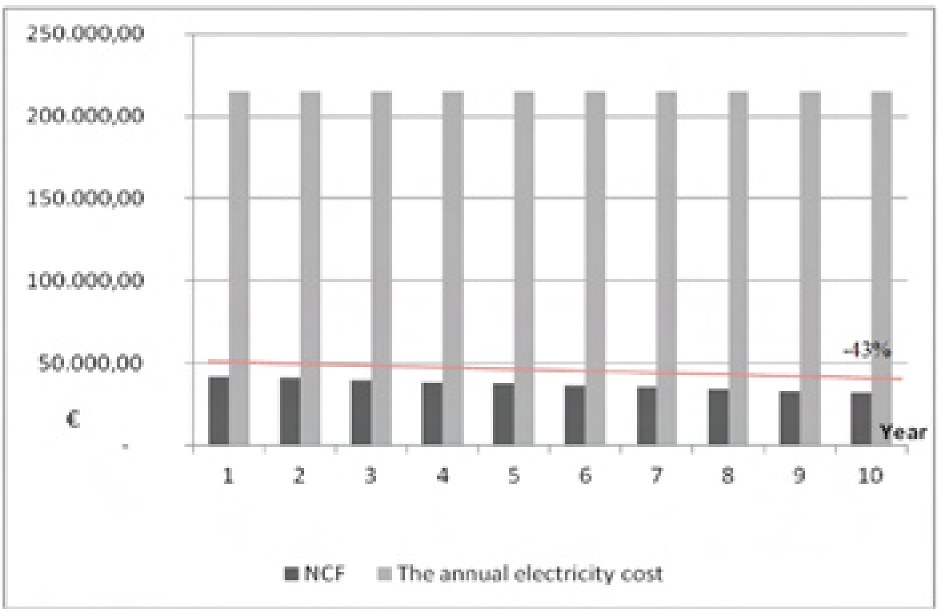


***Figure 10:*** *The impact of the proposed business model to the annual expenses of the electricity*

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Based on this, we can determine and conclude that the integration of the business model is profitable, feasible and very promising for the company, which would particularly be felt on the revenue side of the business: net cash flow calculated on a ten-year average would have amounted to €92,341 per year.

According to the last result, according to the theoretical research, it can also be argued that by purchasing less electrical energy from the grid, the energy system is becoming friendlier to the environment, because it reduces the carbon dioxide footprint. One kWh of electrical energy in Slovenia is equal to 0.618 kg $CO_2$, which in theory means approx. 10 tons of $CO_2$ less in summer time (per month) and 0.9 tons in winter time (per month).

# 4 CONCLUSIONS

The result is a quantitative understanding of how electric forklifts can become a part of the electrical grid. Our conclusion is that the described F2G model of integrating electric forklifts into warehouse energy management probably will not generate enormous amounts power, but it will provide additional storage and back-up the national grid when it will be needed.

We are aware that the technical side includes limitations, e.g. the current batteries of forklifts are not designed for use with the F2G concept, battery cycles should be higher, regulation signal from the national grid is also a problem; Smart Grids must be implemented into this kind of electrical systems, not just on the national level but also on the local (company) level, there are no standards and national laws for F2G and no mass production of the equipment needed for this technology.

Consequently, in this study we have not dealt with the implementation in practice, whether the organization produces and sells electricity, and with questions regarding the registration of additional activities. Everything was focused on the theoretical concept. Despite some limitations, the business model is definitely innovative and economically viable, and with further technological development of batteries it will soon be suitable for practical implementation.

Regarding electric power, the study shows that F2G could become a new power source, which will play an important role in energy management and will also affect costs of logistics operations in warehouses. The forklift will not be just a machine for loading and unloading, but also a battery for renewable energy sources and a new power source for the local (company) or national grid. It will not only reduce demand for electrical energy from the national grid, but will also become an additional source of revenue, making companies more independent and sustainable due to reduced lower carbon dioxide footprints.

Based on the presented facts and calculations, we can confirm the thesis that the integration of environmentally friendly renewable energy sources and new technologies into modern logistics management processes improves energy storage, and reduces negative environmental impacts. This means that due to lower operating costs, the money, time and all forces can be invested in further research, innovations, marketing and etc., which reinforce our brand, thus becoming more flexible and more easily adapted to the global environment and to individual customer requirements.

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This study was focused on a single described theoretical scenario. As already mentioned, a number of F2G scenarios are possible. One that would be useful to analyse and explore is Scenario II (Figure 11) in which the state would not subsidize the purchase of electricity (which is likely to happen in the near future due to saturation). In that case, it would make more sense for the electricity produced from solar energy to be used for local storage needs and in case of energy peaks in the local energy network it could be sold (shipped) from our energy system.

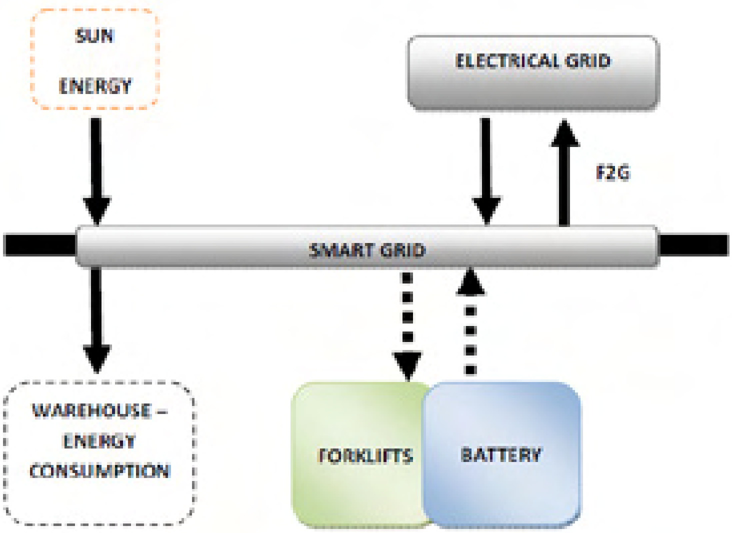


***Figure 11:*** *Business model of F2G integration into warehouse energy management – Scenario II.*

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# THE ITALIAN RENAISSENCE OF THE NUCLEAR OPTION — HOPE OR DESPAIR

# ITALIANSKI PREPOROD JEDRSKE OPCIJE — UP ALI BREZUP

Alberto Milocco[ℜ], Andrej Trkov

**Keywords:** nuclear renaissance, Italy


## Abstract

On 15 February 2010, the Italian government enacted a legislative decree on the site evaluation, commissioning and operation of nuclear facilities. The decree, *de jur*e and *de facto*, opened the road for the construction of new nuclear power plants, which had been abandoned from the time of the Chernobyl accident. This decision is relevant considering the present social movements in northern Africa and the nuclear accidents at Fukushima.

An entirely new nuclear program started, but its continuation is currently hampered by the outcome of a popular referendum, which took place on 12 and 13 June 2011 and addressed the specific issues of the legislative decree of 15 February 2010.

The Italian involvement in the context of nuclear energy is still alive in the area of nuclear research, decommissioning and the management of nuclear projects abroad.

## Povzetek

15. februarja 2010 je italijanska vlada izdala pravni akt o izboru lokacij, licenciranju in obratovanju jedrskih naprav. Ta akt je pravno in formalno odprl pot izgradnji novih jedrskih energetskih objektov, ki je bila opuščena po jedrski nesreči v Černobilu. Odločitev je aktualna, upoštevaje trenutna družbena gibanja v severni Afriki in jedrski dogodek v Fukušimi.


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Jedrski program je dobil nov zagon, vendar je nadaljevanje oteženo zaradi rezultatov ljudskega referenduma, ki je bil izglasovan 12. in 13. junija 2011 in je opredeljeval stališča do določenih členov omenjenega akta.

Italijansko delovanje na področju jedrske energije je še vedno živo na področjih jedrskih raziskav, razgradnje in upravljanja jedrskih projektov v tujini.

# 1 INTRODUCTION

An abstract for this paper was proposed the week after the earthquake that hit Japan on 11 March 2011 and triggered the sequence of events that led to the accident of the Dai-ichi nuclear power station. A possible title had been suggested that cited the 'nuclear hope' more than anything else. After the outcome of the popular referendum on 12-13 June 2011, the abstract has been rewritten and the title has been revised by including the last part ('despair'), which raises questions about the 'hope'. It is, after all, a story with a brave start, a moment of great expectations and a decline, even if the story has not reached its very end (if it exists at all).

# 2 LEGISLATIVE FRAMEWORK

On 23 June 2008, the Italian government approved a decree, ratified on 6 August 2008 into law No. 133, addressing the national energy strategy, explicitly citing the commissioning on the national land of plants for the production of nuclear power.

Article 25 of the law No. 99 from 23 July 2009 states that: 'The Government is delegated to adopt […] one or more legislative decrees of normative reorganisation concerning the subject of the siting on national land of plants for the nuclear energy production and the nuclear fuel fabrication and of systems for the storage of irradiated fuel and radioactive wastes as well as for the final disposal of radioactive materials and wastes and of the definition of offsetting measures […]' [1].

On 15 February 2010, the government enacted the legislative decree on the order of the site evaluation, commissioning and operation in the national land of nuclear facilities, as required by the previously cited law. The decree consists of 35 articles divided into five sections.

Following initiative of the opposition, on 23 March 2011, the President of the Republic issued a decree calling a popular referendum for the abrogation of the prescriptive text in the laws and decrees mentioned above, and bringing about nuclear energy production.

On 31 March 2011, the government approved a decree that suspended for one year the effectiveness of the main body of the decree of 15 February 2010 with the aim of acquiring more scientific evidence on the safety parameters (in the European context) in relation to the localisation, construction and operation of nuclear installations. This decree was ratified (with modifications) into law on 26 May 2011. The modifications abrogated the dispositions regarding the commissioning of new nuclear plants, with a clear attempt to make the referendum question unconstitutional.

On 1 June 2011, the Supreme Court verified the new regulations with reference to the nuclear question of the referendum and decided to request the abrogation from the original

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referendum question being transferred to paragraphs 1 and 8 of article 5 in the new law No. 75 of 26 May 2011.

The popular referendum with this new question and three other questions was held on 12 and 13 June 2011. A total of 54.79% of Italians voted. Among them, an overwhelming opposition against the Italian nuclear plans was shown by voters in Italy (94.75%). Taking into account also the voters abroad, the overall result was 94.05% of positive votes for the abrogation (Table 1).

***Table 1:*** *Official results of the 2011 referendum*

Dipartimento per gli affari interni e territoriali

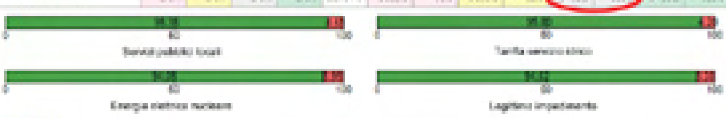
Direzione Centrale dei servizi elettorali

*Referendum 12 - 13 giugno 2011*

Ultimo aggiornamento: martedì 14 giugno 2011 - 4:01

| Percentuale votanti | Servizi pubblici locali | Tariffa servizio idrico | Energia elettrica nucleare | Legittimo impedimento |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| ITALIA | 57.04 | 57.05 | 57.01 | 57.00 |
| ESTERO | 23.07 | 23.07 | 23.08 | 23.12 |
| ITALIA + ESTERO | 54.81 | 54.82 | 54.79 | 54.78 |

| Scrutinio | Sezioni scrutinate | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Regione | 1 | 2 | 3 | 4 | Sez. tot | SI | NO | SI | NO | SI | NO | SI | NO |
| PIEMONTE | Def | Def | Def | Def | 4.834 | 94.67 | 5.33 | 95.20 | 4.80 | 93.14 | 6.86 | 94.30 | 5.70 |
| VALLE D'AOSTA | Def | Def | Def | Def | 150 | 96.58 | 3.42 | 97.00 | 3.00 | 95.19 | 4.81 | 95.79 | 4.21 |
| LOMBARDIA | Def | Def | Def | Def | 9.228 | 93.40 | 6.60 | 94.10 | 5.90 | 91.64 | 8.36 | 93.20 | 6.80 |
| TRENTINO-ALTO ADIGE | Def | Def | Def | Def | 1.016 | 96.84 | 3.16 | 97.11 | 2.89 | 96.07 | 3.93 | 96.29 | 3.71 |
| VENETO | Def | Def | Def | Def | 4.760 | 94.66 | 5.34 | 95.28 | 4.72 | 93.54 | 6.46 | 93.72 | 6.28 |
| FRIULI-VENEZIA GIULIA | Def | Def | Def | Def | 1.377 | 94.98 | 5.02 | 95.63 | 4.37 | 93.41 | 6.59 | 93.91 | 6.09 |
| LIGURIA | Def | Def | Def | Def | 1.800 | 95.69 | 4.31 | 96.23 | 3.77 | 93.98 | 6.02 | 95.01 | 4.99 |
| EMILIA-ROMAGNA | Def | Def | Def | Def | 4.319 | 95.03 | 4.97 | 95.41 | 4.59 | 94.31 | 5.69 | 95.00 | 5.00 |
| TOSCANA | Def | Def | Def | Def | 3.973 | 95.65 | 4.35 | 95.99 | 4.01 | 95.06 | 4.94 | 95.48 | 4.52 |
| UMBRIA | Def | Def | Def | Def | 1.026 | 95.46 | 4.54 | 96.09 | 3.91 | 94.72 | 5.28 | 95.05 | 4.95 |
| MARCHE | Def | Def | Def | Def | 1.588 | 95.90 | 4.10 | 96.33 | 3.67 | 95.16 | 4.84 | 95.34 | 4.66 |
| LAZIO | Def | Def | Def | Def | 5.267 | 96.35 | 3.65 | 96.91 | 3.09 | 95.14 | 4.86 | 95.47 | 4.53 |
| ABRUZZO | Def | Def | Def | Def | 1.639 | 96.45 | 3.55 | 96.98 | 3.02 | 95.65 | 4.35 | 95.55 | 4.45 |
| MOLISE | Def | Def | Def | Def | 392 | 97.42 | 2.58 | 97.77 | 2.23 | 96.77 | 3.23 | 96.51 | 3.49 |
| CAMPANIA | Def | Def | Def | Def | 5.810 | 97.81 | 2.19 | 98.13 | 1.87 | 96.71 | 3.29 | 96.82 | 3.18 |
| PUGLIA | Def | Def | Def | Def | 4.005 | 97.29 | 2.71 | 97.64 | 2.36 | 96.71 | 3.29 | 96.39 | 3.61 |
| BASILICATA | Def | Def | Def | Def | 681 | 97.35 | 2.65 | 97.70 | 2.30 | 96.84 | 3.16 | 96.69 | 3.31 |
| CALABRIA | Def | Def | Def | Def | 2.408 | 98.05 | 1.95 | 98.34 | 1.66 | 97.33 | 2.67 | 96.91 | 3.09 |
| SICILIA | Def | Def | Def | Def | 5.306 | 97.59 | 2.41 | 97.94 | 2.06 | 96.48 | 3.52 | 96.16 | 3.84 |
| SARDEGNA | Def | Def | Def | Def | 1.820 | 98.24 | 1.76 | 98.55 | 1.45 | 98.39 | 1.61 | 96.54 | 3.46 |
| ITALIA | Def | Def | Def | Def | 61.595 | 95.84 | 4.16 | 96.32 | 3.68 | 94.75 | 5.25 | 95.15 | 4.85 |
| ESTERO (comunicazioni) | Def | Def | Def | Def | 1.279 | 76.32 | 23.68 | 75.71 | 24.29 | 67.07 | 32.93 | 74.40 | 25.60 |
| ITALIA + ESTERO | Def | Def | Def | Def | 62.878 | 95.35 | 4.65 | 95.80 | 4.20 | 94.05 | 5.95 | 94.62 | 5.38 |



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# 3 ENERGY SCENARIO

In the past, a few nuclear power plants and facilities operated in Italy. A referendum, following the Chernobyl accident, had the consequence of shutting them down and established a moratorium on the commissioning of new nuclear power plants. Electricity generation increased over time, and currently the Italian energy mix shows a significant proportion of gas use (Figure 1).

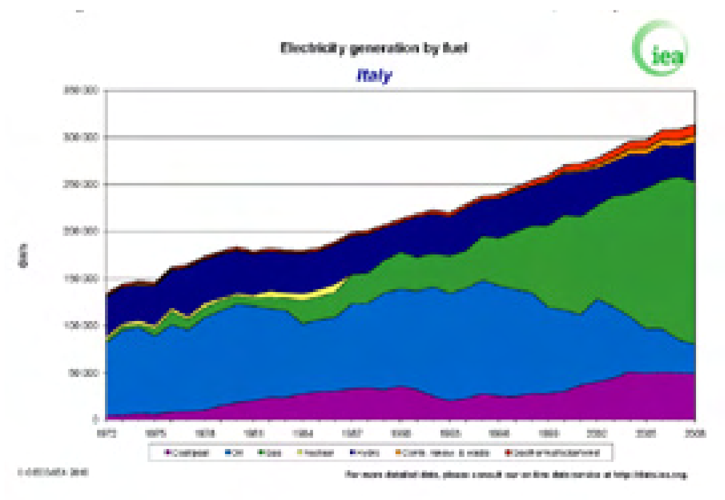


***Figure 1:*** *Sharing by resource for the Italian generation of electricity*

In prospective studies, the energy strategies are usually based on the definition of scenarios. Those defined for the Italian case by ENEA are hereby described [2]. The reference scenarios represent the evolution of the system without new intervention in energy and environment policy, assuming a substantial continuation of the current demographic, technological and economic trends (BAU: Business As Usual). In particular, an evolutionary scenario (BAU HG) assumes an optimistic economic growth on the long period and a moderate increase in the energy price while the stationary one (BAU LG) assumes an economic growth in agreement with the 1990–2010 trend, keeping moderate the energy price evolution. Two other scenarios of intervention, one pro-active (BLUE HG) and another defensive (BLUE LG), explore how the system would evolve if energy and environment policy changed in order to reduce $CO_2$ emissions. The underlying hypotheses on the economy and fuel price growth are essentially the same as for the reference scenarios.

The evolution of the electricity sector shows that the final consumption of electricity will increase for any of the ENEA scenarios (Figure 2). This means that more electrical power facilities have to be installed.

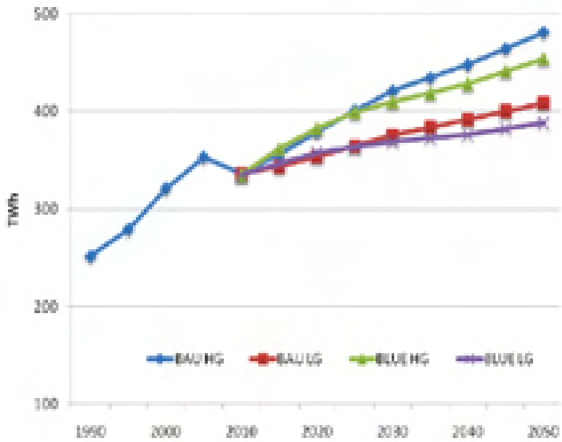


***Figure 2:*** *Consumption of electricity in the ENEA scenarios*

The nuclear option has also been considered for the future energy mix in the reference scenario, resulting in a significant decrease in the dependence from the gas supply (Figure 3). The study was based on the current Italian nuclear plan, which foresees the construction of the first three units by 2020 and a total of 13 GW of nuclear power installed by 2050 (Figure 4).

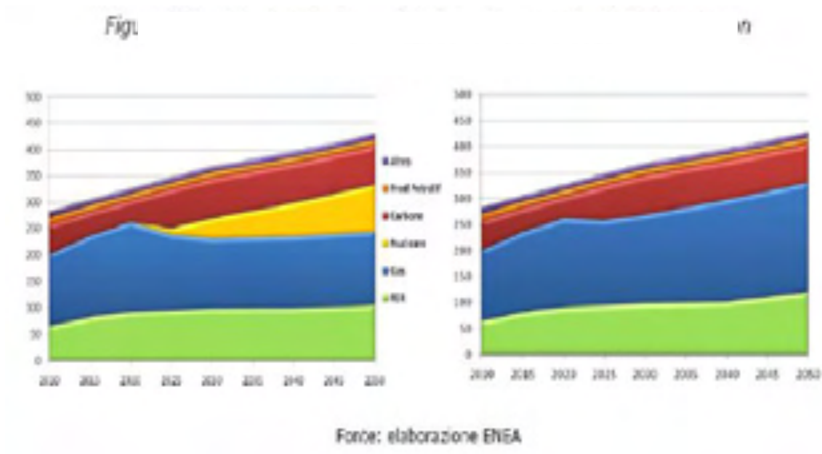


***Figure 3:*** *Electricity production mix with and without nuclear in the reference scenario*

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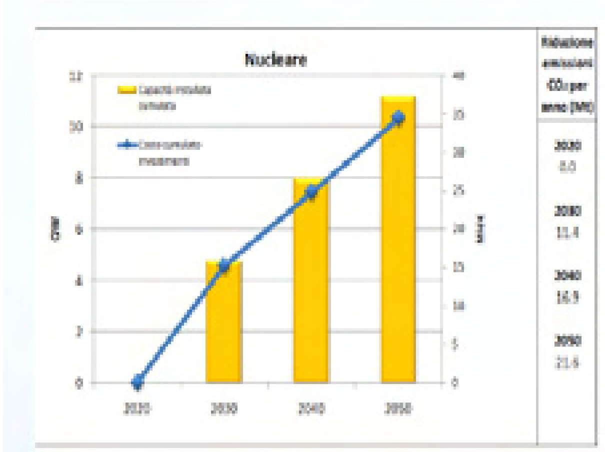


***Figure 4:*** *Capacity, investment cost and reduction of $CO_2$ emissions due to the use of nuclear energy*

Accordingly, all the figures that would have led to the commercial operation of the first unit of the nuclear programme are shown in Figure 5. This information was first presented by ENEL at the supply chain day meeting, held in Rome on 15 December 2010 [3]. The programme, at least as it is now, is not likely to be resumed.

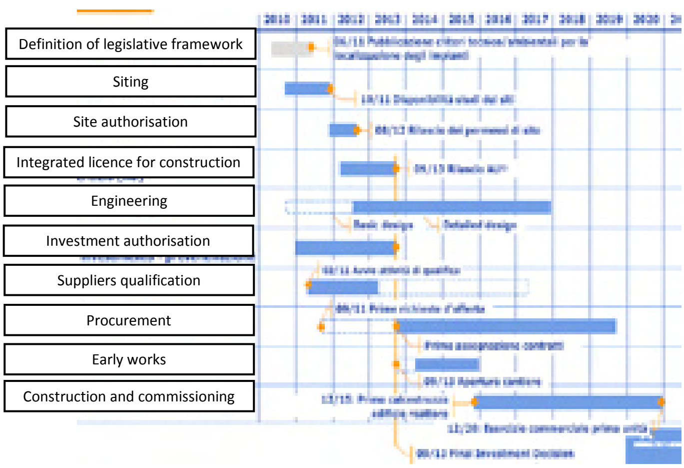


***Figure 5:*** *Former Italian nuclear programme*

# 4 NUCLEAR REALITIES

The nuclear sector always benefits from the commissioning of new nuclear power plants. In the Italian case, major parts of the nuclear investment and expertise have been jeopardised over the previous 20 years. Realities in the context of nuclear energy are only found in the niches of nuclear research, decommissioning or management of nuclear projects abroad. The core

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business of the company SOGIN Spa (SOcietà Gestione Impianti Nucleari) is the decommissioning of the Italian nuclear legacy, consisting of four NPPs and four other nuclear stations, which were devoted to the fuel cycle. Italian research should also be mentioned; it is primarily carried out in research centres like ENEA (Ente Nazionale per le Energie Alternative), CNR (Consiglio Nazionale delle Ricerche), INFN (Istituto Nazionale di Fisica Nucleare) and in many universities. Moreover, institutions dealing with public health or environment often include laboratories for radiation measurements. For instance, the ISPRA (IStituto di PRotezione Ambientale) is responsible for radiation monitoring at national levels and provides advice to regulatory bodies. Some private companies, e. g. Ansaldo Nucleare and Mangiarotti Spa, have maintained the industrial production of nuclear components for foreign markets. The main Italian electricity utility, Enel Spa, is a major player in the European nuclear sector. In Spain, by controlling Endesa, Enel manages six nuclear reactors with a total capacity of about 3600 MW. In Slovakia, by controlling Slovenské Elektrárne, Enel manages four nuclear units with a total capacity of about 1900 MW. Moreover, Enel is involved in the commissioning of the EPR at Flamanville (France), of two new reactors at Mochovce (Slovakia) and of the nuclear station at Cernovoda (Romania).

## 5 ACKNOWLEDGMENTS

The authors acknowledge Mario Pillon (ENEA, Italy) for providing some presentations from the Supply Chain Meeting, 15 December 2010, Rome.

## 6 CONCLUSIONS

In recent years, decisions of the Italian government have created many expectations within the nuclear community. The regulatory framework was on the way to being established and some technical issues were already pointed out. The follow up of the Italian nuclear program is hampered by public opinion, which was manifested in the recent popular referendum on the subject. The concomitance of the referendum with the aftermath of the Fukushima nuclear accident reasonably biased the results of the referendum. The nuclear option should not be *a priori* ruled out from Italian energy policy, taking into account the current energy scenarios.

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# THE THEORY AND APPLICATION OF THE INDUCTION MOTOR DIAGNOSTIC METHODS BASED ON ELECTRICAL SIGNAL ANALYSIS

# TEORIJA IN UPORABA METOD ZA DIAGNOSTIKO ASINHRONSKIH MOTORJEV NA OSNOVI ANALIZE ELEKTRIČNIH SIGNALOV

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**Keywords:** Diagnostics, induction motor, instantaneous power, spectra analysis

## Abstract

In this article, the theoretical basis and developed hardware and software for an induction motor diagnostic system based on electrical signals analysis is presented. The theoretical principles underlying these methods are based on a spectral analysis of the stator current and power signals. The hardware allows data measurement for different operating modes with different loading of the motors. The software allows making an analysis of preliminary recorded data using motor current signature analysis (MCSA) and instantaneous power spectra analysis (IPSA) methods. Experimental tests with real data analysis showed the possibility of utilising the developed methods and equipment for induction motor diagnostic systems.

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## Povzetek

V članku je predstavljen merilni sistem s pripadajočo strojno in programsko opremo za diagnostiko asinhronskih motorjev, ki temelji na spektralni analizi statorskega toka in moči. V predstavljenem merilnem sistemu strojna oprema omogoča meritve podatkov v različnih režimih obratovanja asinhronskega motorja. Programska oprema se uporablja za analiziranje predhodno izmerjenih podatkov z metodama »motor current signature analysis« in »instantaneous power spectra analysis«. Rezultati analize izmerjenih podatkov s predstavljenim merilnim sistemom kažejo na uporabnost programske in strojne opreme ter metod za diagnostiko asinhronskih motorjev.

# 1 INTRODUCTION

At present, induction motors (IM) are the most widely used consumers of electric energy. According to recent research, they consume over 80% of the total amount of electric power, [1]. Induction motors are widely used because of the simplicity of their construction, reliability and relatively low cost. The creation of speed-controlled electric drive systems resulted in increased usage of IM because of the simplicity of their implication into such systems. However, different types of damage can be caused to IM parts under operating conditions, which can lead to untimely motor failure. Every year about 20–25 % of induction motors fail as a result of damage. Thus, the creation of a reliable IM diagnostic system is an important task. In many factories, the failure of one motor can lead to the shutdown of the entire manufacturing process. The operation of electric motors under unsatisfactory technical conditions results both in direct financial losses, and in considerable (about 5–7 %) indirect expenses for electric energy. For this and other reasons, there is a need for IM diagnostics under operating conditions. The most convenient and reliable IM diagnostic methods are based on the analysis of electric signals. There are two convenient methods for on-line IM diagnostic: current spectra analysis and instantaneous power spectra analysis. The first needs only one phase current signal for analysis; therefore, this method is attractive due to its measuring simplicity. The second needs data of three phase currents and voltages; this method is more complicated, but gives more reliable results.

# 2 MOTOR CURRENT SIGNATURE ANALYSIS (MCSA)

MSCA is a very popular diagnostic method because of the simplicity of the signal recording under operation mode. There is a number of works devoted to using MSCA as a medium for detecting the stator windings short-circuits, the rotor imbalances and rotor bar breaks, and also the bearings defects [2]. The concept of this method is IM defects corresponding to certain harmonics in current spectra, as shown below.

## 2.1 Broken rotor bars

In the case of broken bars, the disturbance induces fundamental sidebands of the supply frequency and of the winding factor in the current signal, [2]:

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$$f_{bb} = f_s[1 \pm 2s] \tag{2.1}$$

where $f_s$ is the supply fundamental frequency,

$s$ is the motor slip.

## 2.2 Air gap eccentricity

There are three types of air gap eccentricity: static, dynamic and mixed. All of these eccentricities lead to the appearance of two types of unique current frequencies: around fundamental harmonic ( $f_{eccen\_fun}$ ) and around principle slot harmonic ( $f_{eccen\_prin}$ ) [2]:

$$f_{eccen\_fun} = f_s \pm k f_r \, , \tag{2.2}$$

where $f_r = \frac{1-s}{p}$, where $s$ is the motor slip,

$p$ is the number of pole pairs;

$$f_{eccen\_prin} = \left[ (kR \pm n_d) \left( \frac{1-s}{p} \right) + \eta \right] f_s \, , \tag{2.3}$$

where $R$ is the number of rotor slots;

$k$ is the positive integer number;

$n_d$ is an integer due to dynamic eccentricity;

$\eta$ is the time harmonics present in the motor supply.

## 2.3 Stator windings short-turns

In the case of the inter-turn short circuit of the stator winding, the short-circuit current flows into the inter-turn short-circuit windings. This initiates a negative magnetomotive force (MMF), which reduces the net MMF of the motor phase. Therefore, the waveform of air-gap flux, which is changed by the distortion of the net MMF, induces harmonic frequencies in a stator winding current as, [3, 4]:

$$f_{st} = f_s \left[ \frac{n}{p} (1-s) \pm k \right] , \tag{2.4}$$

where $f_s$ is the supply main frequency;

$n$ is a positive integer number (1, 2, 3…);

$s$ is the motor slip;

$k$ can be equal to 1, 3, 5 or 7.

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## 2.4 Bearing damage

Bearing damage leads to vibrations. Since bearings support the rotor, the vibrations in their turning lead to air gap fluctuations. These variations lead to stator current frequencies given by [2]:

$$f_{brg} = \left| f_s \pm m f_{i,o} \right|, \tag{2.5}$$

where $m = 1,2,3...$, and $f_{i,o}$ is one of the characteristic vibration frequencies, which are based upon the bearing dimensions:

$$f_{i,o} = \frac{n}{2} f_v \left[ 1 \pm \frac{bd}{pd} \cos\beta \right],$$

where $n$ is the number of bearing balls;

$f_v$ is the mechanical rotor velocity in hertz;

$bd$ is the ball diameter;

$pd$ is the bearing pitch diameter;

$\beta$ is the contact angle of the balls on the races.

As can be seen from equations (2.1)–(2.5), all reviewed damage types may lead to similar or identical harmonic components. Thus, additional features are required to determine the specific damage type. Furthermore, it has to be mentioned that electrical distortions and the influence of supplying low quality voltage could lead to the appearance of harmonics in the current signal on the same frequency as fault harmonics. This may lead to an incorrect diagnosis. To eliminate such shortcomings of this method, an additional analysis of vibrations or more complicated mathematical apparatus for analysis are used. However, even this additional analysis does not prevent diagnostic mistakes when low-power IMs with significant influence of voltage non-sinusoidality are under analysis. This fact is especially significant for IM fed by the low-voltage supply of industrial plants.

# 3 INSTANTANEOUS POWER SPECTRA ANALYSIS (IPSA)

Instantaneous power spectra analysis allows avoiding shortcomings of the abovementioned methods [5–7]. It does, however, allow both the detection of fault presence and the estimation of damage level by analysis of proper harmonic value. Thus, it is possible to estimate the energy of fault and the correlation of this energy to additional damage of IM parts under the influence of additional vibrations caused by proper harmonics. Moreover, the instantaneous power spectra analysis allows the analysing of IM operation modes under significant nonlinearity, when it is incorrect to use superposition principle for current harmonics. Furthermore, instantaneous power analysis is more reliable, less dependent on noise, and gives additional harmonic components for analysis, [5-7].

The instantaneous power is defined as:

$$p(t) = u(t)i(t),$$

where $u(t)$ is the phase voltage;

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*i(t)* is the input phase current.

In the case of a motor in good condition running at a constant speed and fed from ideal supply, the expressions of the phase voltage $u(t)$, phase current $i(t)$ and instantaneous power, are the following, [8]:

$$u(t) = \sqrt{2}U_1 \cos(\omega t);$$

$$i(t) = \sqrt{2}I_1 \cos(\omega t - \varphi);$$

$$p(t) = u(t)i(t) = 2U_1 I_1 \cos(\omega t)\cos(\omega t - \varphi) = 2U_1 I_1 \cos(\omega t)\begin{bmatrix} \cos(\omega t)\cos(\varphi) + \\ + \sin(\omega t)\sin(\varphi) \end{bmatrix} = \tag{3.1}$$
$$= U_1 I_1 \cos(\varphi) + U_1 I_1 \cos(\varphi)\cos(2\omega t) + U_1 I_1 \sin(\varphi)\sin(2\omega t),$$

where $U_1, I_1$ are RMS values of phase voltage and current, respectively;

$\omega = 2\pi f_s$ is the angular frequency,

where $f_s$ is the supply frequency;

$\varphi$ is the motor load angle.

Unlike current spectra, which contain only the fundamental component at the frequency $f_s$, the instantaneous power spectra have an average power component $U_1 I_1 \cos(\varphi)$ and fundamental component at frequency $2f_s$.

In order to make a comprehensive analysis of IM defects, it is necessary to analyse the total instantaneous power of three phases, which is the sum of phase instantaneous powers:

$$p_{tot}(t) = u_A(t)i_A(t) + u_B(t)i_B(t) + u_C(t)i_C(t).$$

Total three phase instantaneous power contains more diagnostic information. It allows us to analyse not only the defects that cause phase signals modulations, but also the defects caused by motor or supply asymmetry, and those which lead to phase signals asymmetry. In the case of a symmetrical motor, the signal of total three phase instantaneous power contains only a DC component. Thus, every kind of motor fault or drive system asymmetry leads to the appearance of unique harmonic components, which could be used for the certain detection of fault types.

## 3.1 Rotor bar breaks

As it mentioned above, the rotor bar break causes sinusoidal modulations of the stator current. By analogy to [7], the modulated phase current can be expressed as:

$$i_m(t) = i(t)[1 + I_m \cos(2\pi f_{bb} t)] = i(t) + \frac{\sqrt{2}}{2} I_1 I_m \begin{bmatrix} \cos(2\pi(f_s - f_{bb})t - \varphi) + \\ + \cos(2\pi(f_s + f_{bb})t - \varphi) \end{bmatrix}, \tag{3.2}$$

where $I_m$ is the modulation index;

$f_{bb}$ is the modulating frequency;

$s$ is the motor slip.

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According to expression (3.2), phase current spectra, in addition to fundamental component, contain two sideband components at frequencies $f_s - f_{bb}$ and $f_s + f_{bb}$.

The expression for the modulated phase instantaneous power is the following:

$$p_m(t) = i_m(t)u(t) = P_0 + U_1 I_1 \cos(\varphi)\cos(2\omega t) + U_1 I_1 \sin(\varphi)\sin(2\omega t) + \\ + \left(I_1 I_m U_1 \cos\left[2\pi(f_s - f_{bb})t - \varphi\right] + I_1 I_m U_1 \cos\left[2\pi(f_s + f_{bb})t - \varphi\right]\right)\cos(2\omega t). \quad (3.3)$$

This expression shows that phase instantaneous power spectra, besides DC component $P_0$ and two sideband components at frequencies $2f_s - f_{bb}$ and $2f_s + f_{bb}$, contains an additional component $I_1 I_m U_1 \cos(\varphi)\cos(f_{bb}t)$ at the modulation frequency $f_{bb}$, which is an additional diagnostic parameter.

In the case of a symmetrical drive system there is compensation of harmonic components in three-phase instantaneous power spectra. Thus, it contains only a DC component and a component at frequency $2f_s + f_{bb}$.

Any kind of drive system asymmetry leads to appearance of additional harmonic components in three-phase instantaneous power spectra at the modulation frequency $f_{bb}$, sideband component at frequency $2f_s + f_{bb}$, and fundamental component at frequency $2f_s$.

## 3.2 Air gap eccentricity

In the case of air gap eccentricity, current frequencies expressed by (2.2) lead to modulation of phase current:

$$i_{eccen}(t) = i(t) + \frac{\sqrt{2}}{2} I_1 \sum_{k=1}^{K} \begin{bmatrix} I_{e1k} \cos(2\pi(f_s - kf_r)t - \alpha_{e1k}) + \\ + I_{e2k} \cos(2\pi(f_s + kf_r)t - \alpha_{e2k}) \end{bmatrix}, \quad (3.4)$$

where $I_{e1k}$, $\alpha_{e1k}$ are the current amplitudes and the initial phase angle for frequencies $f_s - kf_r$;

$I_{e2k}$, $\alpha_{e2k}$ are the current amplitudes and the initial phase angle for frequencies $f_s + kf_r$.

In this case, the expression for phase instantaneous power of motor operating under air gap eccentricity is the following:

$$p_{eccen}(t) = i_{eccen}(t)u(t) = P_0 + U_1 I_1 \cos(\varphi)\cos(2\omega t) + U_1 I_1 \sin(\varphi)\sin(2\omega t) + \\ + \sqrt{2}U_1 \cos(2\omega t) \sum_{k=1}^{K} \begin{bmatrix} I_{e1k} \cos\left[2\pi(f_s - kf_r)t - \alpha_{e1k} - \varphi\right] + \\ + I_{e2k} \cos\left[2\pi(f_s + kf_r)t - \alpha_{e2k} - \varphi\right] \end{bmatrix}. \quad (3.5)$$

Air gap eccentricity leads to appearance of sideband components in phase power spectra at frequencies $2f_s - kf_r$ and $2f_s + kf_r$, and additional harmonic components at frequencies $kf_r$.

## 3.3 Stator windings short-turns

By analogy with (3.2), current modulations, caused by stator short-turns, could be described as:

$$i_m(t) = i(t)[1 + I_m \cos(2\pi f_{st} t - \varphi)] = i(t) + \frac{\sqrt{2}}{2} I_1 I_m \left[\cos(2\pi f_{st} t - \varphi)\right], \quad (3.6)$$

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where $I_m$ is the modulation index;

$f_{st}$ is the modulating frequency, according to (2.4);

$s$ is the motor slip.

According to (3.6), the phase current spectra, in addition to supply frequency, contain harmonics on frequencies $f_{st}$.

Power modulations could be described as:

$$p_m(t)=i_m(t)u(t)=P_0+U_1I_1\cos(\varphi)\cos(2\omega t)+ \\ +U_1I_1\sin(\varphi)\sin(2\omega t)+\frac{1}{2}I_1I_mU_1\cos(2\pi f_{st}t-\varphi)\cos(2\omega t). \quad (3.7)$$

Equation (3.7) shows that short turns in stator windings lead to appearance of power signal harmonics on modulating frequencies $f_{st}$ and their combinations with the supply frequency.

## 3.4 Bearings damage

The vibrations caused by bearings damage leads to current modulation at frequencies according to (2.5):

$$i_{brg}(t)=i(t)+\frac{\sqrt{2}}{2}I_1\sum_{k=1}^{K}\begin{bmatrix}I_{b1k}\cos(2\pi(f_s-kf_{brg})t-\alpha_{b1k})+\\+I_{b2k}\cos(2\pi(f_s+kf_{brg})t-\alpha_{b2k})\end{bmatrix},$$

where $I_{b1k}$, $\alpha_{b1k}$ are the current amplitudes and the initial phase angle for frequencies $f_s-kf_{brg}$,

$I_{b2k}$, $\alpha_{b2k}$ are the current amplitudes and the initial phase angle for frequencies $f_s+kf_{brg}$.

By analogy with (3.5), the instantaneous power of motor operating with the bearings damage is the following:

$$p_{brg}(t)=i_{brg}(t)u(t)=p_0(t)+\frac{1}{2}I_1U_1\sum_{k=1}^{K}\begin{bmatrix}I_{b1k}\cos\left[2\pi(2f_s-kf_{brg})t-\alpha_{b1k}\right]+\\+I_{b2k}\cos\left[2\pi(2f_s-kf_{brg})t-\alpha_{b2k}\right]+\\+I_{b1k}\cos(\alpha_{b1k})\cos(kf_{brg}t)+\\+I_{b2k}\cos(\alpha_{b2k})\cos(kf_{brg}t)\end{bmatrix}.$$

Bearing damage leads to appearance of sideband components in phase power spectra at frequencies $2f_s-kf_{brg}$ and $2f_s+kf_{brg}$, and additional harmonic components at frequencies $kf_{brg}$.

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# 4 DEVELOPMENT OF THE EXPERIMENTAL SAMPLE OF DIAGNOSTIC EQUIPMENT

In order to utilise and test these diagnostic methods, special diagnostic equipment should be created. This equipment should consist of two parts: hardware for measuring and recording electrical signals, and software for analysing recorded data according to both diagnostic methods, and presenting diagnostic results to users.

In order to test the possibilities of diagnostic equipment, experimental tests measuring and analysing signals from IM with damage should be done. This feature should be taken into account while hardware is being developed.

## 4.1 Hardware development

Measuring modules with measuring software were developed by authors for the measuring and recording of the electrical signals (voltages and currents), which are necessary for the analysis (Fig. 1).

A photo of the created experimental equipment is shown in Fig. 2.

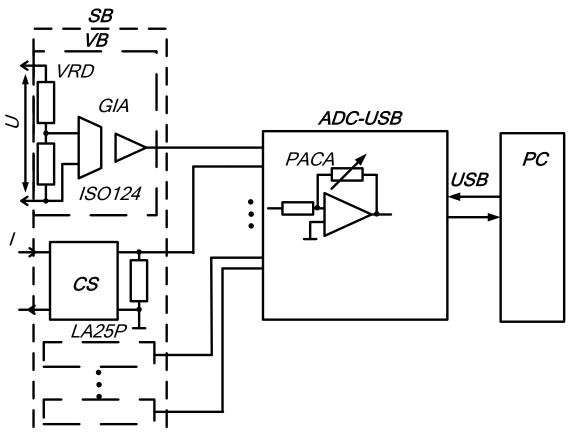


***Figure 1:*** *Measuring module functional circuit (SB – sensor block; VB – voltage block; VRD – voltage resistance divider; GIA – galvanic isolation amplifier; CS – current sensor; PC – personal computer; PACA – programmed amplification coefficient amplifier; USB – PC bus)*

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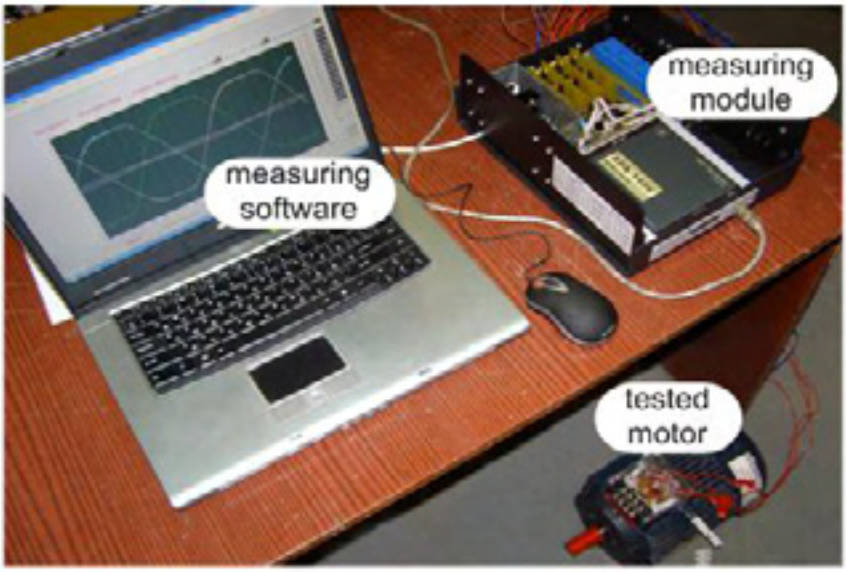


***Figure 2:*** *Photo of the measuring complex*

For simulating the most frequently caused defects of IM, such as rotor bar breaks, stator windings asymmetry and short circuits, bad mounting to the ground and rotor eccentricity, three identical induction motors of type АИР80В4У2 1.5 kW were used. Their design provides the possibility of creating the rotor bar break and turn-to-turn short circuit (Fig. 1, 2).

In order to imitate turn-to-turn short circuits, the taps were provided in one of the phases of stator winding (Fig. 3, Table 1). To imitate rotor bar breaks, apertures were drilled in the places where the bars are attached to cage rings, with the aim of breaking the contact of the bar and the ring. For investigating broken bars, several rotors of identical type with 1, 2 or 3 broken bars, which can be interchanged, were used. A schematic of apertures location is shown in Fig. 4.

The DC generator provided a mechanical load. The motor angular speed can be controlled with a speed sensor. Supply asymmetry could be achieved by using the voltage transformer in one of the supply phases.

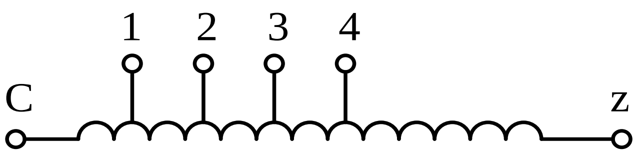


***Figure 3:*** *Stator phase winding taps circuit*

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***Table 1:*** *IM winding resistance measurement data*

| Phase | Resistance value, ohm | | |
|---|---|---|---|
| A | 5.102 | | |
| B | 4.972 | | |
| C | 4.945 | | |
| Taps in phase C | Winding part | Resistance value, ohm | Reduction of winding turns number, % |
| | 1-z | 4.93 | 0.3 |
| | 2-z | 4.878 | 1.36 |
| | 3-z | 4.82 | 2.52 |
| | 4-z | 4.253 | 14 |

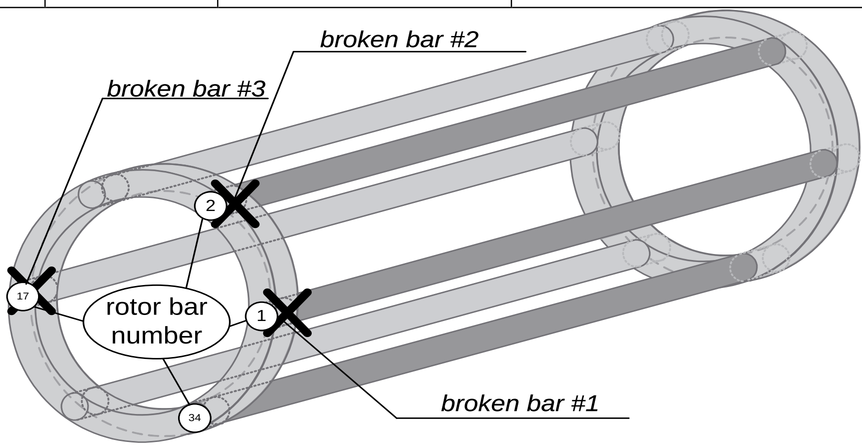


***Figure 4:*** *Scheme of rotor apertures location*

## 4.2 Software development

The software for IM fault detection system was developed based on the expressions for the correspondence of fault type and electrical signal harmonic component known from the MSCA analysis method, [2], and the instantaneous power analysis method, [1]. The user interface is shown in Fig. 5–8. This software allows us to upload preliminary measured data for analysis (Fig.5). There is also a possibility of defining the analysed signal length. Basing on the given signals, the program calculates FFT transformation and shows the signal spectra for each phase of the electric signal (Fig. 6) and for total instantaneous power of three phases (Fig. 7). According to developed algorithms, the program gives a diagnostic result based both on the MSCA method and the instantaneous power analysis method (Fig. 8).

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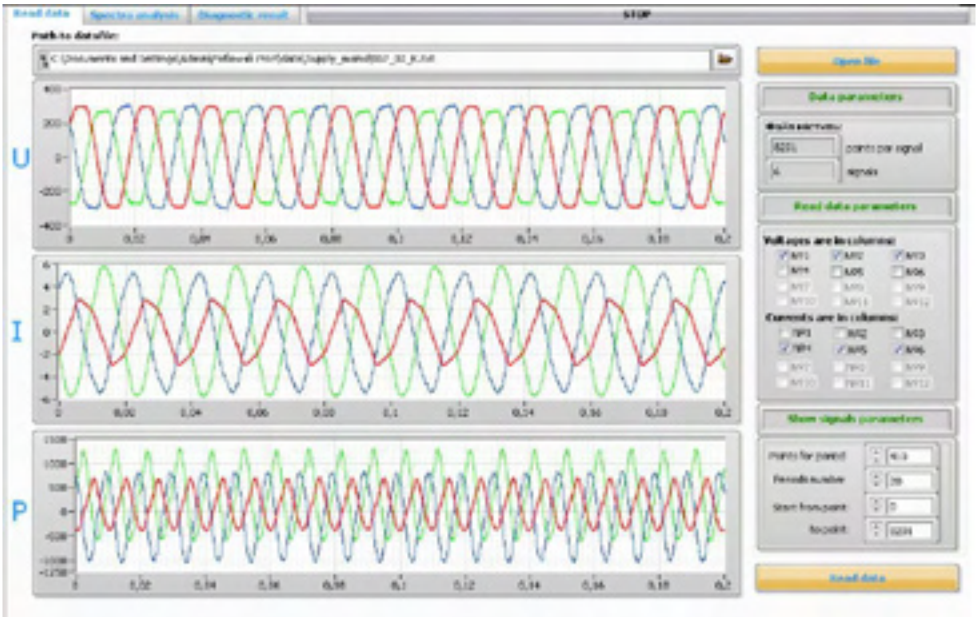


***Figure 5:*** *Read data and signal settings window*


***Figure 6:*** *Spectra analysis for phase electric signals*

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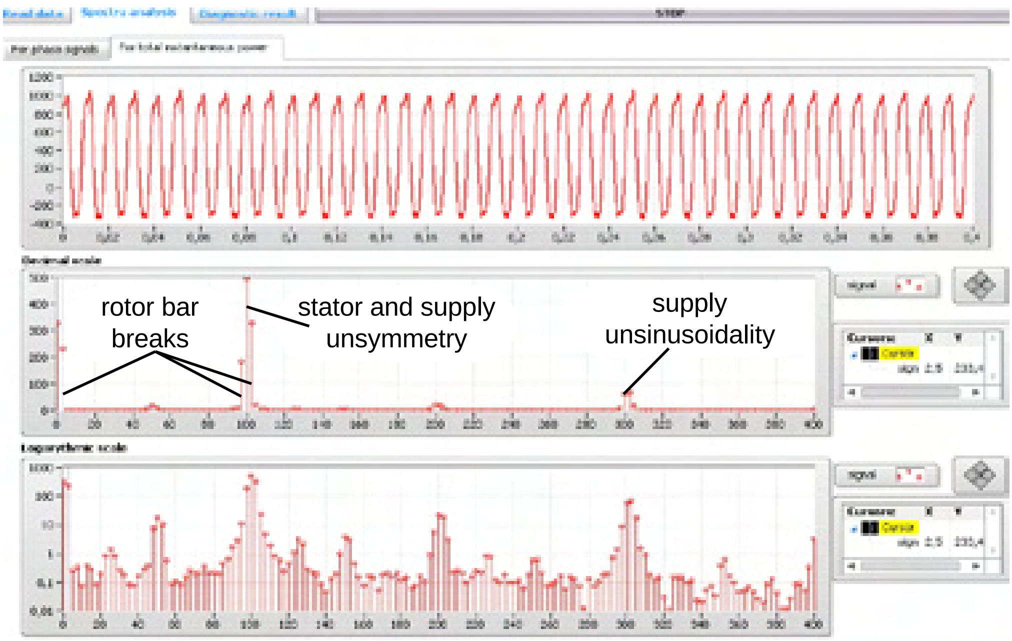


***Figure 7:*** *Spectra analysis for total 3-phase instantaneous power signal*


***Figure 8:*** *Diagnostic results window*

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# 5 EXPERIMENTAL RESEARCH

Analysis was carried out for IM under idle conditions and under full load conditions. The preliminary data have shown that defects could be more obviously manifested in loaded machine signals.

The analysis of the completed experiments makes it possible to come to the following conclusions. When a rotor bar break is imitated and motor operates at full load, a growth of sideband harmonics at frequencies of $50n \pm 2.5$ Hz ($n = 1,2,3\ldots$) in the current spectrum can be observed. Meanwhile, the three phase total power signal besides sideband harmonics contain low-frequency component at frequency of *2.5* Hz, which is an additional diagnostic feature. Due to cross-connections during the formation of instantaneous power harmonics components on the basis of current and voltage components, this component is revealed in the power signal at the frequencies divisible by 2.5 Hz. This component can hardly be noticeable, because of its small amplitude, at the frequencies divisible by the frequency of supply mains (50 Hz). Thus, it is possible to determine the existence of rotor bar breaks by the amplitude values of harmonics of $50n \pm 2.5$ Hz.

Growth of the harmonic amplitude in total three-phase power at frequency of 300 Hz can be explained by the power supply non-sinusoidality.

When turn-to-turn short circuits appear, as well as when there is a stator winding asymmetry, the amplitude of harmonics at frequency of 100 Hz in phases power and total three-phase power increases significantly. This feature is absent in MSCA analysis.

Preliminary analysis of investigated motor carried out using MSCA and instantaneous power analysis techniques showed that under full load conditions both methods demonstrated perfect results for broken bar detection. However, for idle mode, broken bars were detected using only instantaneous power spectra analysis. The same results were obtained for rotor imbalance detection under idle conditions.

Thus, preliminary research leads to the conclusion that both methods are reliable for the detection the most common IM faults in loaded motors, but in case of idle mode the instantaneous power spectra analysis gives much better results because of the additional harmonic components related to damage.

# 6 CONCLUSION

A review of modern methods for IM fault detection resulted in a conclusion about the necessity of development the testing equipment and software for simplifying diagnostic operation. The most easy-used and reliable methods among those reviewed are motor current signature analysis and instantaneous power spectra analysis. Thus, the developed software allows us to make an analysis based on both of these methods. Experimental tests with real data analysis showed the possibility applying the developed software for IM diagnostic systems and showed the advantages of instantaneous power analysis for idle mode.

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# TRANSITION TO A COMMON 20kV DISTRIBUTION NETWORK

# PREHOD NA SKUPNO 20kV DISTRIBUCIJSKO OMREŽJE

Damir Crnković, Željko Hederić[ℜ], Miralem Hadžiselimović

**Keywords:** operation, planning, optimization techniques, electric power system, 20 kV distribution power network, transition

## Abstract

The aim of this paper is to review the basics of operation and planning problems of electric power systems with optimization techniques, considering the example of beginning the development of a new 20 kV distribution power network and its main constraints. The future network development of the power distribution network envisages a transition from 10 kV and 35 kV voltage levels to the 20 kV voltage level. This transition requires the building of a completely new 20(10) kV distribution network. This can be achieved by reconstructing the existing 10 kV power network into 10(20) kV network, which will then continue to operate at 10 kV voltage for some time, and by building a 20 kV power connection for new consumers with power value more than 1 (one) MVA.

## Povzetek

Namen tega članka je pregled osnovnih operativnih problemov pri načrtovanju elektroenergetskih sistemov z optimizacijskimi tehnikami. Tako je v članku na podanem realnem primeru prikazan razvoj novega 20 kV distribucijskega omrežja z upoštevanjem vseh omejitev. Nadaljnji razvoj distribucijskega omrežja električne energije predvideva prehod iz 10 kV in 35 kV napetostnega nivoja na 20 kV napetostni nivo. Ta prehod zahteva gradnjo povsem novega 20(10) kV distribucijskega omrežja. To je mogoče doseči z rekonstrukcijo obstoječega 10 kV

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omrežja v 10(20) kV omrežje, ki v prehodnem obdobju še vedno deluje na 10 kV napetostnem nivoju. Vzporedno s tem pa se za vse nove potrošnike s priključno močjo nad 1 MVA gradi 20 kV distribucijsko omrežje.

# 1 INTRODUCTION

## 1.1 Operation and planning of electric power system

The electric power system is one of the largest systems ever made, comprising a huge number of components, from low-power electric appliances to very high-power large turbo-generators. Running this very large system is certainly a difficult task, and it has caused numerous problems, which can be learned from. While running the present system in an efficient manner, proper insights should be given to the future. In this case, it is important to note that the word "operation" is the normal electric power term used for running the in the current situation.

Referring to the future, the power system experts use the term "planning" to denote the actions required for the future. Past experience is always used for efficient operation and planning of the system. The word "planning" is derived from the transitive verb "to plan", meant as "to arrange a method or scheme beforehand for work", or "proceeding".

The theoretical approach to solving the development of any given technical structure in general is a scientific problem that requires the application of various principles and methodologies. However, what if all scientific methodology has been applied to solve individual requests that are given with real parameters from the existing distribution network? It is then necessary to perform a scientific comparison of possible solutions and confirm this in professional and technical terms.

## 1.2 Power System Planning

Power system planning, [1], must take due consideration of the restrictions imposed by legal requirements, technical standards, political issues, financial constraints and social, political and environmental parameters, which have a strong influence on the system structure, the design and the rating of equipment and thus on the cost of investment and cost of energy, without any justification in terms of security, reliability and economy, and must develop concepts and structures that are technically and economically sound. This includes the planning and project engineering of generation systems, transmission and distribution networks, and the optimization of system structures and equipment, [2], in order to enable flexible and economical operation in the long as well as the short term. Power system planning also has to react to changes in the technical, economic and political restrictions. The key activities are the planning and construction of power stations, the associated planning of transmission and distribution systems, considerations of long-term supply contracts for primary energy, and cost analysis.

The systematic planning of power systems is an indispensable part of power systems engineering, but it must not be limited to the planning of individual system components or the determination of the major parameters of equipment, which can result in suboptimal solutions. Power system engineering, [3], must incorporate familiar aspects regarding technical and

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economic possibilities, but also those that are sometimes difficult to quantify, such as the following:

- Load forecast for the power system under consideration for a period of several years,
- Energy forecast in the long term,
- Standardized rated parameters of equipment,
- Restrictions on systems operation,
- Feasibility with regard to technical, financial and time aspects,
- Political acceptance,
- Ecological and environmental compatibility.

Power system engineering and power system planning require a systematic approach, which has to take into account the financial and time restrictions of the investigations as well as to cope with all the technical and economic aspects for the analysis of complex problem definitions. The planning of power systems and the project engineering of installations are initiated by:

- Demand from customers for the supply of higher load, or the connection of new production plants in industry,
- Demand for higher short-circuit power to cover the requirements of power quality at the connection point (point of common coupling),
- The construction of large buildings, such as shopping centres, office buildings or department stores,
- Planning of industrial areas or extension of production processes in industry that require additional power,
- Planning of new residential areas,
- General increase in electricity demand.

Power system planning is based on a reliable load forecast, which takes into account the developments in the power systems mentioned above. The load increase of household, commercial and industrial customers is affected by the overall economic development of the country, by classification, by land development plans, by fiscal incentives and taxes (for example, for the use or promotion of “green energy”) and by political measures. Needs for power system planning also arise as a result of changed technical boundary conditions, such as the replacement of old installations and equipment, the introduction of new standards and regulations, construction and equipment, the construction of new power stations and fundamental changes in the scenario of energy production, e.g. the installation of photovoltaic generation.

The objective of power system planning is the determination and justification of system topologies, schemes for substations and the main parameters of equipment considering the criteria of economy, security and reliability.

Further aspects must be defined apart from the load forecast:

- The information database of the existing power system with respect to geographical, topological and electrical parameters,
- Information about rights-of-way, right of possession and space requirements for substations and line routes,
- Information about investment and operational costs of installations,
- Information about the costs of losses,
- Knowledge of norms, standards and regulations.

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## 1.3. Optimization Techniques

Most of operational and planning problems, [4], [5], consist of the following three major steps:

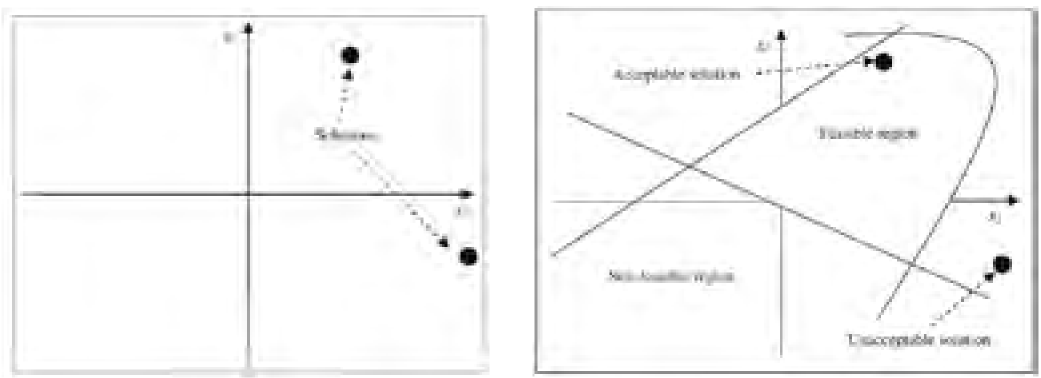
- Definition,
- Modelling,
- Solution algorithm.

In any optimization problem, the decision maker should make a decision about the following items:

- Decision (independent) and dependent variables,
- Constraint functions,
- Objective functions.

Decision variables are the independent variables; the decision maker has to determine their optimum values and, based on those, other variables (dependent) can be determined. For instance, in an optimum generation scheduling problem, the active power generations of power plants may be the decision variables. The dependent variables can be the total fuel consumption, system losses, etc., which can be calculated upon determining the decision variables. In a capacitor allocation problem, the locations and the sizing of the capacitor banks are the decision variables, whereas the dependent variables may be bus voltages, system losses, etc.

An n-decision variable problem results in an n-dimensional solution. A two-dimensional case is shown in Figure 1a).




a) b)

***Figure 1:*** *a) The solution space for a two-dimensional case*
*b) Feasible and non–feasible regions due to constraints*

In a real-life optimization problem, some limitations may apply to the solution space. These are typically technical, economic, environmental and similar limitations; named as constraints that either directly or indirectly divide the solution space into acceptable (feasible) and unacceptable (non-feasible) regions. The decision maker should find a solution point within the feasible region. For instance, in an optimum generation scheduling problem, the active power generations of the power plants should be within their respective maximum and minimum

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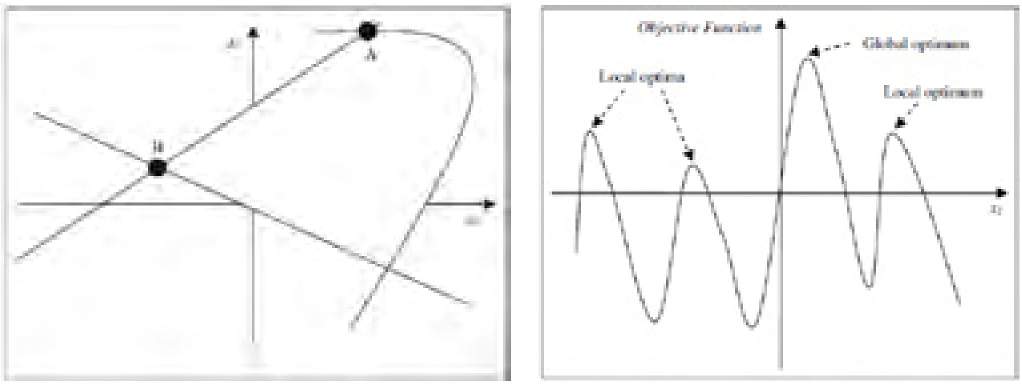
values; or the total generation of the plants should satisfy total load and a specified reserve. In a capacitor allocation problem, a technical constraint may be the maximum number of the capacitor banks, which may be a limit on the total practical investment cost, which should not be violated. The way the constraints behave in a two-dimensional case is shown in Figure 1b).

Among the numerous points within the feasible region of a problem, the decision maker should select the most desirable one. The desirable should, however, be defined. In fact, an objective function is a function in terms of the decision variables by which the decision maker shows his or her desirable solution.

In Figure 2a), if the objective function is defined as maximizing $x_1$, the solution ends up in point A, whereas if minimizing $x_2$ is the objective function, point B would be the final solution. In an optimum generation scheduling problem, the objective function may be chosen as the total fuel cost to be minimized. In a capacitor allocation problem, the objective function may be the investment cost or the system losses or both (to be minimized). The problem is considered to be single-objective, [6], if just one objective function is to be optimized. It is in contrast to multi-objective optimization problems, [7], in which several functions are to be simultaneously optimized. In a practical case, an optimization problem may have many maximum and minimum points.




a) b)

***Figure 2:*** *a) Optimum points in a two-dimensional case*
*b) Local and global optimum points*

For instance, consider the case depicted in Figure 2b) in which the objective function is considered to be a function of only $x_1$ and is to be maximized. As shown, there are some local optima in the sense that they are optimum in the vicinity of nearby points. From those local optimum points, one is the global optimum.

## 1.4. Development of the distribution network

As already noted, a typical power system comprises enormous number of elements, which are:

- Generation facilities
- Transmission facilities (Substations, Network lines and cables

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- Loads

In fact, in power system planning, the details of each element design are not of main interest. For instance, for a generation facility, only the type, the capacity and its location are determined, Figure 3.

The development of the distribution network in the world shows the tendency toward reduction in the number of high voltage levels, i.e. a reduction in the number of distribution transformers and transformer losses.

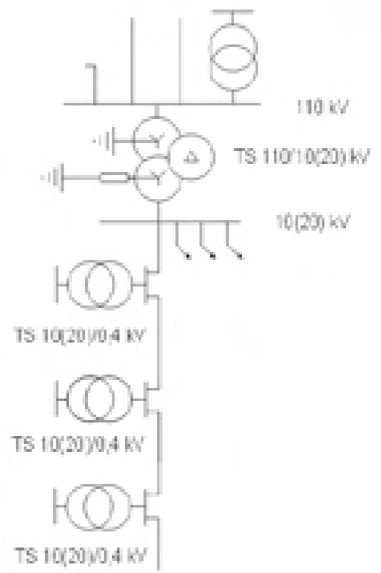


***Figure 3:*** *Transmission and distribution network 110/10(20) kV*

This is achieved with the introduction of new direct transformation 110/10(20) kV between distribution and transmission networks, thus eliminating the need for 35 kV network, i.e. there is no 35/10 kV transformation. This procedure, [8–10], is applied mostly to new distribution substations and networks, changing the 10 kV voltage level to 20 kV voltage level wherever it is possible. This is usually done by building equipment adjusted for 20 kV voltage level, where the network continues to operate at a 10 kV voltage level until necessary conditions for changing to 20 kV voltage level are satisfied, or on places where there are plans to change the complete power equipment in the distribution network powered by TS 110/10(20) kV to 20 kV voltage levels.

The best particular example in the distribution network of the growing city is a newly built TS 110/10(20) kV substation, whose transformation in normal operation is 110/10 kV and 110/20 kV. At present, there are only two 20 kV high voltage lines with average consumption, and changing the voltage level of existing 10(20)/0.4 kV substations from 10 kV to 20 kV voltage is planned. This long-term goal of the entire distribution supply company, i.e. the permanent discontinuance of 10 kV and 35 kV voltage levels, is presented in Figure 3.

In practice, this will be a very complicated procedure, because there are a many 10/0.4 kV substations that do not have built-in equipment to operate at the 20 kV voltage level. Another

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problem is that the present electricity distribution network consists mostly of 10 kV distribution cables, and their replacement with 20 kV cables requires great financial resources.

## 1.5. Growth of the city

Before analysing the development of 20 kV distribution network, the main reason for the growth of the city has to be presented. In many cities in the previous 10 years, many large shopping centres have built. Due to their installed power, which is mostly a few MVA, new substations were built, 10(20)/0.4 kV and 110/10(20) kV. As the connection of new customers to the electricity supply network requires the building and development of a new 10(20) kV power network in the city, the process of building primarily a 20 kV power network and only to a smaller extent a 10 kV power network was started. In our example, for that purpose the 110/10(20) kV-4 substation was constructed, with 2x20 MVA power transformers. The current situation includes building a new 20 kV power distribution network (currently under way) to connect and supply the consumers, [11], listed in the table below, Table 1.

***Table 1.*** *List of new consumers with their total power (KTS – cable substation)*

| Name of consumer KTS 10(20)/0,4 kV | Power (MVA) |
|---|---|
| KTS - C1 | 1 |
| KTS - C2 | 6 |
| KTS - C3 | 5 |
| KTS - C4 | 1 |
| KTS - C5 | 5 |
| KTS - C6 | 6 |
| **TOTAL** | **24** |

Table 1 provides a list of new consumers demanding considerable power for their needs, as these mostly include different types of businesses and trade facilities that require minimum power of 1 MVA, i.e. their total additional power demand amounts to 24 MVA. The supply of these consumers requires building of a new 20 kV cable power line that will receive energy from TS 110/10(20) kV-4, [12], and a new power transformer of 40 MVA built into the TS 110/10 kV-3 substation.

To provide adequate background information, an overview of energy supply conditions for the TS 110/10 kV-3 substation as well as its peak 10 kV current values for the last five years are presented in Figure 4.

Based on the previous diagram, a conclusion can be made that the load of the TS 110/10 kV-3 is constantly growing. Future consumers should also be considered here, such as the new shopping centre, whose peak power has not yet been determined. The load of existing shopping centres can be shown as a good example of 10(20) kV distribution network load, [11], Figure 5.

It can be observed from the presented diagram that, in spite of differences in peak load values, these two shopping centres have very similar load flows, which are primarily influenced by the

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working time of these shopping centres. Due to their demand for more power, future shopping centres will also have higher peak load values, but it is assumed that their load time diagram will correspond to the presented diagram of the existing shopping centres. The only exception for that load time is the time after 9 p.m., when the existing shopping centres are closed (their consumption decreases to a much smaller, but constant value). However, some shopping centres continue to work at night (for example, cinemas, night clubs, etc.).

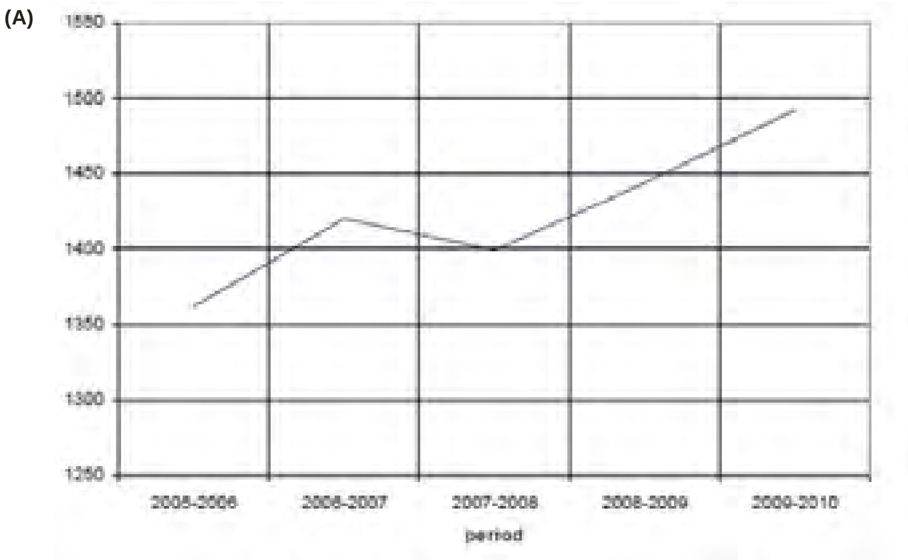


***Figure 4:*** *Load diagram of TS 110/10 kV-3 on 10 kV voltage level in the period 2005-2010*

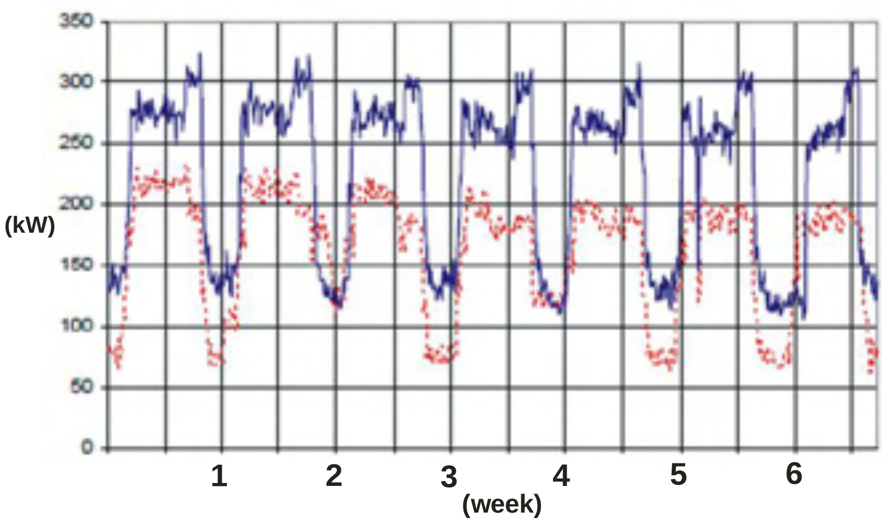


***Figure 5:*** *Load diagram (kW) of two shopping centres for the period of one week*

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Based on the previous load diagram, plans for building a new 40 110/20 kV MVA power transformer are justified.

Only the KTS 10(20)/0.4 kV-3 is currently supplied by 20 kV voltage power. Such a supply of the substation KTS 10(20)/0.4 kV-6 is not possible at the moment due to the impossibility of finding a solution to property rights issues related to the land on which construction of a new high voltage line is envisaged; therefore, instead of using 20 kV voltage level, it is still supplied by 10 kV voltage, as shown in Figure 6.


***Figure 6:*** *Plan of 20 kV electricity distribution network of the city*
*(red line is a new 20 kV high voltage cable, blue line is a city of Osijek detour road)*

According to Figure 6, it can be observed that in the event that the TS 110/10(20) kV-4 substation is not available, it is necessary to ensure secondary supply for customers on 20 kV voltage power from TS 110/20 kV-3.

## 2 POSSIBLE SOLUTIONS OF PLANNING THE 20 kV DISTRIBUTION NETWORK

In previous sections, the scientific aspects of planning, optimization and development of power distribution network in general were considered, with focus on specific energy-related properties of the selected power network that has been taken as an example of development possibilities. Following the basic overview of energy situation in a particular part of the town, the above network is here considered in terms of the basic possible conditions for this situation, i.e. technical, financial and urban conditions.

From the data of the presented power plant map with envisaged positions of future new consumers supplied by 20 kV voltage network, calculations have been made by means of the

Easy Power 8.0 computer program; they show which 20 kV distribution lines are optimal in terms of the maximum current load, losses and voltage drop.

Two solutions are possible:

A) The first solution includes a new 20 kV distribution line from the TS 110/20 kV-4 substation, and it supplies the next nine substations, Figure 7.

In the situation of maximum 20 kV voltage load, it can be observed that such a maximum load should never be allowed for the substation TS 110/20 kV-4, i.e. that it is not possible to satisfy the need for 22 MVA with the existing power transformer of 20 MVA without considering the special time factor of simultaneous customer load or limiting the maximum supply of some consumers. This could be a great problem because the supply of the maximum required amount of electrical power has to be provided to each consumer, which is defined according to the peak load of its consumers. Every consumer will resist any forced reduction of its maximum power on the distribution network, which is otherwise guaranteed to every consumer of the national energy supply company; therefore, this solution should be avoided whenever possible. It can also be observed that according to computer calculations this cable load is so high that even the XHE 49-A 3x1x300 m2, 12/24 kV cable cannot stand this current load over 600 A; there are also high power losses on the first distribution line from TS 110/20 kV-4 substations, almost 2.7% of nominal transformer power of 20 MVA, while the voltage drop is within the allowed values, 4.8%, which is in line with network rules of electricity supply systems, [13], ± 10% tolerance.

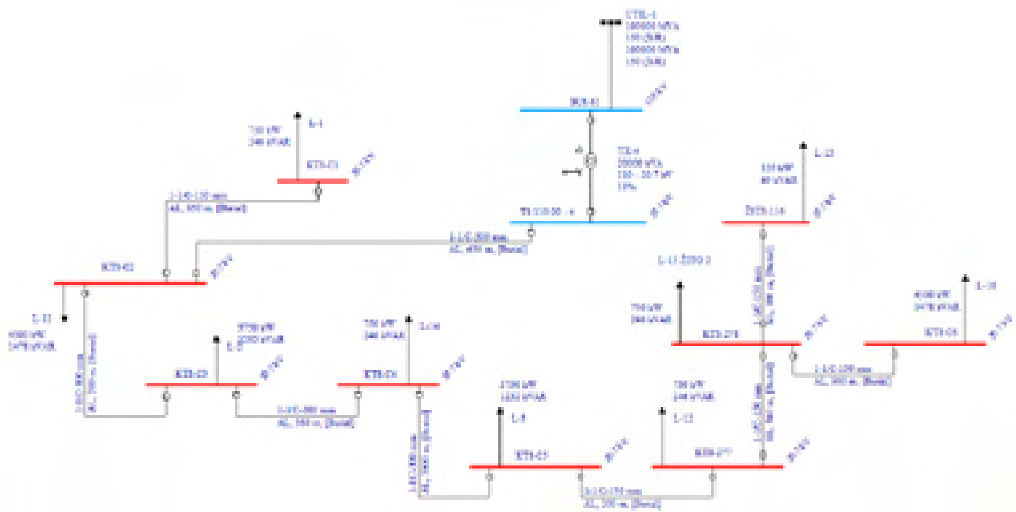

***Figure 7:*** *First solution – 20 kV network scheme*

Considering these calculations and their results, outgoing power from the TS 110/20 kV-4 substation has to be distributed among several 20 kV power lines. Due to the overload of the 20 MVA transformer and the inability of limiting electricity supply for some customers connected to the distribution network, as well as future connection of new consumers, it is necessary to build in a new power transformer of 40 MVA in the TS 110/35/10 kV-3 substation.

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B) The other solution for 20 kV distribution network is presented in Figure 8. The key element here is the reduction of the total load of 20 kV distribution network by building a new 20 kV power line and building in a new transformer of 40 MVA.

The second energy solution provides optimal energy distribution. It is significant that none of the 20 kV power lines is overloaded and the maximum load, according to calculations, is 65.9%. As the TS 110/10(20) kV-4 substation is exonerated (unballasted) by using a new transformer in TS 110/10(20) kV-3; maximum peak load of transformer in TS 110/10(20) kV-4 is 82.5%. Maximum losses in this second solution are on the 110/20 kV transformation in the TS-4 substation; they amount to 3.7%.

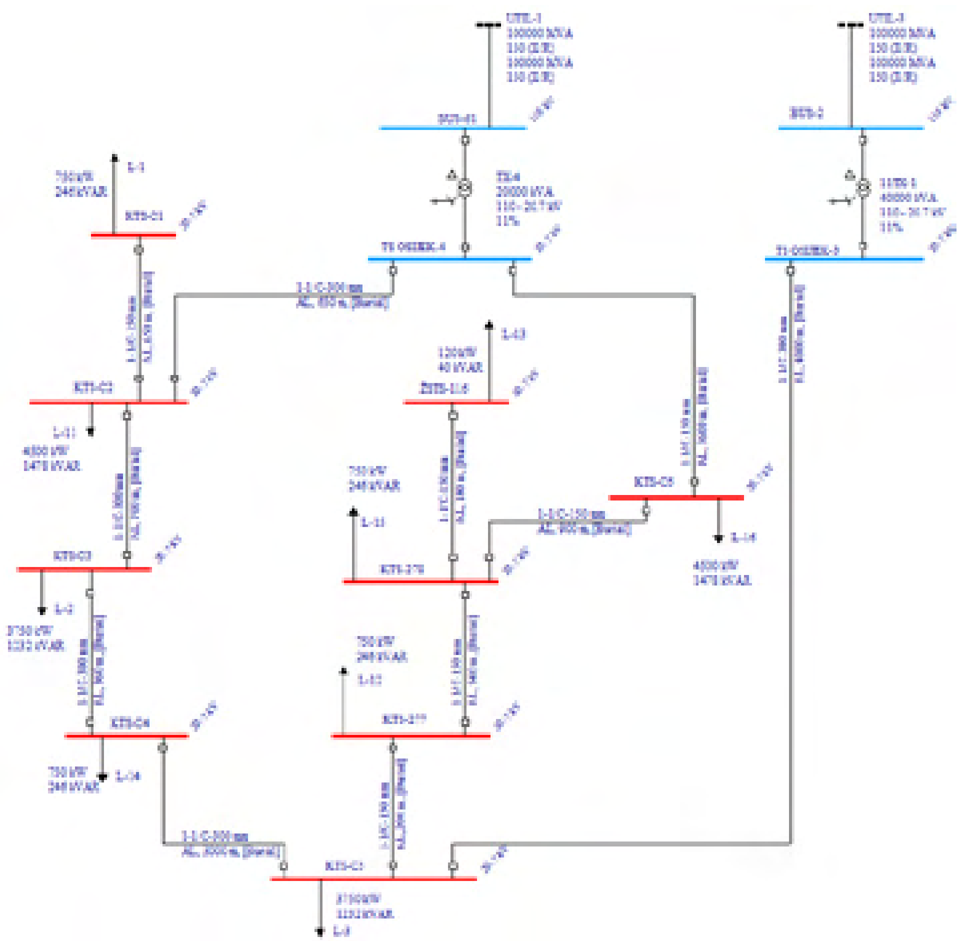

***Figure 8:*** *Second solution – 20 kV network scheme*

In the process of analysing variants A and B, a professional technical analysis was carried out, focused on the possibility of supplying consumer's load, without taking financial and urban requirements for the construction of new energy facilities into account. Due to the exclusivity of energy-related and technical requirements, financial and urban requirements have become secondary requirements in considering the overall situation. In financial terms, it is obvious that the B variant is considerably more expensive as it requires the construction of a new 20 kV overhead transmission line and TS 110/10(20) kV-3 as well as building in of a new 40 MVA transformer with ancillary equipment, which is nearly 250% more expensive than the A variant, but this is the only way to satisfy all consumers. Urban requirements are given by the configuration of energy-related structures of the distribution network in the city, so any changes in this regard are impossible, as they would result in extremely high economic costs. It can be concluded that consumers' need for power and electricity in this example can be satisfied only in terms of possibilities determined by ultimate solutions to technical requirements for the construction of a 20 kV distribution network, whereas financial and urban requirements are fully rejected.

Finally, by comparing solutions A and B, a conclusion can be made that only solution B successfully solved application of 20 kV distribution voltage and fully met the consumers' needs.

# 3 CONCLUSION

Based on the above, a conclusion can be made that the development of 20 kV distribution network based on the given main conditions of planning and optimization steps toward described transition from 10 kV and 35 kV voltage to 20 kV distribution voltage is entirely possible, not only in theoretical planning, but also in real construction, and that it is necessary in the process of construction and development of any power distribution network to carry out individual analysis of all alternatives according to given requirements of the investor, and particularly in accordance with technical and economic possibilities. Of course, this development is feasible not only at regional level, but also at the global level by considering all conditions that can vary from region to region.

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# ESTIMATION OF WIND POWER DENSITY AT AN INTERNATIONAL AIRPORT

# DOLOČITEV GOSTOTE MOČI VETRA NA LETALIŠČU

Dino Masle, Predrag Marić[ℜ], Dario Galić

**Keywords:** wind speed distribution, wind direction, wind power density, goodness of fit.

## Abstract

This paper deals with the development of a statistical model for the assessment of wind power density, using the wind speed data acquired at an international airport. The data were adjusted for the height at which wind power could be harvested. Wind speed data were fitted with several statistical distributions in order to determine the one that best fits the data. It is shown that the Weibull distribution does not fit this particular set of data as well as some other distributions. Fits were tested using Anderson-Darling, Kolmogorov-Smirnov and Cramér-von Mises tests as well as with P-P plot and Q-Q plot. Wind power density, wind rose and comparison between wind speeds at different seasons of the year were calculated to provide additional insight in wind behaviour at the location.

## Povzetek

V prispevku je podan razvoj statističnega modela za ocenitev gostote moči vetra na mednarodnem letališču, na osnovi merilnih vrednosti. Merilni podatki, ki so zajeti tudi po višini, so ocenjeni po številnih znanih statističnih porazdelitvah, s ciljem čim boljšega ujemanja z izmerjenimi vrednostmi. Iz ugotovitev v članku izhaja, da Weibull-ova porazdelitev ni najboljša izbira za konkretne podatke, podobno je tudi z nekaterimi drugimi standardnimi porazdelitvami. Zato so uporabljeni Anderson-Darling, Kolmogorov-Smirnov and Cramér-von Mises testi, katerih rezultati so prikazani na P-P in Q-Q izrisih. Spektralna gostota moči vetra in vetrna roža sta

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primerjalno ocenjena v različnih letnih časih, na različnih merilnih mestih, pri različnih močeh vetra.

# 1 INTRODUCTION

Installed wind power capacity is growing rapidly; in 2009, the growth rate was 31.7%, [1], in 2010 it was 23.6%, [2], and in first half of 2011 the recorded growth rate was 22.9%, [3]. Global energy demand is steadily increasing, [4]; the idea is to fuel that growth with renewable energy sources such as wind power as much as possible. Such demands confirm the importance of an accurate mathematical model for determining the probabilistic properties of wind speed data. Wind power can be calculated from kinetic energy of a moving mass:

$$W = \frac{1}{2} m v^2 \quad (1.1)$$

Substituting mass *m* with:

$$m = \rho V \quad (1.2)$$

Volume *V* with:

$$V = Al \quad (1.3)$$

and length *l* with:

$$l = vt \quad (1.4)$$

yields the final expression for wind energy:

$$W = \frac{1}{2} \rho A v^3 t \quad (1.5)$$

Dividing expression (1.5) with time *t* and blade sweep area *A* will yield the expression for wind power density:

$$P = \frac{1}{2} \rho v^3 \quad (1.6)$$

Where $\rho$ is air density, and *v* is wind speed. Calculating wind power density with average wind speed will give faulty results, because the higher wind speeds that are responsible for the majority of energy production are balanced with lower wind speeds that do not have high energy content. Therefore, it is necessary to calculate wind speed frequency distribution and to calculate wind energy density using that distribution. A two-parameter Weibull distribution is most often used for modelling the wind speed data, but in some cases, depending on the location at which the wind speed measurements are taken, the Weibull distribution probability density function (PDF) is not sufficiently similar to the histogram of the recorded data. Accepting the Weibull distribution without testing alternative distributions may result in a faulty assessment of wind power potentials. That is the reason some other statistical distributions should be tested. Good fit between the recorded wind speed data and the theoretical statistical distribution will give more accurate predictions on expected wind speeds, and consequently, a more accurate prediction of electrical energy produced from wind turbines. Average wind turbine power can be calculated as:

$$P_{avg} = \int_0^{25} P_t(v)\, p(v) dv \quad (1.7)$$

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where $P_t(v)$ is a curve that describes the amount of power that turbine can produce at a certain wind speed, and $p(v)$ is a PDF showing the probability of that wind speed appearing, [5]. The upper limit of the integral is the most common cut-out speed. Since $P_t(v)$ is a known function (property of a turbine), most of the uncertainty comes from the PDF term. Knowing $P_{avg}$ with small uncertainty is practical because it can reduce the risks investors are taking when choosing the location for wind farm and provide good data for the network operator to determine the necessary reserve of the wind farm, [6].

## 2 METHODOLOGY

The data were acquired at an international airport at the standard height of ten meters. Measurements were conducted using a meteorological station permanently installed in the vicinity of the airport. Wind speed measurements were taken in an eight-year period, from March 2003 to May 2011. These measurements produced 2,951 results that represent daily averaged values of recorded wind speeds in meters per second. As a result of such a long averaging interval, very low and high wind speeds were lost. A more serious analysis would have to use measurements with shorter averaging interval in order to produce a more accurate distribution of wind speeds. Wind direction, temperature and air pressure were also measured, and were used to calculate air density and make a simple wind rose. To estimate the wind speeds at a height of 30 m, measurements were adapted using wind profile power law:

$$v_{30} = v_{10}\left(\frac{h_{30}}{h_{10}}\right)^{\alpha} \tag{2.1}$$

where $v_{30}$ and $v_{10}$ are wind speeds at 30 m and 10 m, respectively, and $h_{30}$ and $h_{10}$ are heights at 30 m and 10 m above ground, respectively. Coefficient $\alpha$ is the Hellman coefficient with a value of 0.34 in this case. Adapting was done because the wind speed data are used for assessment of wind power potential, which only makes sense at a height at which wind turbine would be installed. The general idea is to find the statistical distribution that will yield the smallest possible error when compared to the experimental data. Weibull and Rayleigh distributions were chosen for the testing because they are traditionally used in fitting the wind speed data to the statistical distributions, [7],[8], but not because they are intrinsically better than the alternatives, [5]. Lognormal, Pearson type VI, Inverse Gaussian and Generalized Gamma distributions were included because of the good results they delivered for this set of data. Parameters of all distributions were estimated using maximum likelihood method. Anderson-Darling, Kolmogorov-Smirnov and Cramér-von Mises goodness-of-fit (GOF) tests were used to validate the fits. The P-values that tests gave do not show how the distribution follows the data, and are hard to intuitively interpret, so additional graphic tests were included. Those tests are P-P plot, Q-Q plot, an overlay of the histogram of the recorded data with PDF and an overlay of the histogram of the recorded data with CDF. Those four graphical tests combined with three analytical tests provide enough information to determine which of the tested statistical distributions best fits the measured data. Wind power density can be calculated as:

$$WPD = \int_0^{\infty} 8760 \cdot \frac{\rho}{2} \cdot v^3 \cdot p(v)dv \left[\frac{\mathrm{Wh}}{\mathrm{m}^2}\right] \tag{2.2}$$

where *p(v)* is probability of wind speed *v* appearing.

----------

# 3 RESULTS

Some important statistical values on collected wind speed data are given in Table 1.

***Table 1:*** Statistical properties of wind speed data

| **Parameter** | **Value [m/s]** |
|---|---|
| Mean | 3.09 |
| Standard deviation | 1.23 |
| Highest value | 12.4 |
| Lowest value | 0.4 |
| Kurtosis | 6.58 |
| Skewness | 1.49 |

## 3.1 Statistical distribution fitting

Overview of all the parameters estimated using maximum likelihood method is given in Table 2.

***Table 2:*** Estimated parameters

| Distribution | Estimated parameter(s) |
|---|---|
| *Weibull* | $\alpha = 2.72$<br>$\beta = 3.48$ |
| *Rayleigh* | $\theta = 2.36$ |
| *Lognormal* | $\mu = 1.06$<br>$\sigma = 0.38$ |
| *Pearson Type VI* | $a_1 = 41.59$<br>$a_0 = -94.40$<br>$b_2 = 1.00$<br>$b_1 = 28.29$<br>$b_0 = -38.79$ |
| *Inverse Gaussian* | $\mu = 59.15$<br>$\lambda = 44.02$<br>$\theta = -8.07$ |
| *Generalized Gamma* | $\alpha = 8.67$<br>$\beta = 0.04$<br>$\gamma = 0.56$<br>$\mu = 1.11$ |

----------

## 3.2 Analytical GOF

Goodness-of-fit tests results at a 5% significance level are given in Table 3.

***Table 3:*** Goodness of fit test results

| ***Distribution /GOF test*** | ***Anderson-Darling*** | ***Cramér-von Mises*** | ***Kolmogorov-Smirnov*** |
|---|---|---|---|
| *Rayleigh* | Statistic:136.3<br>P-value: 0<br>Reject | Statistic:21.35<br>P-value: 0<br>Reject | Statistic:0.18<br>P-value: 0<br>Reject |
| *Weibull* | Statistic:57.7<br>P-value: 0<br>Reject | Statistic:8.84<br>P-value: 0<br>Reject | Statistic:0.09<br>P-value: 0<br>Reject |
| *Lognormal* | Statistic:7.12<br>P-value: 0<br>Reject | Statistic:0.84<br>P-value: 0<br>Reject | Statistic:0.04<br>P-value: 0<br>Reject |
| *Pearson Type VI* | Statistic:1<br>P-value: 0<br>Reject | Statistic:0.24<br>P-value:0.20<br>Accept | Statistic:0.02<br>P-value:0.01<br>Reject |
| *Inverse Gaussian* | Statistic:2.3<br>P-value: 0.06<br>Accept | Statistic:0.29<br>P-value:0.13<br>Accept | Statistic:0.02<br>P-value:0.01<br>Reject |
| *Generalized Gamma* | Statistic:1.25<br>P-value:0.24<br>Accept | Statistic:0.19<br>P-value:0.28<br>Accept | Statistic: 0.02<br>P-value: 0.05<br>Accept |

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### 3.3 Graphical GOF

Figures 1 to 6 give an overview of all the graphical GOF tests conducted on this set of data.

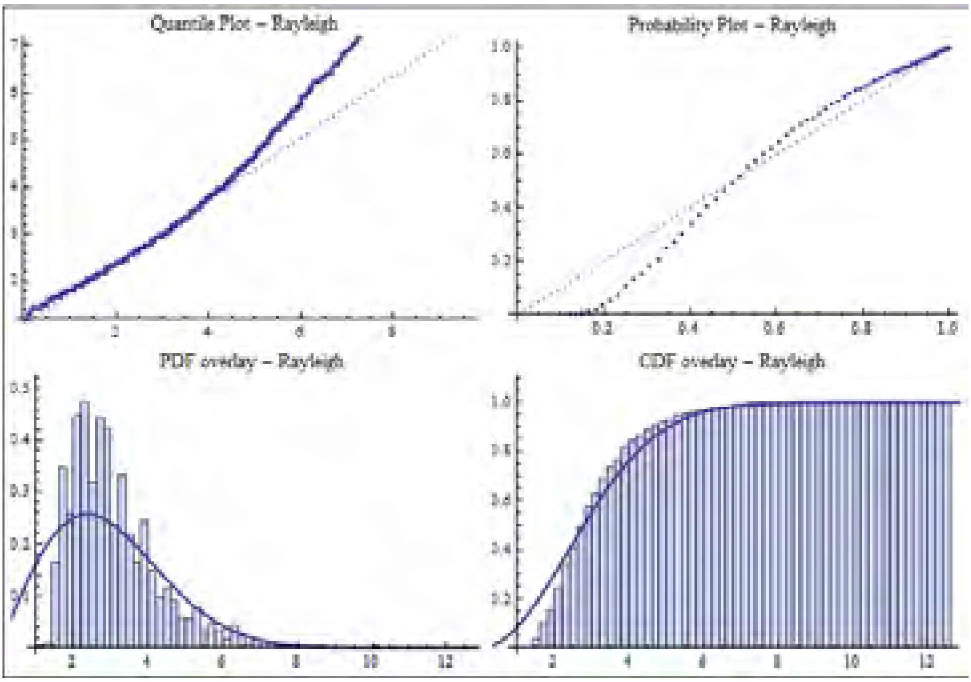


***Figure 1:*** Graphical GOF tests results for Rayleigh distribution.

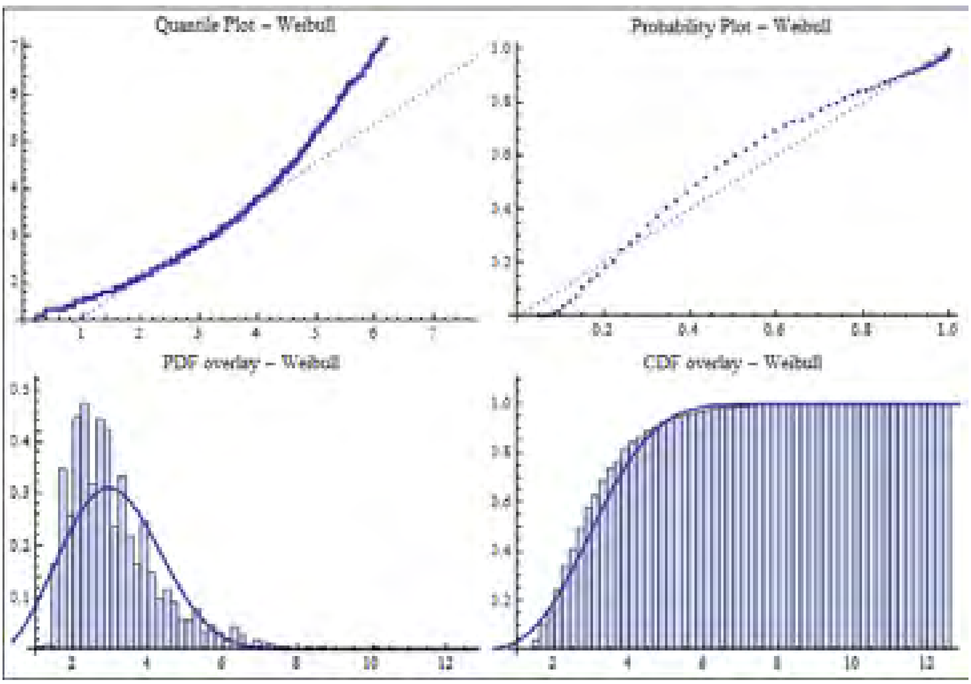


***Figure 2:*** Graphical GOF tests results for Weibull distribution.

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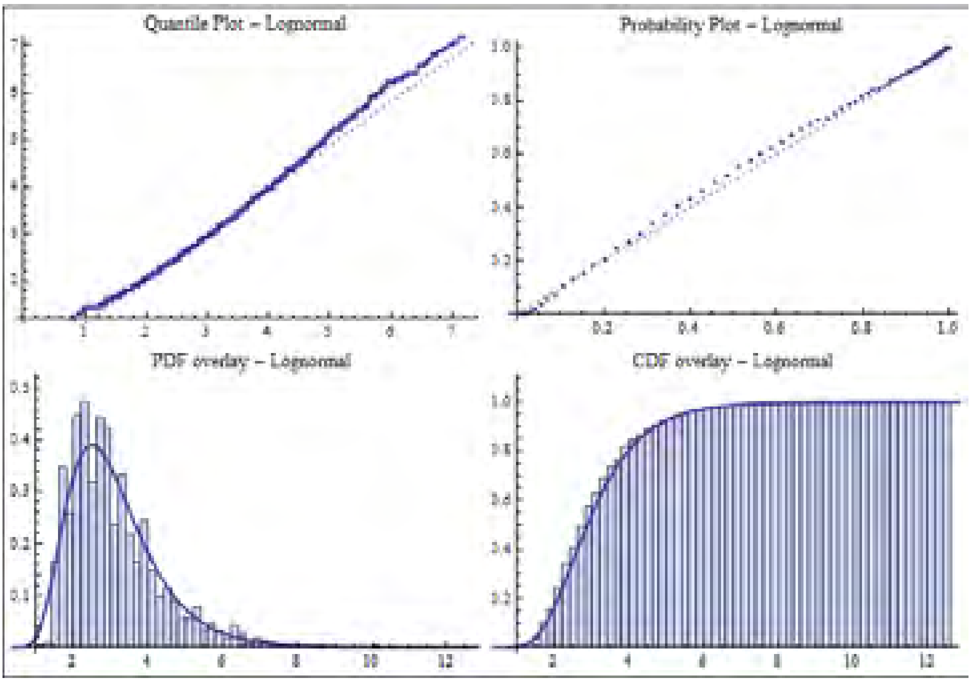


***Figure 3:*** Graphical GOF tests results for lognormal distribution

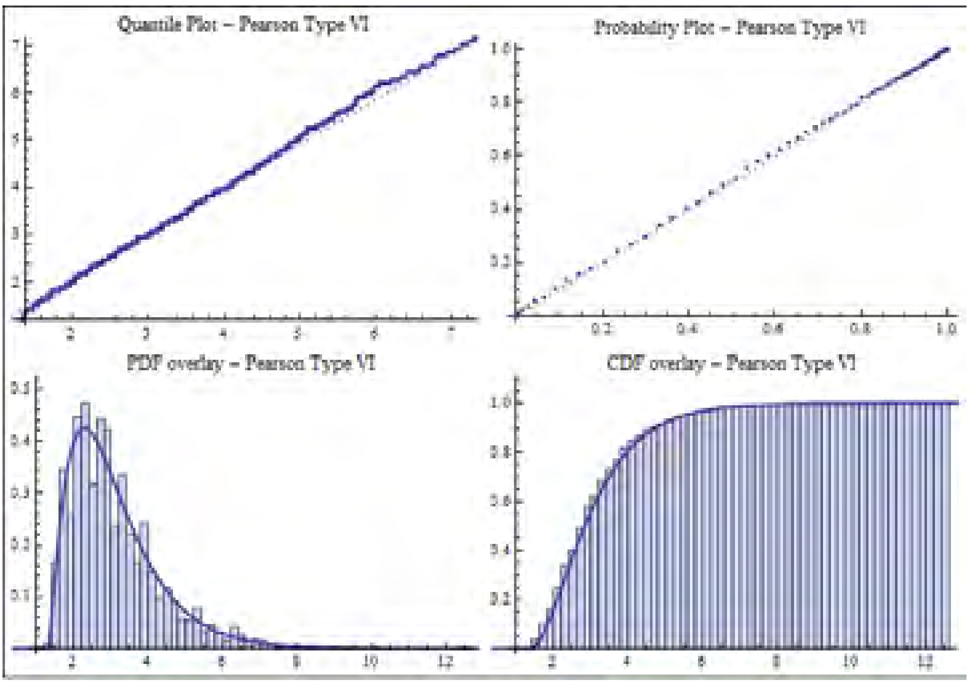


***Figure 4:*** Graphical GOF tests results for Pearson Type VI distribution

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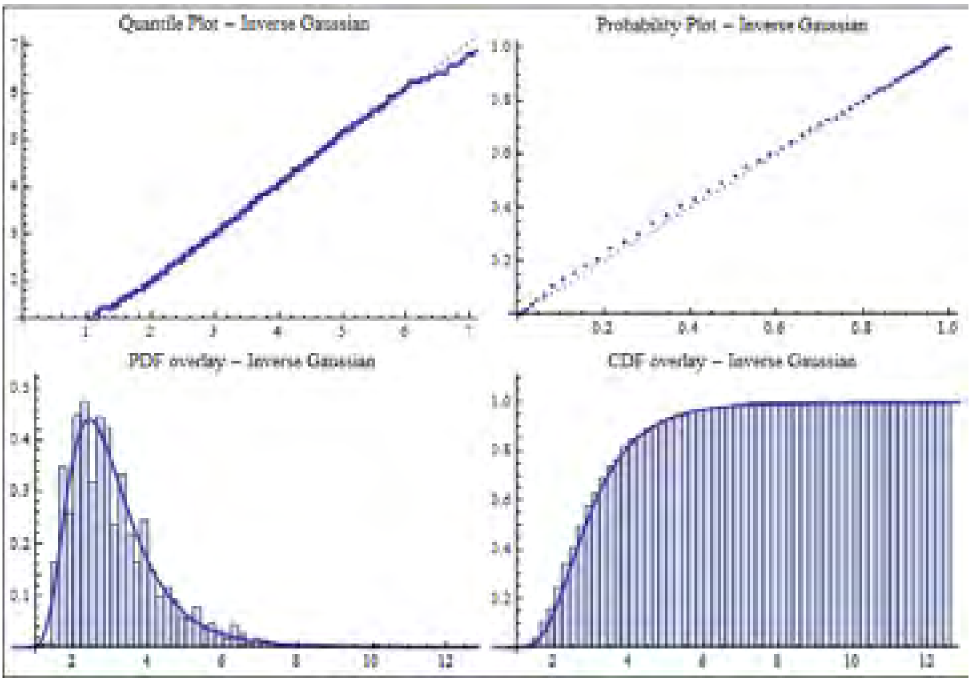


***Figure 5:*** Graphical GOF tests results for Inverse Gaussian distribution

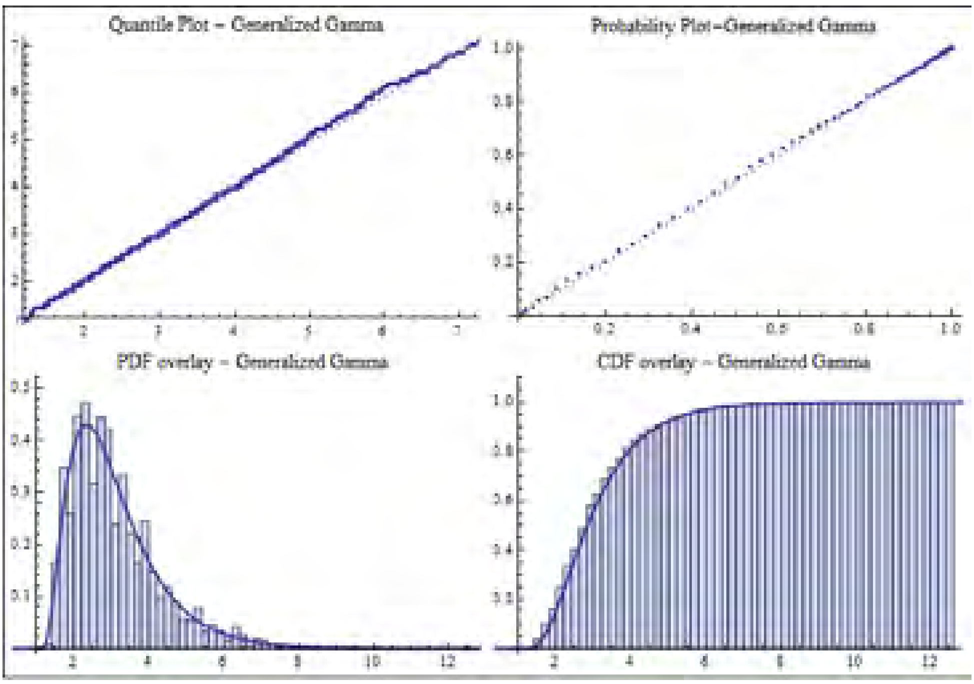


***Figure 6:*** Graphical GOF tests results for Generalized Gamma distribution

----------

It was determined that Generalized Gamma distribution fits empirical data the best; therefore, it will be used in further analysis:

$$p(v) = 195.4\, e^{-6.1(-1.1+v)^{0.55}}(-1.1+v)^{3.82} \tag{3.1}$$

## 3.4 Air density

The collected meteorological data allowed calculation of average air density at the airport:

$$\rho = \frac{0.3438\,\bar{p}}{273.15+\bar{T}} = 1.24\,\frac{kg}{m^3} \tag{3.2}$$

where $\bar{p}$ is average pressure, and $\bar{T}$ is the average temperature. The calculated value differs from air density at standard UIPAC pressure and temperature.

## 3.5 Energy production

The duration of a certain wind speed on a yearly basis can be calculated:

$$t = 8760 \cdot p(v) \tag{3.3}$$

where *t* is duration of the wind speed *v*, 8760 is number of hours in one year, and *p(v)* is previously determined probability density function. Figure 7 shows a plot of expression (3.3).

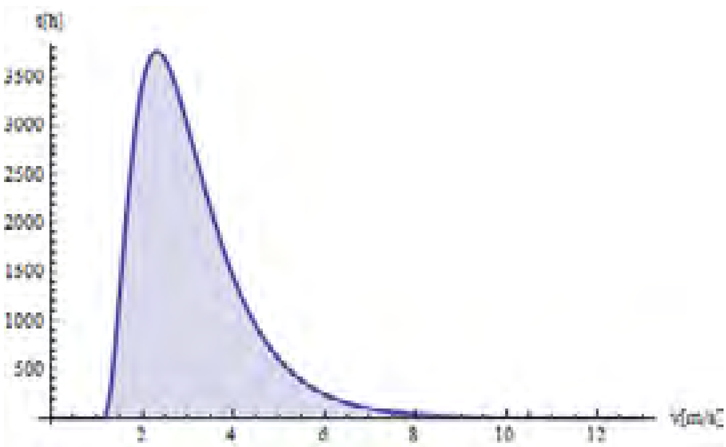


***Figure 7:*** PDF of expected wind speed durations

The previous expression can also be shown in the form of a more common duration curve:

$$t = 8760 \cdot (1 - P(v)) \tag{3.4}$$

where *P(v)* is the cumulative density function of Generalized Gamma distribution. Figure 8 shows the plot of expression (3.4).

----------

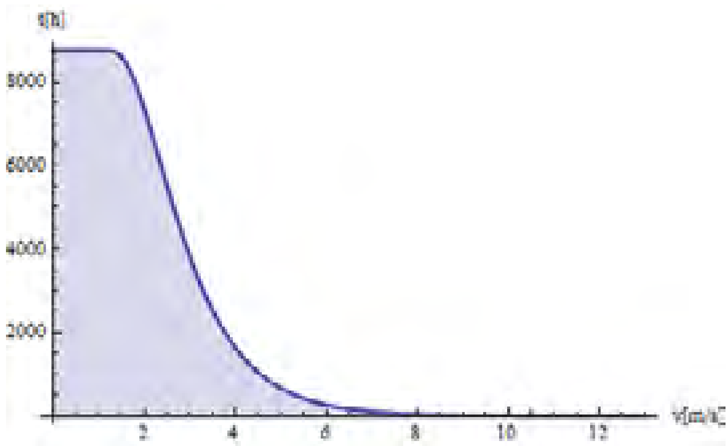


***Figure 8:*** Wind speeds duration curve

The cut-in speed is the minimal required wind speed for the wind turbine operating. Since this paper does not deal with the selection of the turbine based on the probabilistic properties of the wind, or with further technical limitations of wind energy exploitation, the cut-in speed will be set to a common 3.2 m/s in order to demonstrate how energy production depends on wind speed. Expression (3.5) shows the duration that wind speeds will be lower or equal to the cut-in speed:

$$\int_0^{3.2} p(v)dv = 0.62 \tag{3.5}$$

Wind energy contained within that 62 % is:

$$WPD_{62} = \int_0^{3.2} \frac{\rho}{2} \cdot v^3 \cdot 8.760 \cdot p(v)dv = 50.16\ \frac{\mathrm{kWh}}{\mathrm{m}^2} \tag{3.6}$$

Energy from the 38% where the wind speeds will be greater than cut-in speed is calculated as:

$$WPD_{38} = \int_{3.2}^{\infty} \frac{\rho}{2} \cdot v^3 \cdot 8.760 \cdot p(v)dv = 204.47\ \frac{\mathrm{kWh}}{\mathrm{m}^2} \tag{3.7}$$

Although the wind turbine will idle for 62 % of the year, energy wasted in that period will only account for 19.6% of the total energy that the wind contains, because of the third exponent of wind speed in relationship between wind speed and energy produced per year (1.5). A visual representation is shown in Figure 9.

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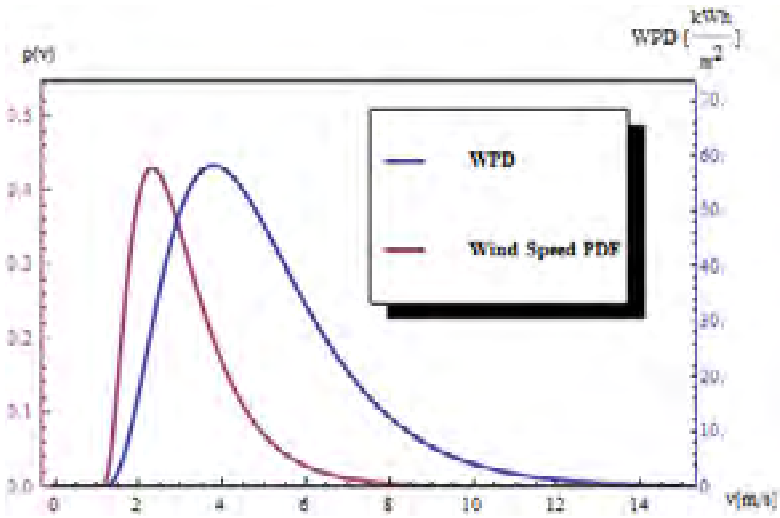


***Figure 9:*** Comparison of wind speed distribution and wind power density at a certain wind speed

## 3.6 Additional insight in wind behaviour at airport

Since the data were collected in period of eight years, it was possible to show how the wind probabilistic properties change depending on the seasons. Figure 10 shows the differences in wind speed distributions for different seasons.

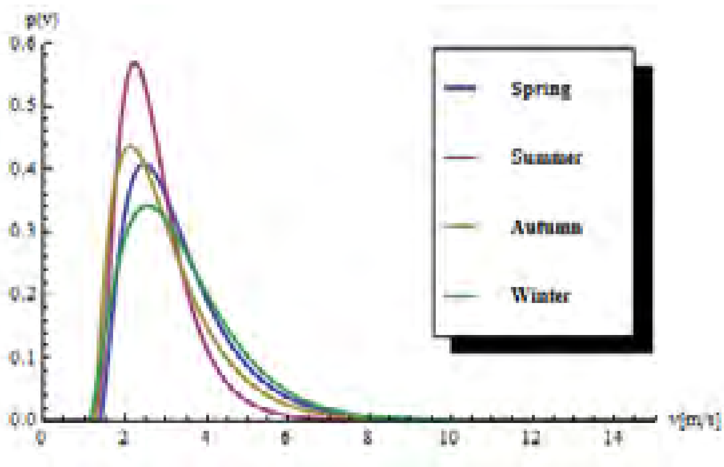


***Figure 10:*** Wind speed distributions throughout seasons of the year

It can be seen that the winter is the ideal season for wind energy production due to the higher amount of high wind speeds. Summer, however, has lot of low-to-medium wind speeds that produce the peak in probability density function. Once wind speed distributions are known for different seasons, it is not difficult to calculate wind power densities dependent on wind speed (Figure 11, Expression 2.2). Table 4 shows wind power densities for all seasons (cut-in speed and other limitations not taken into account).

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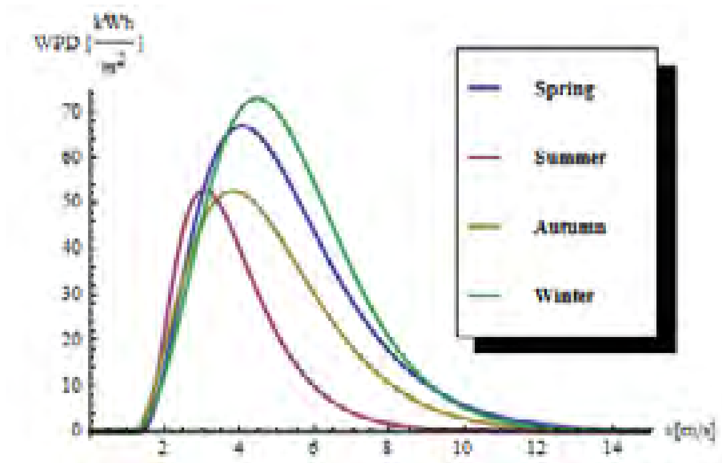


***Figure 11:*** Wind power densities throughout seasons

***Table 4:*** Wind power density per season

| **Season** | **Value [kWh/m²]]** |
|---|---|
| *Spring* | 304.2 |
| *Summer* | 152.6 |
| *Autumn* | 229.4 |
| *Winter* | 329.6 |

Wind direction data were also available and were used to assemble a crude wind rose - circular histogram.

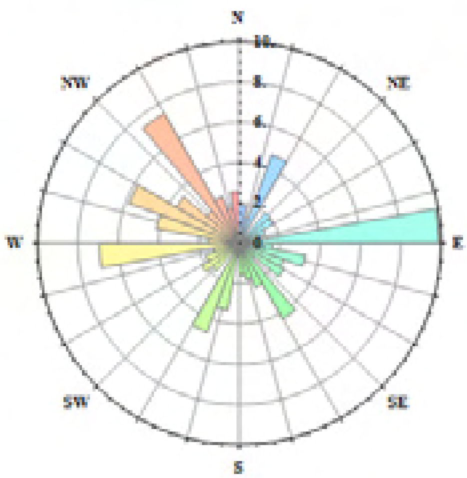


***Figure 12:*** Wind rose –circular diagram

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# 4 CONCLUSION

It has been shown that Generalized Gamma and Inverse Gaussian distributions fit the data better than other simpler distributions included in this paper. P-values calculated from Kolmogorov-Smirnov, Anderson-Darling and Cramér-von Mises are within a 5% confidence level and suggest that Generalized Gamma distribution should be chosen to approximate empirical data. It is interesting to see that the most commonly used distributions for describing wind speed distributions, namely Rayleigh and Weibull distributions do not fit this particular set of data very well. It is possible that the data with shorter averaging interval could be fitted with Rayleigh or Weibull distributions. Distributions with more parameters tend to describe empirical data better. In this case, it can be concluded that the area around this international airport should not be considered as the first-choice for wind energy exploitation because of relatively low wind speeds for the most time of the year.

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