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EDITORIAL

This regular first issue in 2021 marks the 70th year of publishing the Journal of Energy. We are especially happy due to the fact that our Journal was included into INSPEC (Information Services for the Physics and Engineering Communities) citation database of journals. INSPEC is a bibliographical database published by the Institution of Engineering and Technology from London, and it indexes and contains works from the fields of physics, electrical engineering, computer science, information technology, technical sciences. That is a great motivation for the future work of the editorial board, to achieve better quality of works covering different topics of energy system.

The first paper is entitled as "On the Future of Fission and Solar Energy". It deals with climate change stating that is better to accept a few false alarms rather than be unprepared for a climate catastrophe. As is stated there is very little time left, only 4 to 8 years, for mitigation measures. Nuclear fission now presents a formidable fleet of some 450 reactors benefitting from over 50 years of operational experience. Throughout decades of development, they reached outstanding safety standards, exceeding those of most renewable sources. However, the threat of climate change is calling this perspective into question, as nuclear technology requires long-term stability of institutions. The future of nuclear fission will be determined after the expiration of the next decade with the development of hydro, solar and wind energy as replacements.

The next paper is "How COVID-19 lockdown has impacted demand curves of Croatia and the surrounding countries ". In condition of global pandemic caused by COVID 19, prediction of total consumption is even more challenging task. New restrictive rules, that completely changed behavior of consumers, their daily routine and habits, have been adopted in most of the European countries. Hence, these lockdown restrictive measures affected the volume of electricity consumption and the shape of demand curves as well. This paper analyzes some of the cases with very variable electricity load, due to volatile households' behavior, on cases of Croatia and countries in the region.

The third paper is "Dynamic Stability Enhancement Through the Application of Stabilizers of Electromechanical Oscillations ". Power system dynamic stability is one of key issues system engineers face. Oscillations that regularly occur in the system, limit the transmission capability of the network. The need to study the stability of power systems has been increasingly growing along with the development of power systems and their grouping into large interconnections. The focus of this paper is determining the dynamic stability of a synchronous generator, and thus the power system, by applying the general theory of stability of dynamic systems.

The fourth paper is "Maintenance of Filter at The Gas Turbine Compressor Intake and Electric Transformer Connector Based on Operational Reliability". The article analyzes the operational reliability of filter on the gas turbine compressor intake and the operational reliability of electric transformer connector. Empirical data (statistical sample) were collected to determine the failure density function $f(t)$, the hazard function $\lambda(t)$, and the expected value of mean time to failure MTTF. The numerical model was created in the Minitab 19 software tool. The Anderson-Darling test was used to accept or reject the hypothesis.

The fifth paper is "Influence of Composition of Power Plant Fleets and Ownership of Transmission and Distribution Networks to Incumbent Company's Business Success in Some Former Socialist EU Countries". By joining the EU, companies from eastern countries, which until then had largely operated in regulated circumstances, had to adapt to the open market. Liberalization and deregulation were imposed on them as new mantras, in contrast to ensuring the supply at all costs and addressing social issues. How these companies flourished in new circumstances is a legitimate topic for managerial research. This article researches the impact of the "hard assets" composition that those companies operated, on their expected business success after a multi-year adjustment period. Positivistic research philosophy, "case study", and the deduction approach are used. This paper is an extraction from an author's MBA dissertation.

Goran Slipac
Editor-in-Chief

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On the Future of Fission and Solar Energy

SUMMARY

Our attitudes towards the risks of climate change must be reconsidered. We must recognise that the consequences will be huge and inevitable if we do not act now. Better to accept a few false alarms rather than be unprepared for a climate catastrophe. An outstanding example is the calculation by groups from Germany and the UK in 2009 (1) of the allowable emissions of CO_2 before a 2°C increase in global temperature is exceeded. This leaves very little time, only 4 to 8 years, for mitigation measures.

Nuclear fission now presents a formidable fleet of some 450 reactors benefitting from over 50 years of operational experience. Throughout decades of development, they reached outstanding safety standards, exceeding those of most renewable sources. However, the threat of climate change is calling this perspective into question as nuclear technology requires long-term stability of institutions. The future of nuclear fission will be determined after the expiration of the next decade with the development of hydro, solar and wind energy as replacements. For Croatia, in view of future climate insecurity, we cannot recommend the construction of a nuclear power plant built to operate from 2043 to 2083 (2) as a replacement for the outgoing NE Krško plant. Instead, we should intensify the development of our renewable resources.

EARLY YEARS OF NUCLEAR ENERGY, START IN WAR TIMES

The effect of the discovery of nuclear fission in 1939, just before World War II, was of tremendous historic importance. It made possible a release of large amounts of energy from a miniscule amount of fuel. Soon, under the threats of war, nuclear scientists produced the first atomic weapon, which ended the second world war in 1945 (3). Nuclear science attained scientific prestige and influence. No doubt that the promise of a new energy source stimulated far-reaching research into its peaceful use. Fission energy benefitted from lavish investments and annual support during its early years when nuclear programs were a matter of national prestige, and, after 1949, regrettably, of military importance (4.). Looking back over the last 50 years, we can see that initially nuclear development was broadly based. Many types of reactor were tried, but over the years that wide selection was narrowed down, leaving us with only a small number of reactor types that satisfy nuclear safety, technical and economic criteria. Dominant now are PWR (Pressurized Water Reactor) reactors. That long period of development produced extremely safe PWR reactors, capable of operating for decades. Indeed, after a working life of forty years, many even obtained life extensions. These reactors, initiated by a group of outstanding scientists and developed over more than 50 years, represent an invaluable and unrepeatable accumulation of financial resources, worldwide scientific and technical knowledge and experience.

NUCLEAR ENERGY IN FORMER YUGOSLAVIA

The Yugoslav nuclear program was initiated with the building of five nuclear institutes from 1947 to 1950. Details can be found in the 2015 HAZU publication (5). In its early years, the program was mainly dictated by political motives - fear of the Soviet Union. Indeed, from 1948 until Stalin's death in 1953, some politicians, fearing Soviet Union aggression against Yugoslavia, pretended to be working on nuclear weapons. However, later developments had a strong influence on Yugoslavia's nuclear program. A large hydroelectric plant was under construction at Đerdap in Serbia. Serbian ambition thus satisfied, the time was ripe with the completion of Đerdap I scheduled for 1971 (1081 MW for Serbia) and the abandonment of nuclear ambitions in FCNE (Federal Commission for Nuclear Energy), for the initiation of a program to build a nuclear power station in the west of Yugoslavia, where, it was argued that the region lacked coal deposits. The decision in 1970 by the two western republics of Slovenia and Croatia to embark jointly on construction (7) of a nuclear reactor, using foreign investment, was based on sound economic arguments. At that time a second joint Croatian-Slovenian nuclear power plant was prepared for construction in Croatia. Following the break with the Soviet Union, the non-alignment policy had become the main driving force behind Yugoslav external political activity. Work on nuclear weapons was incompatible with Tito›s leading position in the non-alignment movement. When, in 1974, Tito laid the foundation stone on the site of the future nuclear power station to be built under IAEA supervision and approval, he was sending a clear political message. Moreover, the location of the power plant at Krško, in Slovenia, provided the American- Yugoslav project with additional international security, as was proven by NP Krško operating without interruption throughout the 1990-95 war, when reliable production of electricity was essential (8). The reactor for Slovenia and Croatia, of the Pressurized Water Reactor (PWR) type, was built by American industry with Westinghouse as the main contractor. It started commercial production in 1983. The Krško plant proved to be one of the best.

OUR WORK ON NPP KRŠKO

I am presenting my personal view here, as I consider it to be relevant to the future of fission energy and solar energy. I was the founder member of the Croatian nuclear society in 1992, having been active in nuclear physics and nuclear energy from the late fifties to the present day. My memories range from meetings of the Federal Nuclear Commission (Savezna komisija za nuklearnu energiju) to recent days when the main topic has become global warming and climate change. With the construction of the first joint nuclear power station at Krško in Slovenia, Croatian and Slovenian scienti-

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sts, engineers and technicians gained invaluable experience in top science and technology from leading experts in nuclear technology. Many attained the highest level of knowledge in nuclear science. We are all proud of our contributions to nuclear technology and we are grateful for the technical help we received over more than half a century.

A COMMENT ON THE SAFETY OF PWR REACTORS

With about 450 reactors now in operation, the last major nuclear accident was at the US

Three Mile Island power station in 1979 (9), on a PWR reactor with a containment building to stop radiation escaping into the surroundings. Even at an early stage of development, prior to the many improvements made in later years, containment buildings proved to be very effective. Nuclear fission is, according to most surveys, amongst the safest sources of production of large amounts of energy, as was recently admitted even by the usually very critical Union of Concerned Scientists (10). The accident at Chernobyl in 1986 in the former Soviet Union took place with an entirely different type of reactor, without containment, that would never have received an operating license in the West (11). The last nuclear accident happened at Fukushima, Japan, initiated by the devastating earthquake in 2011 (12), causing loss of human life in the tens of thousands, but none that could be ascribed to the effects of radiation (13).

WORK ON GLOBAL WARMING BY THE ZAGREB GROUP

I remember ironic smiles at my mention of global warming, sometime in the early nineties, when the problem with fossil energy was being discussed and the argument for nuclear energy was formulated. I was an early bird, with a chapter on global warming in my book on nuclear energy, published in 1993 (14), introducing the main concepts. After a pause of a few years (1994-2005) devoted to the problems of demining, investigating nuclear methods of mine detection, I returned to energy problems. Ten years on, global warming was recognized as the most dangerous long-term environmental threat. Our own research on the topic began in about 2007. First, working with scientists from the University of Zagreb and the Academy of Sciences, we showed, for the first time, that nuclear fission had the potential on a worldwide scale to effectively contribute towards the mitigation of global warming by replacement of fossil fuels (15). This was confirmed by published research in the years 2010-2019 (16,17,18,19). These publications were important as they demonstrated the possibility of using fission energy to combat global warming at an earlier phase, before solar energy could make a significant contribution. The technical reason for delay was that efficiency of solar photovoltaic energy required time to reach economically interesting values for large-scale electricity production. Some twenty years ago, solar energy was not capable of large energy production, but we witnessed fast progress during the twenties, when the production of wind and solar energy, as predicted by world surveys (21) and (22), overtook nuclear.

In the present dangerous climate of uncertainty, it is time to rethink the future of fission energy. For Croatia, it is a question of whether or not to rely on nuclear energy after the year 2043 (on the assumption that Croatia will be sharing 50% of Krško's power production) when the existing agreements between the two owners expire. NP Krško should be closed no later than 2043, by which time we will already be deep into the climate change years. In my opinion, it would not be wise to build a nuclear power plant that would operate from about 2043 to 2083 or longer. We must be sure to be able to fulfil all our obligations as owners of the nuclear plant, including decommission and taking care of spent fuel. Our commitments would extend into the next century. That is not a good idea in the unpredictable times we are facing. Owing to the present lack of adequate carbon-free energy sources, other than hydroelectricity, we are currently in a position of being dependent on fission as our main source of carbon-free energy. But the wisdom of using nuclear fission energy, despite its successful development, is debatable. The main problem is the long-term safety of radioactive nuclear materials. If their security cannot be ensured long-term in the wild weather conditions we expect to prevail after about 2053, with all the ensuing repercussions, then the long-term future of fission is dubious. There are examples of safe storage of spent fuel by Finland and Sweden (23) but the question is the unit costs of low capacity storage is open. We must be sure that highly radioactive materials can be safely stored for a long time. But we cannot even be sure that in 50 years' time organizations to ensure the long-term safety of radioactive waste will exist. Surveys and controls will be needed for many decades, even centuries. Should this be impossible to guarantee under future climatic and social conditions, then we have to think very seriously about the wisdom of continuing with fission energy in our country after 2043. This opinion should be independent of European attitudes to nuclear energy, as many political considerations and obligations are to be respected. However, as nuclear fission problems can be expected to emerge from countries outside the Non Proliferation Treaty regime, we are not optimistic.

LATE INVESTMENT IN RENEWABLE ENERGY

While it is true that nuclear energy was privileged in its early years, it also true that photovoltaics were slow to develop. Initial investments in solar and wind energy were much smaller. Production of solar and wind energy is now modest relative to nuclear energy. However, solar energy plans are much more ambitious for the future, as presented in IRENA (20) and in IEA reports (21), (22). Present annual production of solar and wind energy is nominally at some 750 GW in average power, but in reality about 11 %, of that. Figures for wind power with average annual value of 550 GW are similar, except for higher efficiency (about 20%). There is a fleet of about 450 nuclear power reactors now in operation. They produce about 10% of the world's electric energy. This is currently about 285 GW of average power on the annual level. About 1600 further nuclear power stations of about 1000 GW would be needed to replace all coal power stations (24). Future decisions on fission energy on a world-wide scale will require very careful consideration (25). At the moment, important discussions are in progress. The European Union has asked the TEG (Technical Expert Group) of the EU to assess the nuclear contribution to the mitigation of global warming. The TEG mandated the European Joint Research Council to prepare the study. Over the coming months, JRC will prepare to give a technical assessment of the question "whether corresponding economic activity qualifies as contributing substantially to climate mitigation or climate adaptation". The result will influence the financing of European nuclear projects.

Whatever the results of the JRC may be, they cannot ignore the drive and inertia of large nuclear industries and projects, as shown by ITER project. Croatia is not a country for a large nuclear projects, however, Croatia is well positioned for solar and wind energy and possess good backing of hydro energy. With nuclear energy available up to 2043, it can use the years up to 2043 to expand its solar and wind potentials, to cover the end of nuclear contribution by 2043.

THE FUTURE OF NUCLEAR FISSION VERSUS PHOTOVOLTAIC ENERGY

However, climate changes also force us to take a new look at the future of electricity production. We now have two outstandingly advanced technologies, nuclear and photovoltaic, capable of producing large amounts of carbon-free energy, but they have very different long-term prospects in these times of climate change. Nuclear energy requires an extensive supporting infrastructure, from nuclear legislation to the production of massive components such as pressure vessels and heat exchangers and to small but technically challenging fuel rods. Operational nuclear safety imposes many limitations on the reactor design. Highly radioactive spent fuel needs storage and supervision for decades and even centuries. Owing to high initial investment costs, nuclear power plants must have long lifetimes to be profitable. Nuclear power stations have controls and regulations, the cost of which does not vary with the size of the plant. This discourages the building of small plants and explains why a typical plant is of 1000 MW in electric power.   Photovoltaic cell units, on the other hand, are small and can be multiplied without limitation. The unit cost is high, but steadily decreasing. The cell units are ubiquitous, offering countless uses, thus reducing the cost. However, the prime advantage of photovoltaic relative to nuclear energy is that it avoids dealing with radioactivity. The principal disadvantage is the low energy density of stored energy. There is no replacement for petrol in sight but there is scope for development, perhaps hydrogen if production becomes cheaper. Countries with a good proportion of hydro-electric power will be at an advantage. Croatia is in a relatively good position.

ON HISTORIC MISTAKES MADE WITH NUCLEAR FISSION IN THE PAST

Looking back over the history of nuclear fission energy we can register two mega blunders, which have compromised the benefits to human society of the discovery of nuclear fission. They are even more regrettable in these uncertain times of climate problems. The first monumental blunder was committed by the Soviet Union in its rejection of the generous Western offer to unilaterally ban nuclear weapons and to establish international authority (International Atomic Developments Authority) over the use and development of peaceful nuclear energy, presented as the “Baruch plan” to the UN by the US delegation in 1946 (26). This generous Western offer, backed by most of the top scientists of the time, including Robert Oppenheimer, was rejected by the Soviet Union which was working on its own nuclear weapon that exploded in 1949. The significance of this wrong turn cannot be overestimated. It was the most fateful one in centuries. The history of the arms race is detailed in a book by Nobel prize winner Noel-Baker (27). As a result, a deadly dangerous arms race started and eventually developed by the eighties into ludicrous “overkill” stock-piling of nuclear arms. We were lucky to escape annihilation when targeted by over 50 000 nuclear weapons, most of them stronger than those thrown on Hiroshima and Nagasaki. The second blunder, with a similar negative effect, occurred later, at the end of the Cold War, in the nineties. With the disappearance of one side from the arms race following the breakdown of the Soviet Union, there was a good chance of removing and banning all nuclear weapons. But the USA were revelling in their unique position as the only nuclear superpower. As a result of their short-sighted, egoistic policy, shortly afterwards several new nuclear countries emerged. New, illegal nuclear weapons countries appeared in addition to the five acknowledged nuclear countries (USA, UK, France, Soviet Union and China). Political control over these newcomers (Israel, Pakistan, India and North Korea) is very problematic and can only become more so in the political anarchy that is expected to follow the climate crisis. How can this situation be regarded as a positive development? Thanks to these two fatal faults, the idea of stopping the proliferation of nuclear weapons was compromised beyond repair. The result is a dangerous negative effect on the future of fission energy. With four nuclear states rampaging out of control, we shall need a nuclear policeman to protect the rest of the world. And this (international) police force would need an overwhelming nuclear force. Not a nice prospect! Let us hope for better solutions.

ON SOME LONG-TERM PREDICTIONS AFTER 2040.

But for the short-sighted USA policy at the end of the era of confrontation between the two blocks, the chances of nuclear disarmament would have been real. Being an old Pugwash member (28), for me this was a colossal blunder on top of which we now have the problem of global warming. This is the reason why we should be suspicious of any long-term predictions for our future. We can predict floods in the regions of the Mekong and Bangladesh deltas, because they have already started. Draughts in North Africa are spreading, climate change is already here. Surprising positive feedback processes are starting. However, predictions for 2050 can only be extrapolations from what is already happening, plus a pinch of imagination. The pictures of the future by Tong et al. (29) or from Millar et al. (30) are wishful thinking at best. In our present world situation it is impossible to predict main world events for more then 15-20 years ahead. There will be many repercussions when the temperature increase exceeds 3°C. We are on the cusp of disaster. Melting of permafrost is expected and will release methane, a very active greenhouse gas. Without the use of force, the authorities will not be able to stop mass movements of millions of migrants coming from areas made uninhabitable by climate changes. That means mass murders and would spell the end of democracy. Those millions would not even know that we, the rich people of Europe and the US, the initial cause of their sufferings, are to blame. This is the basic reason why we cannot predict the future with any certainty, certainly not after the years 2030-2035. As consolation, may I recall the definition of an optimist by a great physicist, Rudolf Peirls, at that time in Birmingham: “An optimist is a person who believes that the future is uncertain”. We must be prepared for climate emergencies, sooner rather than later.

A WARNING FROM A GROUP OF OXFORD AND POTSDAM SCIENTISTS

A group of serious scientists has issued a warning. On reading the paper by the Potsdam and Oxford groups, published in Nature in 2009 (1), it became clear to me, should their results be correct, that there is much less time to stop global warming than was previously thought. We respect this serious and well-argued work, but we do not know how crossing the limit will manifest itself, or where. That would require more knowledge of meteorology. The Mekong delta, Bangladesh, Florida, the Arctic region, the Antarctic ice sheet? According to their calculations, up to the year 2000 we would emit 1000 Gt of CO_2 before breaching the commitment of not exceeding an increase of 2°C in global temperature. But by now we have already spent a considerable part of this “emission capital” - around 770 Gt - so we have only 230 Gt left to keep emissions below the 2°C rise in global temperature. Now, in 2021, we have about four years left before we cross over into the region where the temperature increase will exceed 2°C. Our annual carbon dioxide emissions at present from all sources amount to about 43-45 Gt. Ironically, there has been a slight decrease due to a reduction in carbon use as a consequence of the Corona virus pandemic having slowed down the world economy!

FALSE HOPES IN NUCLEAR FUSION AND CARBON CAPTURE AND STORAGE (CCS)

Unfortunately, we cannot expect to be saved by fusion energy in the earliest climate emergencies. According to the 2018 report by the Director General of ITER (31), laser installation could be completed by 2035. This refers only to the experimental ITER device and does not take into account that at least 10 to 15 more years will be required to complete and test the following DEMO (32) installation and to use it as a thermonuclear power plant. The basic laws of physics dictate that future fusion devices would have to be of a similar size to ITER. Creating the outer wall of a fusion chamber remains an outstanding and unsolved problem. To build a fleet of plants capable of having an impact on carbon emissions would demand advanced technology and thus could not engage a large circle of countries. Technical and material problems would be serious and could take us well into the sixties. As plans to use CCS are only at the stage of discussion about technologies, whilst there is no-one with any serious idea of how to store at least several Gt of CO_2 ,some thousand times more than current annual storage would need. So, we cannot expect a serious contribution from CCS. Paper by Biello is a serious evaluation, independent of the short-term interests of the coal industry (33). Meanwhile, there is bluster from the coal industry and so-called scientists working on impossible projects paid by coal business.

Faced with such serious warnings about what could happen in the next ten years, we would be foolish to ignore them. We must be prepared for the likely future. Should it give us a miss, we will be grateful, but we must not count on it. As stated previously, we have grave misgivings about investing all our efforts to stop global warming in CCS and nuclear fusion, both likely to fail, whilst neglecting more imminent dangers. On the basis of the prediction by Meinshausen et al, (1), we should be prepared for much earlier emergencies. Unlikely success with fusion will come too late, in the sixties. In the meantime, we must develop solar energy to the point where it can first replace electricity production from coal and gas, and thereafter when it could also replace power from nuclear fission.

IN CONCLUSION

My life was in fission energy, as can be seen from most of my earlier work, but the future of humanity lies in solar energy. Use it, curtail wastage and abuse, and it should provide enough energy for everybody, without entailing unpredictable and dangerous geo-engineering experiments.

REFERENCES

[1.] Meinshausen M., Meinshausen N., Hare W., Raper S.C.B., Frieler K., Knuitti R., Frame D.J., Allen M.R., 2009. Greenhouse gas emission targets for limiting global warming to 2 °C, Nature 458,

[2.] In former Yugoslavia one nuclear power plant was buildt , at Krško in Slovenia of PWR type and power of 670 MWapp. It started operation in 1983 and with planned life extension it retire by 2043. Two republics, Croatia and Slovenia, share the costs and produced energy on equal 50-50 parts.

[3.] World war II ended with capitulation of Japan following two atomic bombs thrown on Hiroshima and Nagasaki on 6. and 9. August 1945

[4.] Soviet Union explodes its first atomic device in 1949. I can be taken as start of nuclear arms race. The exgsictence of many thousends of atomic bomb ever since present a permanent possibilty of destroying all life on the planet. There are reports many case of close escapes and there are some irresponsible nuclear weapon countries.

[5.] Vladimir Knapp, Ivan Supek i jugoslavenski nuklearni program, U povodu 100. obljetnice rođenja, HAZU, Rasprave i građa za povijest znanosti, str.89-113, Zagreb 2015.

[6.] Death of Stalin in 1953 marks a reversal point of confrontation with countries of Eaistern block

[7.] Decision to build the first nuclear power plant was reached by Yugoslav Eletricity Industry (Jugoslovenska elektoprivreda), a top joint authority of federal adminstration

[8.] An uninterupted electicity supply from nuclear power Krško was very important in the early war days of Serbian agresion on Croatia

[9.] Most serious accident on PWR plant occured on the reactor from the Three Mile Island in 1979. Pressure vessel suffered heavy damage from partly molten reactor core but only very small part of radioactivity ascaped beyond the border of power station. In years later many improvement on contaiment have additionaly increased safety.

[10.] S. Clemmer, J. Richardson, S. Sattler, D. Lochbaum: The nuclear power dilemma, *Union of concerned scientists*, 2018. Available at: https://www.ucsusa.org/sites/default/files/attach/2018/11/Nuclear-Power-Dilemma-full-report.pdf, (Accessed 15.11.2020)

[11.] Big reactor not exported with pressure tubes cooled by water at low pressure Unsafe design, caused the Chernobyl accident in 1986. Without containment which resulted in very large release of radiuaccivity into surounding see for example

[12.] V.Knapp, Černobilj, 10 godina poslije, Energija, no 2, 49-54, 1996.

[13.] V.Knapp ,Udes na elektrani Fukushima u perspektivi, Zavod za primjenjenu fiziku, 2012

Stošić, AREWA, Despite Fukushima the Nuclear Perspectives still hold, HND persentation 28.11.2011,detailed account of the earthquake and the subsuquent accident on the Fukushima power plant. Detaljan izveštaj o potresu i okolnostima koji doveli do udesa na elektrani Fukušima

Later reports on the Fukushima accident available

[14.] V.Knapp, Novi izvori energije: energija fuzije i fisije, Školska knjiga, 1993.

[15.] OECD/IAEA, 2008, Uranium 2007: Resources, Production and Demand A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency (2007). Available at: https://www.eea.europa.eu/data-and-maps/indicators/net-energy-import-dependency/oecd-iaea-2008-uranium-2007, (Accessed 11 Nov 2020).

[16.] Knapp V., Pevec D.,Matijević M., 2010. The Potential of Fission Nuclear Power in Resolving Global Climate Change under the Constraints of Nuclear Fuel Resources and Once-through Fuel Cycles. Energy Policy 38, 6793-6803.

[17.] Pevec D., Knapp V., Trontl K., 2012. Long Term Sustainability of Nuclear Fuel Resources, in: Revankar, S, T, (Ed.), Advances in Nuclear Fuel. Intech, Rijeka, pp. 1-26.

[18.] Knapp V., Pevec D., Matijević M., Crnobrnja B., 2016. Fission Energy Perspective Relevant for Combating Climate Change, Journal of Energy and Power Engineering. 10, 651-659

[19.] Knapp V. and Pevec D. 2018, Promises and limitations of nuclear fission energy in combating climate change. Energy Policy 120, 94-99.

[20.] International Renewable Energy Agency, https://irena.org/solar, (Accessed 15.11.2020)

[21.] IEA reports on solar energy https://www.iea.org/reports/world-energy-outlook-2020/outlook-for-electricity#abstract, (Accessed 15.11.2020)

[22.] IEA reports (World Energy Technology Perspectives 2020) Available at https://www.iea.org/reports/energy-technology-perspectives-2020 (Accesed 15.11.2020)

[23.] It would to early to give data for storage of spent as the figures for joint storages do not exist or are very tentative. Future international storages under IAEA or EU supervision could be economical and safe

[24.] Knapp V., Pevec D., Matijevic M., Lale D., 2017. Carbon Emission Impact for Energy Strategy in which All Non-CCS Coal Power Plants Are Replaced by Nuclear Power Plants. Journal of Energy and Power Engineering. 11, 1-10.

[25.] Report by EU Research Council will be due in the first half of 2021

[26.] Baruch, member of US delegation to UN conference in 1946, Available at: https://www.atomicarchive.com/resources/documents/deterrence/baruch-plan.html, (Accessed 15.11.2020)

[27.] Noel-Baker P. 1958. The Arms Race – A programme for World disarmament, John Calder Ltd, London

[28.] Pugwash Conferences on Science and World Affairs, https://pugwash.org/, (Accessed 11 July 2020).

[29.] Tong D., Zhang Q., Zheng, Y., Caldeira K., Shearer C., Hong C., Qin Y., Davis S.J. 2019. Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. Nature 572, 373-377

[30.] Millar R.J., Fuglestvedt J.S., Friedlingstein P., Rogelj J., Grubb M.J., Matthews H.D., Skeie R.B., Forster P.M., Frame D.J., Allen, M.R. 2017. Emission budgets and pathways consistent with limiting warming to 1.5°C. Nature Geoscience 10, 741- 747

[31.] Statement on the ITER progress, report by Bernard Bigot, Director general, 2020. *ITER Organisation. Special issue 7*, Available at: https://www.iter.org/multilingual/io/7/337, (Accessed 11 July 2020).

[32.] Reaction d+t is only a basic requirements. Many problem are to solved before operation of fusion device could be economical. One the most important is a damage to the first wall of the reaction chamber

[33.] Biello, D., 2016. Carbon Capture May Be Too Expensive to Combat Climate Change. Scientific American 314, 59- 65.

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How COVID-19 lockdown has impacted demand curves of Croatia and the surrounding countries

SUMMARY

Electrical energy is a specific commodity because it can't be stored in significant quantities, so accurate day-ahead forecasting of total consumption plays a crucial role in stable operation of the whole power system. In order to maintain the adequacy, power generation and electricity consumption have to be constantly in a balance.

Electricity demand curve is very sensitive and vulnerable to a lot of different factors that can be categorized in several main groups that include social, stochastic and weather dependent factors.

In condition of global pandemic caused by COVID 19, prediction of total consumption is even more challenging task. New restrictive rules, that completely changed behavior of consumers, their daily routine and habits, have been adopted in most of the European countries. Hence, this lockdown restrictive measures affected the volume of electricity consumption and the shape of demand curves as well.

This paper analyzes some of the cases with very variable electricity load, due to volatile households' behavior, on cases of Croatia and countries in the region. Additionally, results are compared with the electricity load of Italy and Sweden whose economy and industry are well developed. Consumption of Sweden was interesting to observe because of its totally different approach of mitigating corona virus, without lockdown restrictions.

KEY WORDS

corona virus, COVID-19, electricity load curve, electricity demand forecasting, lockdown restrictions

1. INTRODUCTION

This research aims to investigate the impact of the COVID-19 on the shape of Croatian load curve and the consumption of electricity in general. Furthermore, a brief analysis of a situation in the region was carried out and the results will be presented.

Many people claim that the corona crisis in Italy and Europe escalated after the Champions League match in Milano on 19th of February 2020 where Atalanta hosted Valencia. Suddenly, a few days after that match Italy became, by far the most affected European country and the city of Bergamo one of its worst-hit towns. The first case of COVID-19 infection in Croatia was confirmed in the last week of February, precisely on 25th of February 2020. As the patient number zero was marked a young guy who attended that football match in Milano. As time was passing, the number of people infected by the coronavirus disease was growing daily, but fortunately, the exponential rise of new cases was mitigated [1].

Consequently, the National crisis management was set up to fight the coronavirus and slow down the spreading of the virus among the population [2]. In cooperation with the government some new rules, that completely changed the way most of the citizen's life, have been adopted.

These rules and restrictions incorporated not only the suspension of lessons in all schools and all universities but also temporarily end of work in all kindergartens. Furthermore, employers were forced to enable working from home to most of their employees, if it is anyhow possible. Otherwise, they had to reduce the number of people sitting in the office at the same time. All public meetings, public occasions, sports competitions, trade fairs, and gatherings for the purpose of religion were strictly forbidden. In addition to this, service activities that are not essential for the functioning of the community were also stopped. Hence all museums, theaters, disco clubs, libraries, gyms and fitness centers, bars, hairdressers closed their doors. Permission to work but with strict rules had only supermarkets, bakeries, restaurants with food deliveries, and pharmacies. Furthermore, all kinds of public, city, and intercity transport were suspended.

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Living under these lockdown restrictions completely changed our daily routines and past habits, thus we had to forget the life we had before. Therefore, it is likely to expect significant changes in electricity consumption.

This research focuses on gathering and analyzing electricity consumption data for Croatia and neighboring countries during the COVID-19 pandemic.

2. ELECTRICITY DEMAND FORECASTING

Electricity load forecasting is a complex task which incorporates a variety of variables that directly or indirectly affect the demand for an electricity [3]. Electric energy consumption is the actual energy demand in the real time made on existing electricity supply [4].

Electricity consumption is a vital part of economic activity and an irreplaceable part of our daily needs. Thus, electricity load profile ([5], [6], [7]) reflects "an electrical activity of the hearth of a nation, region or individual customer" like an ECG [8]. It surely represents holistic pulse of customers at an observed moment.

Accurate planning of the day-ahead electricity load can also significantly help system operators with less activation of ancillary services in the real time. Thus, it is important to have a reliable method for electricity consumption prediction and consider time decomposition which includes long, medium and short-term framework [9] . A variety of factors mentioned in [10] in long-term and medium-term load pattern forecasting, such as population, economic development, climate, etc. influence the total electricity load of one country. There are plenty of existing load forecasting methods that can be used for a day-ahead consumption planning. An overview and review of such electricity consumption planning methods were given in [11]. Generally, models could be divided into intelligent non-linear models that incorporate advanced technologies such as Artificial Neural Network ([12],[13]), grey prediction models [10], and statistical analysis models. Moreover, there are also a variety of other hybrid models. One of such developed models is presented in this chapter. This model consists of factors divided into three key categories: weather dependent factors related to the load, social factors connected to the load, and stochastic factors that affect load changes [14]. This is presented by the following equation:

$$P(t)=\alpha^{*}P_{w}(t)+\beta^{*}P_{s}(t)+\gamma \tag{1}$$

Where:

- $P(t)$ – total electricity load in a certain period
- $P_w(t)$ – weather dependent factor of the total load
- α – coefficient correlated with the weather dependent factor
- $P_s(t)$– social dependent factor of the total load
- β – coefficient correlated with social dependent factor
- γ – constant for estimating stochastic load changes

Furthermore, each of these variables, which behave like independent or partly dependent functions is then further decomposed and analyzed in individual sub-functions. For example, a weather dependent factor incorporates air temperature, wind speed and direction, cloudiness as well as type and intensity of a precipitation. Furthermore, there is also a humidity (dew point) which affects a load curve in cases of high and low temperatures.

This is presented in following equation:

$$P_{w}(t)=\alpha_{1}{}^{*}T(t)+\alpha_{2}{}^{*}C(t)+\alpha_{3}{}^{*}Ws(t)+\alpha_{4}{}^{*}Wd(t)+\alpha_{5}{}^{*}Rt(t)+\alpha_{6}{}^{*}Ri(t)+\alpha_{7}{}^{*}H(t) \tag{2}$$

Where:

- $P_w(t)$ – weather dependent factor of the total load
- $T(t)$ – external temperature dependent factor
- $C(t)$ – cloudiness dependent factor
- $Ws(t)$ – wind speed dependent factor
- $Wd(t)$ – wind direction dependent factor
- $Rt(t)$ – precipitation type dependent factor
- $Ri(t)$ – precipitation intensity dependent factor
- $H(t)$ – humidity (dew point) dependent factor
- $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7$ – coefficients for estimating load changes with correspondent weather dependent factors

This example is just one of the multiple ways of forecasting electricity consumption that illustrates its complexity. Such challenge can be described like forecasting both "nature" and "society" during a timeline which affect the shape and values of the forecasted load curve. Naturally, in countries with higher industrial development and lower share of households' electricity consumption, load forecasting can be considered somewhat easier since a household consumption can be very fluctuating and unpredictable. An example of such a country where a load forecasting is a tremendous challenge is Croatia where the majority of the electricity demand consists of households. Thus, when forecasting the electricity demand curve a special consideration for social factors (holidays, weekends, semi-working days, public events, lockdown restrictions, etc.) has to be taken into account. Even the slightest weather or social changes can significantly impact the total load curve. The main analysis of this paper considers the impact of COVID-19 and corresponding lockdown measures on the electricity demand curve and how to read its data. Such pandemic has significantly affected behavior of demand curves and it has to be taken into account while analyzing realised electricity load curves during such period and forecasting electricity load curves in ever similar period in any stage in the future.

3. ANALYSIS OF ELECTRICITY DEMAND CURVES

This chapter will describe and analyze gathered data for Croatia and neighboring countries in terms of electricity consumption as well as give an overview of restrictive lockdown measures and how they affect overall electricity consumption. The analysis will be carried out and results compared to the previous historic data in the following subsections. In addition, the analyses was expanded to the case of Sweden which, although is not in the region with others, is an interesting case to compare with due to its complete opposite approach in national strategy of not imposing the restrictive lockdown measures.

Period of analysis is 14 weeks and exact periods of each week are presented in Table 1.

Table 1. Analyzed period

	2019.	2020
Week 1	25.2.-3.3.	24.2.-1.3.
Week 2	4.3.-10.3.	2.3.-8.3.
Week 3	11.3.-17.3.	9.3.-15.3.
Week 4	18.3.-24.3.	16.3.-22.3
Week 5	25.3-31.3.	23.3.-29.3
Week 6	1.4.-7.4.	30.3.-5.4.
Week 7	8.4.-14.4.	6.4.-12.4.
Week 8	15.4.-21.4.	13.4.-19.4.
Week 9	22.4.-28.4.	20.4.-26.4.
Week 10	29.4.-5.5.	27.4.-3.5.
Week 11	6.5.-12.5.	4.5.-10.5.
Week 12	13.5.-19.5.	11.5.-17.5.
Week 13	20.5.-26.5.	18.5.-24.5.
Week 14	27.5.-2.6.	25.5.-31.5.

Table 2. Total number of new weekly confirmed COVID-19 cases

	Italy	Croatia	Hungary	Slovenia	Bosnia	Serbia	Sweden
Week 1	1557	7	0	0	0	0	13
Week 2	5686	5	8	16	2	1	189
Week 3	16605	36	31	237	19	54	829
Week 4	35158	187	128	189	141	133	874
Week 5	38551	478	280	321	251	553	1794
Week 6	31259	469	297	258	368	1167	3130
Week 7	27415	418	714	191	292	1722	3653
Week 8	22609	271	526	123	267	2688	3902
Week 9	18703	159	599	72	248	1724	4255
Week 10	13042	66	452	38	358	1422	3677
Week 11	8353	91	249	16	212	650	4005
Week 12	6365	39	251	6	161	496	3821
Week 13	4423	18	221	2	97	549	3316
Week 14	3161	2	120	6	118	253	4083

Along with weekly total load data, the number of weekly COVID-19 positive cases has been gathered for each of analyzed region. Table 2 presents data of new weekly confirmed COVID-19 cases for each of the analyzed region.

However, due to a vast difference in sizes of countries, and thus a much higher number of confirmed cases for larger countries, for purpose of this analyses it is better to look at number of cases per 10 000 residents.

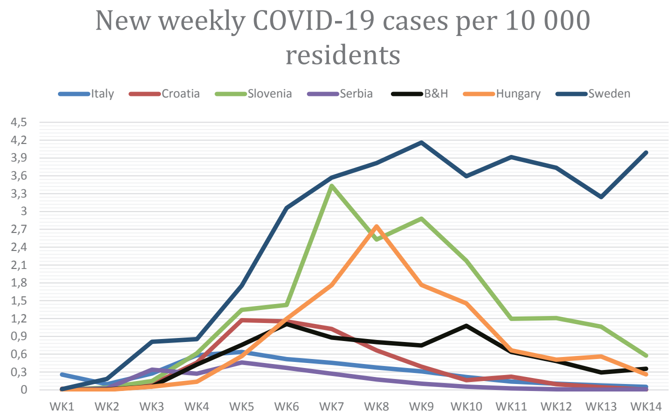


Figure 1 Number of new weekly COVID-19 positive cases per 10 000 residents for each respective region

As seen in *Figure 1*. Sweden has the highest rate of COVID-19 positive cases per 10 000 residents and their trend from week 7 to week 14 is not declining as it is the case for other countries in this analysis. The main reason for this is that Sweden is the only European country that decided to take a different approach in the battle with the COVID-19 pandemic. They decided against the majority of restrictive measures or a complete lockdown that was introduced in other countries. Instead, they decided to try to overcome the pandemic by acquiring a herd immunity effect. Considering their specific approach, it is very interesting to include Sweden in the total load analyses and comparison with the rest of the countries in the region.

3.1. ELECTRICITY DEMAND OF CROATIA

Forecasting the load curve of Croatia is a challenging task. As there is a significant lack of industry, compared to the leading European countries, the highest share of the load comes from the end-consumers and households. Thus, the forecasting of electricity load curves has a wide range of options due to the stochastic and fluctuating behavior of households' consumption as well as external conditions such as weather and social impact. Observation of Croatian total load was made for 14 weeks starting from the last week of February to the end of May. During the first three observed weeks, there were no signs of the impact of corona virus on the demand curve. Despite the COVID-19's presence in Croatia, there weren't any new rules or restrictions that would change people's lives and daily habits. Life was as usual as before, but things started to change in the week 4 (16.3.2020.-22.3.2020.) when the National crisis management decided to close all schools, universities, and kindergartens to mitigate the spreading of corona virus. From Thursday 19.3.2020., all public events and gatherings were forbidden. Only necessities such as supermarkets, pharmacies, and restaurants with food delivery options have had working permits. All other service activities had temporarily locked their doors. From the Sunday of week 4 (22.3.2020.) all kinds of public transport were stopped. Some of these restrictive rules, such as suspending tram and train traffic, closing the majority of shops and markets, were an obvious cause for the decrease in the electricity consumption. On the other hand, it is hard to estimate how the school closing has affected electricity demand because all pupils and students had to follow the lectures using TV, tablets, and computers.

The demand curve shows that the total load fell off or decrease in regards to the previous week when restrictions haven't been yet adopted. Contrary to what might be expected, the total load of the fifth week has increased. However, it is mostly due to harsh weather conditions that incorporate extreme coldness for this period of the year, snow, and wind during most of the week which can be seen in *Figure 3* and *Figure 4*. On the demand curve, it can be noticed that even though the temperatures were very low, electricity consumption fell in mornings hours, and increase significantly later, around noon, during afternoon and in the evening. The shape of the demand curve had completely changed and the daily peak was almost as high as the evening peak which is uncharacteristic to previous historic data. In nearly all hours (exception of the morning), consumption was higher than the one in the previous weeks, which can be interpreted by the fact that people woke up later and postponed their usual morning activities and habits since most of them worked from home. In certain hours total load was similar to the period before restrictions. In the sixth observed week, temperatures were also under average, however, the total load has decreased. Summertime calculation (Day-light saving time) led to reaching the evening peak in the twenty-first hour, and more daylight affected consumption too.

During the seventh week, the consumption continued to fall, and it was nearly 32 GWh lower than the previous week. This has marked the highest difference of realized load between two continuous weeks which can be explained by the fact that it was Easter week, and the holiday has significantly impacted total load. Monday of eights' week was a holiday as well, and the total load was also lower than the previous week. However, the demand curve had almost the same shape. It was slightly translated in the downwards direction.

The ninth week was very similar to the previous with an insignificant rise in total consumption. Restrictive rules, adopted during the lockdown, have been cleared starting from week ten. At the beginning of week ten, supermarkets started to reopen, except for the ones in shopping centers. Furthermore, certain services activities, which don't require close contact between people have also started to reopen along with public transport. However, the lowest consumption was achieved in this week, and from that point, the load started to slowly recover in the upcoming weeks. From the eleventh week, it was allowed for all services activities to reopen their doors (hairdressers, barbers, beauticians, etc.). The last phase of restrictions clearing started in week twelve, when shopping centers, bars, and restaurants were reopened. In the last three weeks, the shape of the demand curve changed mostly in the afternoon „gap" when the total load has risen. In addition, this evening consumption reached a peak in the twenty-second hour.

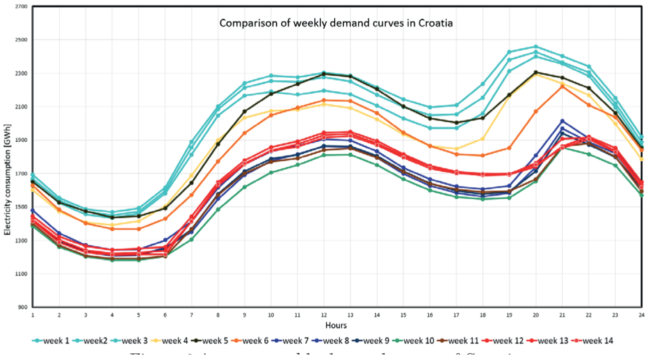


Figure 2 Average weekly demand curves of Croatia

Electricity consumption, in general, is mostly dependent on external conditions such as weather. Some of these parameters are, as already mentioned in the Chapter 2, air temperatures, cloudiness, precipitation, wind speed, wind direction and humidity. A comparison of all of these parameters would be too complicated and nearly impossible, hence, only the air temperature will be taken into consideration in future analysis and comparison with previous historical data.

Following figures (3-6), present average daily temperatures in cities of Zagreb and Split during 14 weeks (98 days) in the year 2019 and 2020.

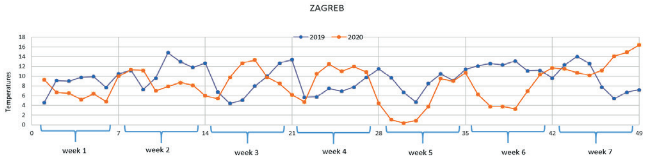


Figure 3 Average air temperature in Zagreb during first seven weeks

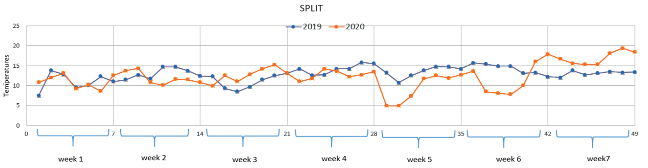


Figure 4 Average air temperature in Split during first seven weeks

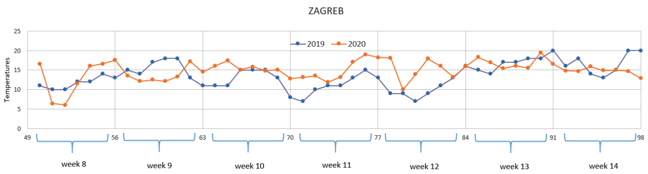


Figure 5 Average air temperature in Zagreb during second seven weeks

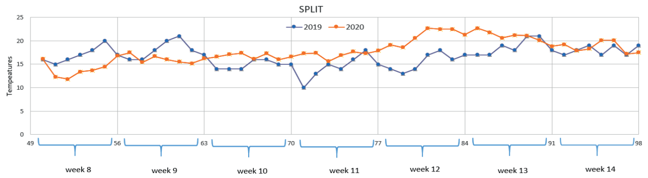


Figure 6 Average air temperature in Split during second seven weeks

Almost in all weeks during the lockdown the total load has decreased in regards to the same period in the previous year which can be seen in *Figure 7*. Only in week five, electricity consumption has risen by 1,57% in comparison with the previous year, even though the new restrictive rules have been adopted. The main reason was certainly weather conditions and very low temperatures as it is shown in *Figure 3* and *Figure 4*. The impact of new restrictive measures on electricity consumption can be seen in a total load of week six when temperatures were also lower than the ones a year ago, but the total load fell by 2,44%. After the restrictions have been released, the total load started to slowly recover. However, it was almost insignificant. There was still a big difference between the same period of the previous year because previous May has been much colder as it can be seen in *Figure 4* and *Figure 5*.

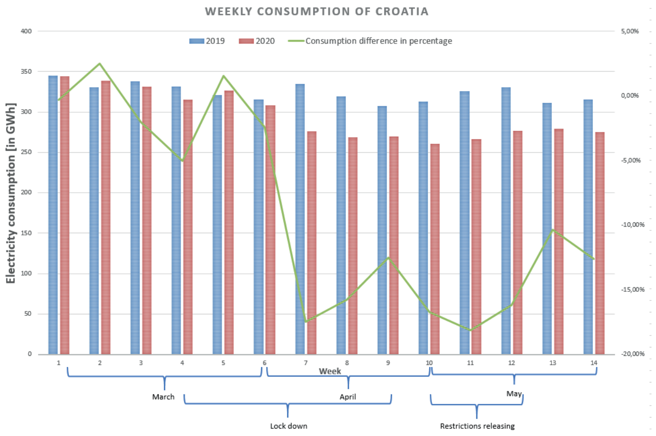


Figure 7 Comparison of weekly total load of Croatia for 2019 and 2020

3.2. ELECTRICITY DEMAND OF NORTHERN ITALY

North Italy was the worst-hit region of the country. Coronavirus spread rapidly after the Champions League match between Atalanta Bergamo and Valencia that was held in Milano, on the 19th of February. It is believed that it is the main reason why Bergamo has become the epicenter of the pandemic. North Italy is the most developed part of the country and it incorporates the following regions: Val D'Aosta, Piemonte, Liguria, Lombardia, Trentino, Veneto, Friuli Venezia Giulia, and Emilia Romagna. A significant contribution to a total load of North Italy is the industry and it is a major reason why electricity consumption decreased significantly during the lockdown. *Figure 8* shows that the total load has not instantly decreased within the first two weeks of COVID-19 appearance in Northern Italy. However, as the number of confirmed COVID-19 cases grew, restrictive measures were introduced. Moreover, the downwards trend of total load continued from week 3 to week 6 where it reached its minimum with roughly 35% of the total weekly load decrease in comparison with the previous year. Furthermore, week 7 in 2020 includes Good Friday and Easter Sunday holidays, while in 2019 such week was in week 8. These holidays in most of Europe significantly influence the shape of the load curve and Italy especially. As can be seen in , from weeks 7 to 14, the total weekly load has begun to recover reaching roughly 10% of the total load decrease in week 14. However, this assertion has to incorporate influence of different dates and weeks of Eastern holidays when we make conclusions about exact "tipping point" when and why the load curve started to ascend.

According to *Instituto Superiore di Sanita,* almost 80% of the total confirmed cases by 3rd of June 2020 were from the regions listed above. Thus, this paper focuses on North Italy rather than the entirety of Italy. Due to the strong economy and developed industry, the recovery of the total load is significantly faster in comparison with other regions analysed in this paper.

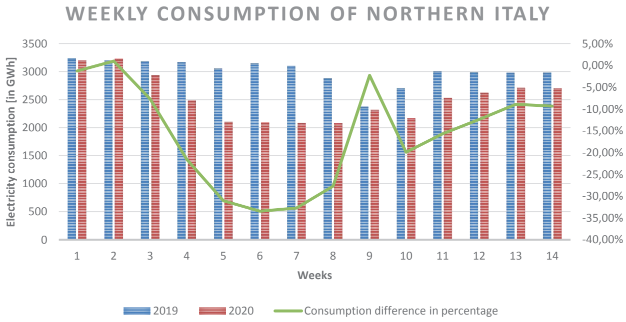


Figure 8. Comparison of weekly total load of North Italy for 2019 and 2020

3.3. ELECTRICITY DEMAND OF SLOVENIA

Similar to the case of Croatia, Slovenia decided to tackle the COVID-19 pandemic with strict restrictions and lockdown. The first cases appeared in roughly the same period, and as previously shown in *Figure 1*. Slovenia had one of higher rates of COVID-19 infections per 10 000 residents. However, with their governmental measures, they managed to control and stop further growth of cases. From week 7 and on, their measures proved efficient, and the decline in newly infected people has started.

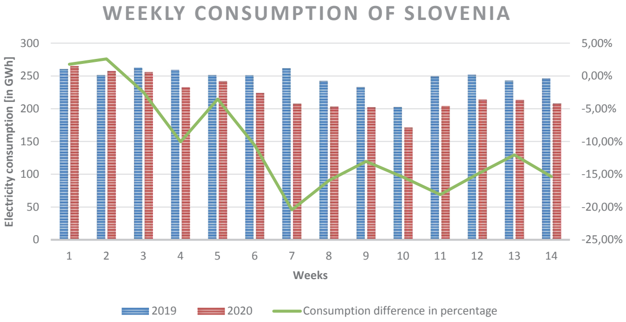


Figure 9 Comparison of weekly total load of Slovenia for 2019 and 2020

Figure 9 presents a comparison of the Slovenian total load in 2019 and 2020. A clear impact of COVID-19 can be seen in the decrease of the total load which has peaked in week 7. A peak difference between these two years is roughly 20% of the total load. This is also the period where the number of new cases has peaked. As the pandemic has been put under control, from week 8 and on, the total load has started to slowly recover. However, their recovery is at a moderate rate and the aftermath of COVID-19 is still present in significantly lower consumption (roughly 15% lower).

3.4. ELECTRICITY DEMAND OF SERBIA

Although the first cases of COVID-19 in Serbia arose in a similar period as the rest of the region, the first 6 weeks marked the total load increase in comparison with the previous year. One of the reasons for this is that their national strategy has decided to wait with restrictive measures and lockdown, and the weather impacted the total load. However, once the number of cases has significantly risen, they introduced strict restrictions and a complete lockdown. Furthermore, a police hour has been enforced during some weekends where people were not allowed to leave their homes unless it was a must. This can be seen in *Figure 10* where their total load has decreased by nearly 10% in week 8. From this point on, their load was slightly lower in comparison with the previous year.

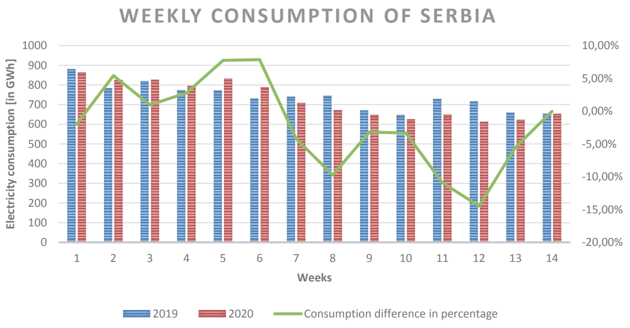


Figure 10 Comparison of weekly total load of Serbia for 2019 and 2020

The case of Serbia shows signs of COVID-19 pandemic consequences on the total load, however, they are not as significant for the total load as the previously analyzed case of North Italy. Moreover, the analysis has not been as in-depth as the case of Croatia as the goal was to present overall total load data comparison.

3.5. ELECTRICITY DEMAND OF HUNGARY

The first cases of COVID-19 in Hungary appeared in the second analyzed week. In comparison with other countries in the region, the initial situation in Hungary appeared well as they counted one of the lowest amounts of COVID-19 cases in the first few weeks. *Figure 1* graphically shows that they had one of the slowest starts in COVID-19 cases. However, the peak in new cases was also later than in other countries. Naturally, the restrictive measures were also implemented in a different time period from other countries. The situation is also translated into the total load curve. In the first three weeks, Hungary marked an increase in the total load in comparison with previous years. Moreover, as the number of cases grew and restrictive measures had been introduced, the decline of the total consumption had begun. Similar to the cases of Croatia and Slovenia, Hungary also experienced the lowest total load in week 7. The total load had decreased by nearly 15% in comparison with the previous year. From this point on, the difference has been fluctuating but it has never recovered above the 7% decrease in the total load.

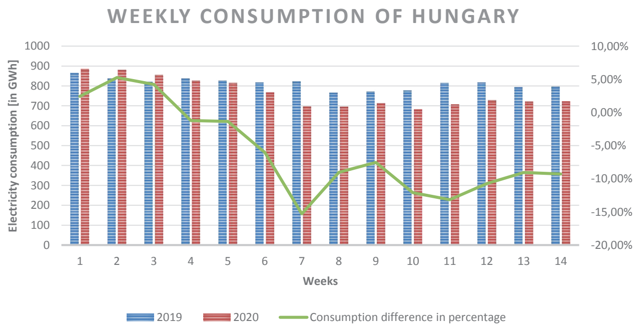


Figure 11 Weekly total load comparison of Hungary for 2019 and 2020.

The case of Hungary is similar to other analysed cases where the COVID-19 pandemic significantly decreased countries' total load due to restrictions.

3.6. ELECTRICITY DEMAND OF BOSNIA AND HERZEGOVINA

The case of Bosnia and Herzegovina is challenging to analyze. Despite other countries in the region marking economic and electricity consumption increase, Bosnia and Herzegovina marked a total load decrease even in weeks before the COVID-19 pandemic. Considering their total load decrease before the pandemic, it is hard to judge exactly how huge is the impact of COVID-19.

Data presented in Table 2. shows a similar trend between the number of cases in Bosnia and Herzegovina as in Croatia and Hungary. Interestingly, the number of weekly cases has not gone above 1.25 per 10 000 residents which is the lowest in the region, besides Italy.

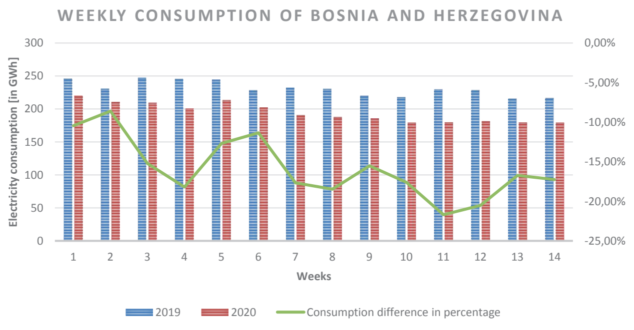


Figure 12 Weekly total load comparison of Bosnia and Herzegovina for 2019 and 2020.

Figure 12 shows a total load decrease in all of the 14 analyzed weeks which is not the case for any other country analyzed in this paper. The COVID-19 pandemic peaked between weeks 4 and 11, and the highest decrease in the total load was in week 11 (20% decrease in relation to the previous year). Generally, their load is very fluctuation and there are no signs of its recovery in this analyzed period.

3.7. Electricity demand of Sweden

As previously mentioned at the beginning of Chapter 3, Sweden decided to take a different approach in battle with this pandemic. Rather than introducing serious restrictive measures and enforcing a lockdown, it was decided that the national strategy was to try to acquire the herd immunity effect. Naturally, this meant that the number of COVID-19 positive patients was much higher in comparison with other countries which can be seen in *Figure 1*. Contrary to other observed countries, the number of infected people has not declined in upcoming weeks either which is an expected outcome due to the lack of restrictive measures.

However, this strategy meant that the Swedish economy and industry would not take such a hit as other countries observed in this paper. Thus, it is expected that the total load should not massively decline either.

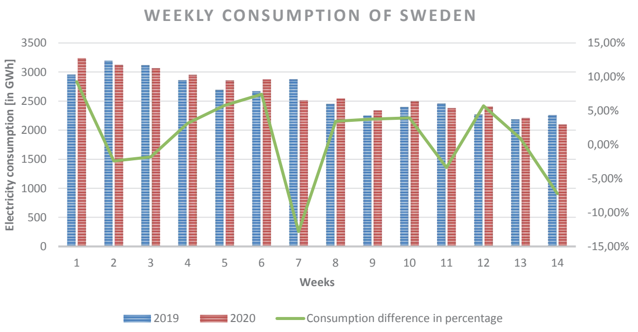
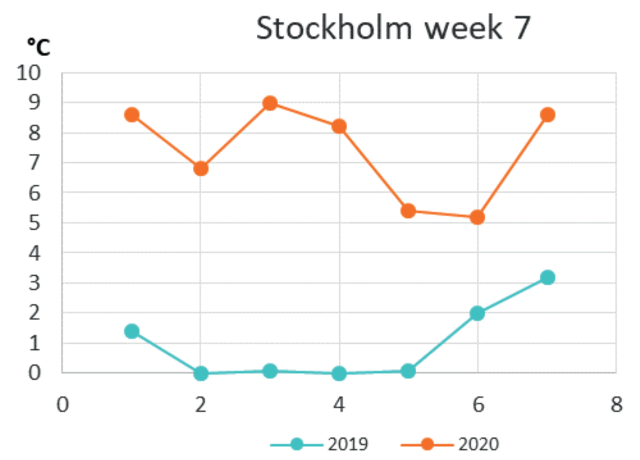


Figure 13 Weekly total load comparison of Sweden for 2019. and 2020

As seen in *Figure 13* the total load of Sweden was very similar in the majority of weeks for the years 2019 and in 2020. Undoubtedly, some differences in the total load are always going to exist due to a vast variety of external factors. However, when compared to other analyzed countries in this paper, there is no significant decline besides week 7. The main reason for this is the temperatures in Sweden in 2019 were extremely low in that period. Temperature data is presented in *Figure 14* where the average weekly temperature in 2019 was around 1 Celsius degree while the temperature in 2020 was around 8 Celsius degree which is more standard for that period of the year. Consequently, a total load of week 7 in 2019 was significantly higher than it would have been with regular temperatures. Thus, the conclusion is that the main reason for the decline was not COVID-19 pandemic but the extreme weather conditions in the previous year.



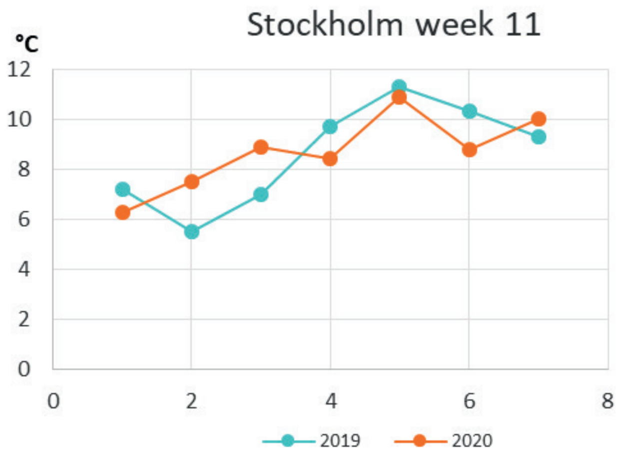


Figure 14 Temperature differences in week 7 and week 11 for Stockholm, Sweden.

Moreover, the total consumption has even increased in weeks almost two-thirds of the weeks.

With Sweden's different approach, it can be seen that the total load has not been as affected during the pandemic as much as it was in other analyzed countries. Furthermore, judging from the total load, their economy and industry have not suffered either.

4.RESULTS AND DISCUSSION

Analysis and data provided in chapter 3 indicate how sensitive a total load of a country is. A variety of external factors significantly affects the consumers' behavior, and thus, the electrical energy consumption. This paper focuses on the social dependent factor connected to the load – COVID-19 pandemic.

The most in-depth analysis was provided for the case of Croatia which is characterized by a very volatile total load. Although the weather-dependent factor is important and cannot be completely neglected, a detailed analysis of it was not provided for cases besides Croatia.

Initially, this paper was meant to include only Croatia and its region (surrounding countries). However, the case of Sweden is extremely interesting and useful for comparison and evaluation of what affects the load the most.

Results indicate that the COVID-19 pandemic caused significant load decrease throughout Europe which was foremost in the period of harsh working restrictions or lockdowns. Cases of Croatia, North Italy, Slovenia, Hungary, and Serbia all suffered a significant load decrease in comparison with previous years. The period of first COVID-19 appearance was similar and each of these countries started to introduce restrictive measures.

A graphical display of the load difference of the three most interesting cases (Croatia, North Italy and Sweden) is provided in *Figure 15*. The highest load decrease was present in North Italy (up to 35% decrease in comparison with previous years), while Croatia, Slovenia, Hungary, and Serbia all experienced load decrease up to 15%. This only further confirms how strong the industry of North Italy is in terms of the load consumption as it drastically decreased in the period of harsh restrictions and lockdown. On the other hand, it can also be seen that a load of North Italy also has started recover significantly faster than the load of any other analyzed country which once again supports the premise that the industry has a significant share in the total load. Nevertheless, it must not be forgotten the influ-

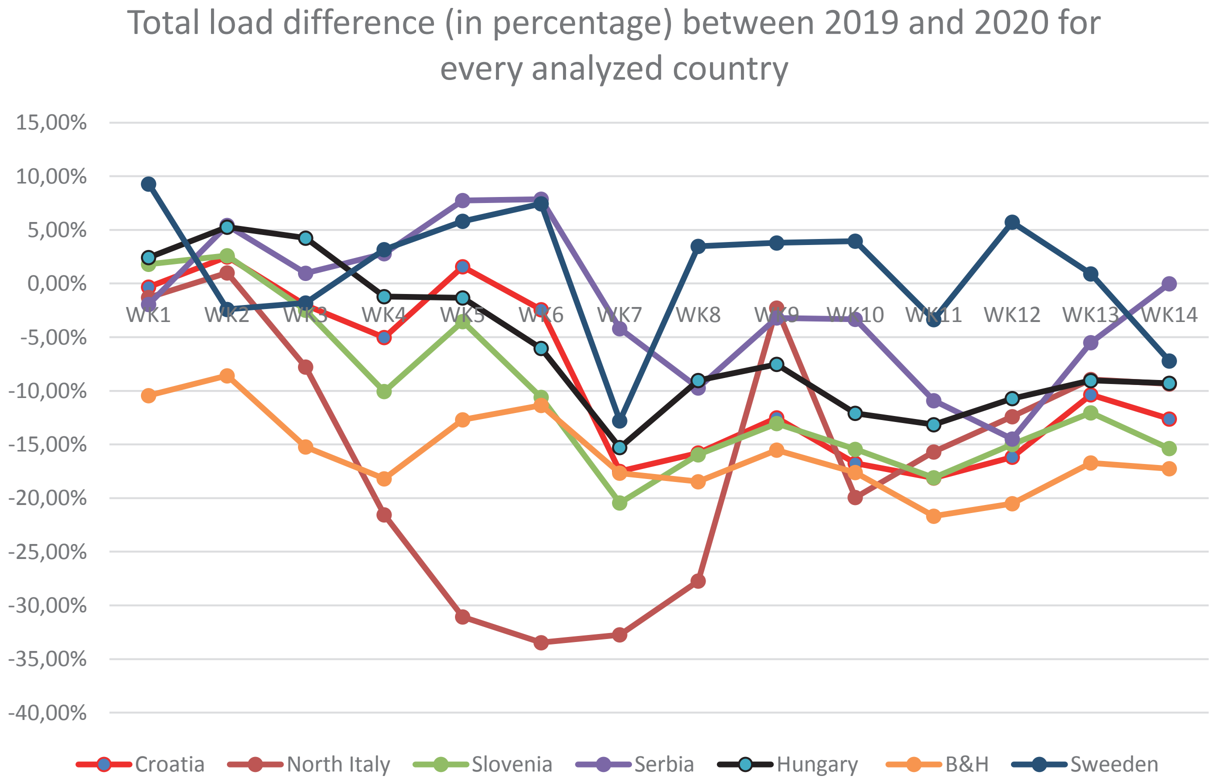


Figure 15 Comparison of total load differences between 2019. and 2020. for analyzed countries

ence of different dates and weeks 7 and 8 in 2019 and 2020 which partly contribute to such steep decline and rise while comparing those two years.

The rest of the countries in the region have also started to recover in terms of load, however, it is at a more moderate rate. For the case of Bosnia and Herzegovina it is rather difficult to provide the right judgement. The results of the analysis imply that they have not suffered a significant load decrease in comparison with previous year which can be somewhat expected due to their poor relative industry contribution in total load share and partly due to different holidays during weeks 7 and 8 comparing most of other countries.. However, there are also uncertainties regarding the data.

Contrary to all of the 6 cases, Sweden has taken a completely different approach and introduced nearly no strict restrictions or lockdowns. Their total load is slightly fluctuating, and even increasing in some weeks. They had the highest number of COVID-19 positive cases (per 10 000 residents) of all 7 analyzed countries, and their numbers have not been declining either. This indicates that it is not the number of COVID-19 positive cases that directly and significantly affect the load, but the governmental measures that affect it the most.

Generally speaking, it is expected that the higher number of positive cases would force countries in such restrictive measures and lockdowns which will result in a significant load decrease. However, the case of Sweden proved to us that there are exceptions and that some countries deploy different national strategies. Hence, it is of the utmost importance to keep in track with all national decisions regarding the restrictions, strategies, or lockdowns measures when planning a day-ahead (or further) load.

Moreover, the analysis shows that there are a lot of similarities between countries in the region, especially the ones with similar industrial development. It can be useful to observe their overall situation regarding the load trend, however, it is dangerous to blindly replicate their strategies as it was shown that load is extremely sensitive to all external factors.

5. CONCLUSIONS

This paper clearly shows the complexity of load forecasting and how the stochastic behavior of many influential factors can significantly contribute to the shape of realized load curve. Although there are usually many more examples of a weather influence on the load shape, this particular example teaches us all how social influence can also be important. Its significance is even more influential due to several reasons:

- Such events like sudden pandemic spread and adequate lockdown measures like in those several weeks usually cannot be foreseen in a year ahead, a quarter ahead, or even a month ahead load forecasting process and as a such could be marked as “Black Swan” effect [15].
- Nevertheless, such rare cases with significant impact, no matter how rare they are, must never be underestimated, especially if they have already occurred several times in the history [16] and when contemporary power systems, economic systems, and the whole globalized society are vulnerable [17], [18] to such outbreaks and potential lockdown measures
- Consequences of such measures jeopardize lives and livelihoods [19] of most of the electricity customers and if the statement that “*emotion = energy in motion*” [20] is applied to all customers in a portfolio or a country, an electricity demand response can be significant, sudden and sometimes even long-lasting, usually depending on the economic strength of the observed country [21] or customer’s portfolio
- Such sudden electricity demand response has directly affected electricity prices [22]in Italy, there is an ongoing pandemic of coronavirus disease 2019 (COVID-19 and the whole electricity sector [23] as well as the entire power sector [24].

Therefore, this case can be very useful for understanding the sensitivity of the load curve, its importance in vital technical and economic processes in the globalized world, and necessary adjustments to the “new normal” conditions [25] which might last for some time in the forthcoming future and affect most of the electricity customers.

REFERENCES

[1] R. Čivljak, A. Markotić, and I. Kuzman, “The third coronavirus epidemic in the third millennium: What’s next?,” *Croat. Med. J.*, vol. 61, no. 1, pp. 1–4, 2020, doi: 10.3325/cmj.2020.61.1.

[2] S. Dodig, I. Čepelak, and I. Pavić, “AGE AND SARS-COV2 INFECTION,” *Acta Med Croat*, vol. 74, pp. 135–144, 2020.

[3] H. Cho, Y. Goude, X. Brossat, and Q. Yao, “Modeling and forecasting daily electricity load curves: A hybrid approach,” *J. Am. Stat. Assoc.*, vol. 108, no. 501, pp. 7–21, 2013, doi: 10.1080/01621459.2012.722900.

[4] Wikipedia, “Electric energy consumption.” 2020, Accessed: Sep. 10, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Electric_energy_consumption,.

[5] Wikipedia, “Load profile.” 2020, [Online]. Available: https://en.wikipedia.org/wiki/Load_profile.

[6] HOPS, “Daily Load,” 2020. https://www.hops.hr/en/daily-load (accessed Sep. 10, 2020).

[7] Entsoe, “Load data,” 2020. https://transparency.entsoe.eu/ (accessed Sep. 10, 2020).

[8] Wikipedia, “Electrocardiography.” Accessed: Sep. 10, 2020. [Online]. Available: https://en.wikipedia.org/wiki/Electrocardiography#cite_note-4.

[9] E. Almeshaiei and H. Soltan, “A methodology for Electric Power Load Forecasting,” *Alexandria Eng. J.*, vol. 50, no. 2, pp. 137–144, 2011, doi: 10.1016/j.aej.2011.01.015.

[10] S. Ding, K. W. Hipel, and Y. guo Dang, “Forecasting China’s electricity consumption using a new grey prediction model,” *Energy*, vol. 149, pp. 314–328, 2018, doi: 10.1016/j.energy.2018.01.169.

[11] A. Khosravi, S. Nahavandi, D. Creighton, and D. Srinivasan, “Interval type-2 fuzzy logic systems for load forecasting: A comparative study,” *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1274–1282, 2012, doi: 10.1109/TPWRS.2011.2181981.

[12] A. Khan *et al.*, “Forecasting electricity consumption based on machine learning to improve performance: A case study for the organization of petroleum exporting countries (OPEC),” *Comput. Electr. Eng.*, vol. 86, 2020, doi: 10.1016/j.compeleceng.2020.106737.

[13] F. Kaytez, “A hybrid approach based on autoregressive integrated moving average and least-square support vector machine for long-term forecasting of net electricity consumption,” *Energy*, vol. 197, p. 117200, 2020, doi: 10.1016/j.energy.2020.117200.

[14] Vitec Software Group, “Model theory.” Vitec, 2014, [Online]. Available: http://viteceducandi.com/.

[15] Wikipedia, “Black swan theory.” 2020, [Online]. Available: https://en.wikipedia.org/wiki/Black_swan_theory.

[16] G. McGillivray, “Coronavirus is significant, but is it a true black swan event,” 2020. https://theconversation.com/coronavirus-is-significant-but-is-it-a-true-black-swan-event-136675 (accessed Sep. 20, 2020).

[17] B. Gates, “The next outbreak? We’re not ready,” 2015. https://www.youtube.com/watch?v=6Af6b_wyiwI (accessed Sep. 20, 2020).

[18] T. D. S. D. Show, “Bill Gates on Fighting Coronavirus.” https://www.youtube.com/watch?v=iyFT8qXcOrM.

[19] U. N. D. Programme, “Socio-economic impact of COVID-19.” https://www.undp.org/content/undp/en/home/coronavirus/socio-economic-impact-of-covid-19.html.

[20] authenticityassociates, “Emotions Are Energy : The bodymind connection and e-motion.” https://www.authenticityassociates.com/emotions-are-energy/.

[21] UNIDO, “Coronavirus: the economic impact,” 2020. https://www.unido.org/stories/coronavirus-economic-impact-10-july-2020.

[22] E. Ghiani, M. Galici, M. Mureddu, and F. Pilo, “Impact on Electricity Consumption and Market Pricing of Energy and Ancillary Services during Pandemic of COVID-19 in Italy,” *Energies*, vol. 13, no. 13, p. 3357, 2020, doi: 10.3390/en13133357.

[23] IEA, “Covid-19 impact on electricity,” 2020. [Online]. Available: https://www.iea.org/reports/covid-19-impact-on-electricity.

[24] T. Bakovic, “The Impact of COVID-19 on the Power Sector,” 2020.

[25] WHO, “COVID-19: ‘new normal,’” 2020. https://www.who.int/westernpacific/emergencies/covid-19/information/covid-19-new-normal.

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Dynamic Stability Enhancement Through the Application of Stabilizers of Electromechanical Oscillations

SUMMARY

Power system dynamic stability is one of key issues system engineers face. Oscillations that regularly occur in the system, limit the transmission capability of the network. The need to study the stability of power systems has been increasingly growing along with the development of power systems and their grouping into large interconnections. The focus of this paper is determining the dynamic stability of a synchronous generator, and thus the power system, by applying the general theory of stability of dynamic systems. Furthermore, the procedure for the initial adjustment of the parameters of a conventional (IEEE3 type PSS1A) stabilizer of electromechanical oscillations is briefly described based on the frequency response analysis of a linear generator model also known as the Heffron-Phillips generator model.

KEY WORDS

dynamic stability, electromechanical oscillations, stabilizers

1. INTRODUCTION

Power system dynamic stability is one of key issues system engineers face as the electricity supply chain is inherently non-linear, interconnected and can be affected by various disturbances [1]. Oscillations that regularly occur in the system, limit the transmission capability of the network. Due to the continuous increase in the integration of renewable energy sources (RES), power systems nowadays operate close to the limits of dynamic stability. The notion of dynamic stability of the power system is related to the problem of low-frequency (in the order of 0,2 - 3 Hz) electromechanical oscillations that occur due to small operating disturbances in the system and arise from the physical properties of synchronous generators [2]. Insufficiently damped electromechanical oscillations, or more precisely, power fluctuations, limit the transmission of electricity. If these oscillations are not damped at all, the protection system is activated and the generator is separated from the network. The failure of one generator can often cause considerable disturbances to the remaining generators in the system and the consequent loss of synchronism can lead to the breakdown of the entire system. In worst-case scenario, this can result in the breakdown of the entire power system. Complex mathematical problems regarding the operation of a power system are solved by different heuristic algorithms. Perhaps one of the most popular solutions in this field is the application of particle swarm optimization (PSO) [3][4][5][6][7][8][9]. However, methods such as simulated annealing (SA)[10], differential evolution (DE)[11], artificial bee colony (ABC)[12][13][14], Tabu search (TS)[15] and the genetic algorithm (GA)[16][17] are also being used. These algorithms were developed by observing the social behavior of living creatures and eventually became models applied in optimization methods. Efficient damping of electromechanical oscillations can be achieved by implementing electromechanical oscillation stabilizers in digital synchronous generator excitation control systems. Power system stabilizers (PSSs) are incorporated into the system in order to provide the damping torque necessary to suppress oscillations and are used to improve system reliability [18]. The adoption of PSSs started along with the very development of the power system [3] and has been explored by numerous research studies [19]. These studies analyzed various techniques for tuning PSS parameters. Some focused on robust control [20][21][22], others on optimization methods [23]. In more recent times, modules of artificial intelligence (AI) also found their way to system stability issues through the application of fuzzy [24][25] and neuro-fuzzy logic [26][27]. The majority of these approaches focus on angular speed deviation ($\Delta\omega$). Some techniques that use this approach suffer from computational complexity, require a significant amount of memory or are non-adaptive to changing operating conditions and different system configurations [3].

The focus of this paper is determining the dynamic stability of a synchronous generator, and thus the power system, by applying the general theory of stability of dynamic systems. Furthermore, the procedure for the initial adjustment of the parameters of a conventional (IEEE3 type PSS1A) stabilizer of electromechanical oscillations is briefly described based on the frequency response analysis of a linear generator model also known as the Heffron-Phillips generator model. The paper is organized as follows. After the introduction and a literature review of the subject matter in section 1, section 2 describes the dynamic stability of a synchronous generator. In section 3, the possibilities for improving the dynamic stability using electromechanical oscillation stabilizers are presented and elaborated. Section 4 concludes the paper.

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2. DYNAMIC STABILITY OF A SYNCHRONOUS GENERATOR

The need to study the stability of power systems has been increasingly growing along with the development of power systems and their grouping into large interconnections. Today, as we witness a surge of renewable energy sources (RES), system stability issues seem to be more important than ever. Power system stability is defined as »the ability of a system to remain in its initial state after a disturbance or to assume a new equilibrium state, given that the system state variables remain within the limits that ensure system integrity« [20]. Depending on the observed physical quantity, the stability of the power system can be divided into three types: angular, frequency and voltage. Angular stability refers to the ability of synchronous generators in the power system to remain in synchrony after a disturbance. Depending on the magnitude of the disturbance, it can be divided into (1) stability during large disturbances (transient stability) and (2) stability during small disturbances (dynamic stability). Although large disturbances such as short circuits and outages of large generating units posed as the greatest threat to the power system in recent decades, more and more attention is paid to the system's behavior during small disturbances that result in low-frequency electromechanical oscillations, i.e. oscillations of characteristic synchronous generator variables.

2.1.ELECTROMECHANICAL OSCILLATIONS EXAMPLE

The occurrence of electromechanical oscillations is easiest to understand on the example of changing the operating point of the generator shown in Figure 1.

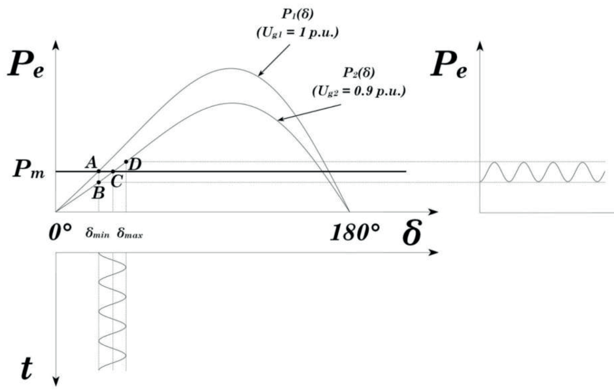

Figure 1 Occurrence of electromechanical oscillations

By abruptly changing the voltage reference value U_g with 1 p.u. at 0,9 p.u., the generator switches from characteristic $P_1(\delta)$ to characteristic $P_2(\delta)$. Due to the inertia of the rotor, load angle (δ) cannot be changed immediately, so the output electric power (P_e) falls to a value corresponding to point B. Since at point B the input mechanical power (P_m) is greater than the electrical one, the acceleration force accelerates the machine which causes the electric power and the load angle to increase. At point C, the electrical and mechanical power are of equal value ($P_e = P_m$), but the rotational speed is higher than synchronous ($\omega > \omega_s$) which is why the generator will not steady in the equilibrium position, but will rather continue to increase the output electrical power. As the electrical power increases, the (negative) amount of acceleration power increases. At point D, the machine has a synchronous speed ($\omega = \omega_s$) and a maximum negative acceleration, which is why it starts to slow down and the load angle decreases. At point C, the electrical and mechanical power are equal ($P_e = P_m$), but the speed is less than synchronous ($\omega < \omega_s$), so the generator will not steady in the equilibrium position, but will accelerate to point B, reducing the output electrical power. The described process then starts from the beginning and over time it is attenuated after which the generator assumes an equilibrium state at point D ($P_e = P_m$).

2.2. DYNAMIC STABILITY ANALYSIS OF A SYNCHRONOUS GENERATOR

The equation of moment balance on the axis of a synchronous machine in the generator mode is expressed by (2.1) [28]:

$$J\frac{d\omega_m}{dt} = M_m - M_e - D_m\Delta\omega_m \tag{2.1}$$

Where: J – sum of inertia moments of the drive machine and synchronous generator [kgm^2], ω_m – mechanical speed of rotor rotation expressed in mechanical work [rad/s], M_m – mechanical torque of the propulsion machine [Nm], M_e – electromagnetic moment of synchronous generator [Nm], D_m – coefficient that considers the influence of the damping winding during transients [Nms] and $\Delta\omega_m$ – change in mechanical speed of rotor rotation [rad/s]. The mechanical speed of rotation of the rotor can be expressed as:

$$\omega_m = \omega_{sm} + \Delta\omega_m = \omega_{sm} + \frac{d\delta_m}{dt} \tag{2.2}$$

Where: ω_{sm} – synchronous speed [rad/s] and δ_m – rotor angle of the synchronous generator [rad]. By including expression (2.2) in expression (2.1) the following equation is obtained:

$$J\frac{d}{dt}\left(\omega_{sm} + \frac{d\delta_m}{dt}\right) = M_m - M_e - D_m\Delta\omega_m \tag{2.3}$$

Since the synchronous speed is constant, expression (2.3) can be written as:

$$J\frac{d^2\delta_m}{dt^2} = M_m - M_e - D_m\frac{d\delta_m}{dt} \tag{2.4}$$

If the left and right equations in expression (2.4) are multiplied by the synchronous rotational speed ω_{sm}, the following equation is obtained:

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} = M_m\omega_{sm} - M_e\omega_{sm} - D_m\omega_{sm}\frac{d\delta_m}{dt} \tag{2.5}$$

Furthermore, considering the fact that the product of the torque and the speed of rotation are equal to the force, expression (2.5) can be written as:

$$J\omega_{sm}\frac{d^2\delta_m}{dt^2} = P_m - P_e - D_m\omega_{sm}\frac{d\delta_m}{dt} \tag{2.6}$$

The product $J\omega_{sm}$ in expression (2.6) is called the angular momentum and is denoted by M. However, the amount of angular momentum can differ significantly from one machine to another because it primarily depends on the size of the machine itself, so it is more practical to express the angular momentum through inertia, H. Machines of the same type (e.g. steam turbo-generators) have similar inertia constant values regardless of their size [20]. The inertia constant is defined by the expression:

$$H = \frac{W_k}{S_n} = \frac{\frac{1}{2}J\omega_{sm}^2}{S_n} \tag{2.7}$$

Where: H – inertia constant [s], W_k – kinetic energy of the rotor at synchronous speed [J] and S_n – nominal apparent power of the synchronous generator [VA]. The relationship between the angular momentum and the inertia constant is defined by the expression:

$$M = J\omega_{sm} = \frac{2HS_n}{\omega_{sm}} \tag{2.8}$$

By including expression (2.8) in expression (2.6) the following equation is obtained:

$$\frac{2H}{\omega_{sm}} S_n \frac{d^2\delta_m}{dt^2} = P_m - P_e - D_m\omega_{sm}\frac{d\delta_m}{dt} \tag{2.9}$$

It is often desirable to express the synchronous speed in electrical rad/s and the angle of the rotor in electrical work, because then the angle of the rotor corresponds to the load angle of the generator. Therefore, expression (2.9) can be written as:

$$\frac{2H}{\frac{\omega_s}{p}} S_n \frac{d^2\left(\frac{\delta}{p}\right)}{dt^2} = P_m - P_e - D_m\frac{\omega_s}{p}\frac{d\delta}{dt} \tag{2.10}$$

or abbreviated as:

$$\frac{2H}{\omega_s} S_n \frac{d^2\delta}{dt^2} = P_m - P_e - D\frac{d\delta}{dt} \tag{2.11}$$

Where: ω_s – synchronous speed expressed in electrical [rad/s], p – number of pole pairs of a synchronous generator, δ – load angle of the synchronous generator expressed in electrical [rad] and – o general damping coefficient [Nm]. If left and right sides of the equation in expression (2.11) are divided by the nominal apparent power of the generator, the following expression is obtained:

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e - D\frac{d\delta}{dt} \tag{2.12}$$

Expression (2.12), in which all quantities are expressed in unit values (hereinafter p.u.), is called the oscillation equation and represents the basis for the analysis of transient and dynamic stability. The oscillation equation is a nonlinear differential equation of the second order, so it can be written in the form of a system of two differential equations of the first order:

$$\begin{aligned} 2H\frac{d\Delta\omega}{dt} &= P_m - P_e - D\Delta\omega \\ \frac{d\delta}{dt} &= \omega_s\Delta\omega \end{aligned} \tag{2.13}$$

2.3. LINEARIZATION OF THE OSCILLATION EQUATION

As stated earlier, the oscillation equation is a nonlinear differential equation. The reason for this is the highly nonlinear dependence of the output electric power on the load angle, which is given by the expression:

$$P_e = \frac{E_qU_g}{x_d}\sin\delta + \frac{U_g^2}{2}\frac{x_d - x_q}{x_dx_q}\sin(2\delta) \tag{2.14}$$

That is, in the case of a machine with a round rotor (for which), by the expression:

$$P_e = \frac{E_qU_g}{x_d}\sin\delta \tag{2.15}$$

Where: E_q – induced electromotive force in the armature of the synchronous generator [p.u.], U_g – voltage at the terminals of the synchronous generator [p.u.], x_d – actance of the synchronous generator in the longitudinal axis [p.u.] and x_q – reactance of the synchronous generator in the transverse axis [p.u.]. For the purposes of dynamic stability analysis, it's possible to linearize the output characteristic of the synchronous generator, i.e. to approximate it with the tangent at the operating point (P_{e0}, δ_0) as shown in Figure 2.

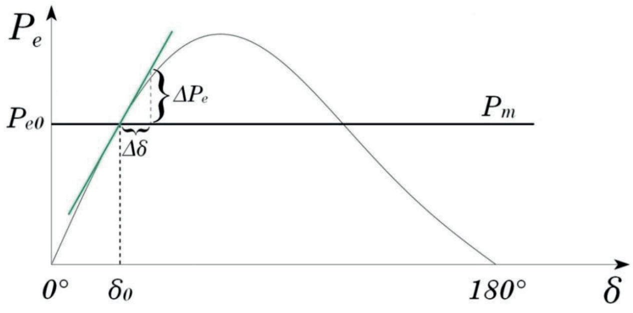

Figure 2 Linearization of the output characteristic of a synchronous generator

By linearizing the output characteristic of the synchronous generator in the vicinity of the operating point (P_{e0}, δ_0), the expression is obtained:

$$\Delta P_e = \left.\frac{\partial P_e}{\partial\delta}\right|_{\delta=\delta_0}\Delta\delta \tag{2.16}$$

In addition, the following expression is obtained:

$$\Delta P_e = \left[\frac{E_qU_g}{x_d}\cos\delta_0 + U_g^2\frac{x_d - x_q}{x_dx_q}\cos(2\delta_0)\right]\Delta\delta \tag{2.17}$$

Where: ΔP_e – change in electrical power of the synchronous generator [p.u.], δ_0 – he amount of the load angle of the synchronous generator at the operating point where the linearization was performed [rad] and $\Delta\delta$ – change of load angle of synchronous generator [rad]. The term assigned to the change of the load angle in expression (2.17) is called the coefficient of power (moment) of synchronization and is denoted by k_{sP}. Therefore, expression (2.17) can be written as:

$$\Delta P_e = k_{sP}\Delta\delta \tag{2.18}$$

It was said earlier that the oscillation equation can be written in the form of a system (2.13). In the case of small disturbances where there are small deviations of the load angle during the first oscillation, the system (2.13) can be written as:

$$\begin{aligned} 2H\frac{d\Delta\omega}{dt} &= (P_{m0} + \Delta P_m) - (P_{e0} + \Delta P_e) - D\Delta\omega \\ \frac{d}{dt}(\delta_0 + \Delta\delta) &= \omega_s\Delta\omega \end{aligned} \tag{2.19}$$

Where: P_{m0} – input mechanical power at the initial operating point [p.u.], ΔP_m – change of input mechanical power [p.u.], P_{e0} – electrical power of the synchronous generator at the initial operating point [p.u.], ΔP_e – change of electric power of the synchronous generator [p.u.], δ_0 –

load angle of the synchronous generator at the initial operating point [rad] and Δδ – change of load angle of the synchronous generator [rad]. Since before the disturbance, the synchronous generator was in an equilibrium state in which $P_e = P_m$ (2.19), the following expression is obtained:

$$2H\frac{d\Delta\omega}{dt} = \Delta P_m - \Delta P_e - D\Delta\omega \qquad \frac{d\Delta\delta}{dt} = \omega_s \Delta\omega \tag{2.20}$$

That is:

$$2H\frac{d\Delta\omega}{dt} = \Delta P_m - k_{sP}\Delta\delta - D\Delta\omega \qquad \frac{d\Delta\delta}{dt} = \omega_s \Delta\omega \tag{2.21}$$

System (2.21) represents the oscillation equation which, for the purposes of analyzing the dynamic stability of a synchronous generator, is linearized in the vicinity of the operating point in which the generator was located before the disturbance, i.e. the transient. In Figure 3, the basic model of the linearized oscillation equation is presented.

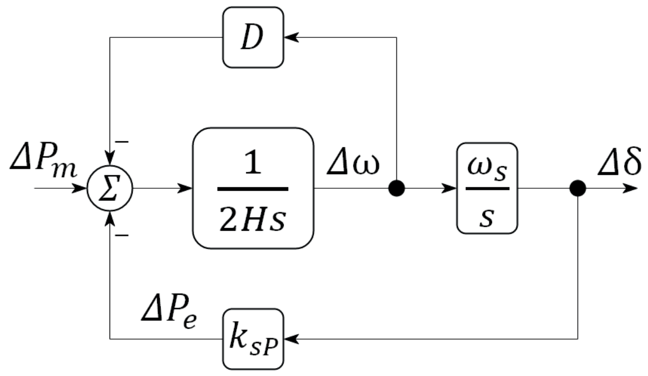

Figure 3 Basic model of the linearized oscillation equation

2.4. MODEL OF THE OSCILLATION EQUATION IN THE STATE SPACE

The analysis of the stability of complex dynamic systems, such as the electric power system, starts from the system model in state space. The model of a dynamic system in state space is described by a system of equations:

$$\dot{x} = Ax + Bu \qquad y = Cx \tag{2.22}$$

Where: – derivation vector of system state variables, x – vector of system state variables, u – vector of system input variables, y – vector of system output variables, A – system matrix, B – management distribution matrix and C – output matrix. The linearized oscillation equation of the synchronous generator written in the form of system (2.21) can be represented in the state space by a system of matrix equations:

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix} = \begin{bmatrix}-\frac{D}{2H} & -\frac{k_{sP}}{2H}\\ \omega_s & 0\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix} + \begin{bmatrix}\frac{1}{2H} & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta P_m\\ 0\end{bmatrix} \qquad \begin{bmatrix}\Delta\delta\\ 0\end{bmatrix} = \begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix} \tag{2.23}$$

Where the system matrix has a special significance in the stability analysis:

$$A = \begin{bmatrix}-\frac{D}{2H} & -\frac{k_{sP}}{2H}\\ \omega_s & 0\end{bmatrix} \tag{2.24}$$

Namely, the characteristic polynomial of system *A(λ)* according to [28] is obtained, with the knowledge of the matrix of system *A*, according to the expression:

$$A(\lambda) = \det\,(A - \lambda I) \tag{2.25}$$

Where: *I* denotes the unit matrix. By further elaboration of the expression (2.25) we get:

$$A(\lambda) = \lambda^2 + \frac{D}{2H}\lambda + \frac{\omega_s k_{sP}}{2H} \tag{2.26}$$

Furthermore, by solving the equation *A(λ)* = 0, the so-called eigenvalues of the system are obtained. Since this equation is a characterized by a second-order polynomial, two eigenvalues are obtained:

$$\lambda_{1,2} = -\frac{D}{4H} \pm \sqrt{\frac{D^2}{16H^2} - \frac{\omega_s k_{sP}}{2H}} \tag{2.27}$$

As in reality for a synchronous generator operating in an electric power system it is true that in expression (2.27) the subtractor under the root is larger than the subtractor, the eigenvalues are conjugate complex quantities. Conjugate complex pairs of eigenvalues are generally indicators of the inherent oscillatory behavior of the system [29]. Therefore, a synchronous generator in a power system can be considered an oscillating system in which, during transients, there is an interaction or exchange of energy between the rotor of the unit and the rest of the power system.

2.5. INFLUENCE OF EIGENVALUE CHARACTER ON DYNAMIC STABILITY

Eigenvalues generally take the form of:

$$\lambda_i = \sigma_i + j\omega_i \ ; \ i = 1, 2, \dots, n \tag{2.28}$$

Real part of the eigenvalue represents the attenuation, while the imaginary part represents the oscillation frequency of the system. A dynamic system is stable if the real parts of all its eigenvalues are less than zero [29]:

$$Re\{\lambda_i\} < 0 \ ; \ \forall i \in \mathbb{N} \tag{2.29}$$

If the above is applied to a synchronous generator in a power system whose typical values are given by expression (2.27), it is obvious that the dynamic stability of the generator is conditioned by a positive value of the damping coefficient D, or the stability of the positive damping moment. Interestingly, the synchronous generator begins to lose stability only at the moment of changing the sign of the real part of the eigenvalues. Therefore, the points to which it applies are the following:

$$Re\{\lambda_i\} = 0 \; ; \; \forall i \in \mathbb{N} \tag{2.30}$$

Together, these numbers form the limit of dynamic stability. In Figures 4-6, possible responses of the synchronous generator depending on the character of the eigenvalues are shown.

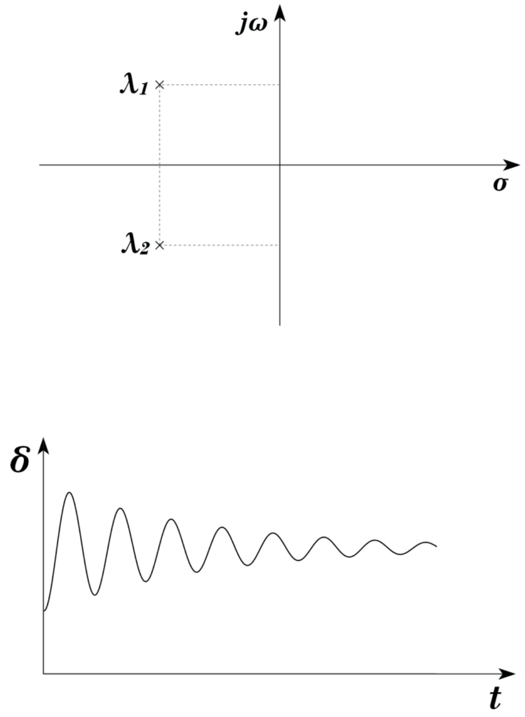

Figure 4 Re{λ1,2} < 0, The synchronous generator is stable

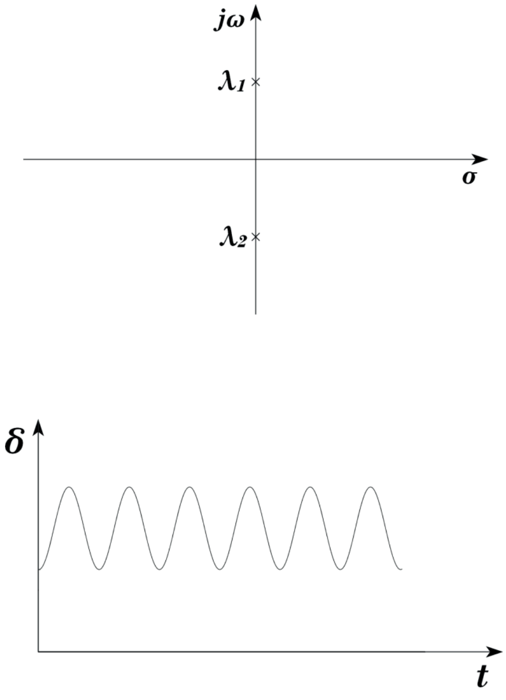

Figure 5 Re{λ1,2} = 0, The synchronous generator is at its stability limit

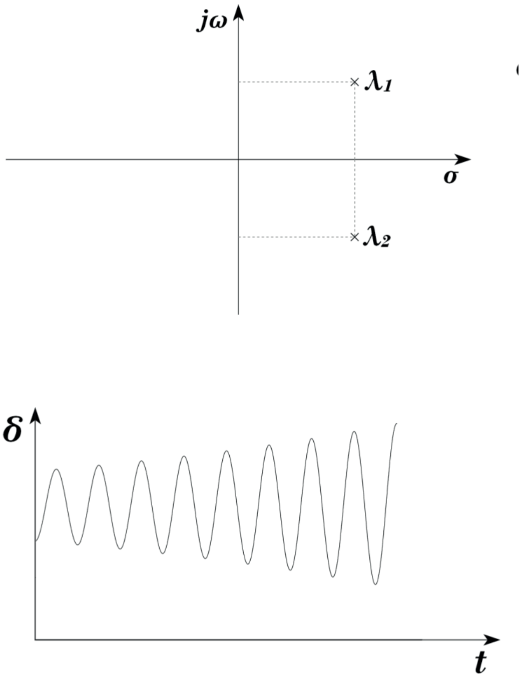

Figure 6 Re{λ1,2} > 0, The synchronous generator is oscillatory unstable

3. IMPROVING DYNAMIC STABILITY THROUGH THE USE OF ELECTROMECHANICAL OSCILLATION STABILIZERS

In the past, the problem of damping electromechanical oscillations was solved by installing a larger number of damping windings in the pole shoes or the rotor body, depending on the type of machine. In 1969, de Mello and Concordia proposed the introduction of an additional control circuit in the excitation systems of synchronous generators with the aim of damping electromechanical oscillations [30]. This additional control circuit was later called the Power System Stabilizer. The role of the stabilizer is to recognize the occurrence of electromechanical oscillations and acting through an automatic voltage regulator in an artificial way to create an additional component of damping torque on the rotor which is in phase with the change of speed. Nowadays, the stabilizer of electromechanical oscillations is an indispensable part of digital excitation control systems [31].

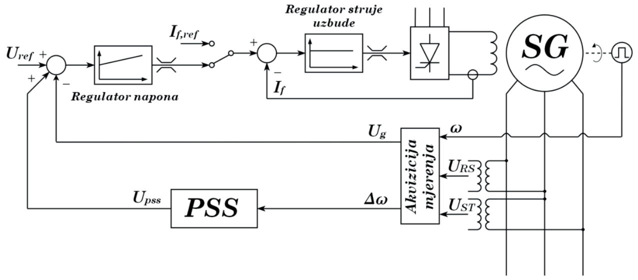

Figure 7 Classical excitation control circuit structure with PSS

3.1. STRUCTURE OF A CONVENTIONAL STABILIZER OF ELECTROMECHANICAL OSCILLATIONS

From the control theory point of view, stabilizers of electromechanical oscillations are linear elements. The structure of a conventional (IEEE type PSS1A) stabilizer is described by a transfer function:

$$G_{pss}(s) = K_{pss}\frac{T_f s}{1+T_f s}\frac{1+T_1 s}{1+T_2 s}\frac{1+T_3 s}{1+T_4 s} \qquad (3.1)$$

From the transfer function of the stabilizer it can be seen that it consists of: K_{pss} high-pass filter, time constant T_f and phase compensators. Among the mentioned members of the transfer function of the stabilizer, phase compensators play a crucial role. This is due to the fact that a necessary condition for the correct operation of the stabilizer is that the artificially created damping torque component is in phase with the change of speed. Therefore, it is necessary to compensate for the phase delay introduced by other components in the excitation system (e.g. PI voltage regulator). The mentioned phase delay compensation is achieved by phase compensators. In addition to phase compensators, an important role is played by a high-pass filter that must remove DC signals in order for the stabilizer to operate only during transient states of the system.

3.2. HEFFRON-PHILLIPS SYNCHRONOUS GENERATOR MODEL

The initial adjustment of the parameters of the electromechanical oscillation stabilizer is performed before commissioning and based on the analysis of frequency responses of the linear model of the synchronous generator (also known as the Heffron-Phillips model of the generator). The mentioned model is extremely precise in the environment of a certain operating point for which it was made [32]. In addition, it requires knowing only basic parameters of the synchronous generator which makes it suitable for synthesis of stabilizers and control circuits in general. The Heffron-Phillips generator model is shown in Figure 8.

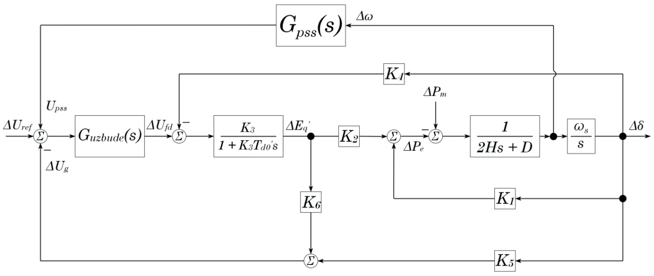

Figure 8 Heffron-Phillips model of the synchronous generator

3.3. DETERMINATION OF THE TIME CONSTANT OF A HIGH-PASS FILTER

It is not necessary to explicitly determine the cut-off frequency, i.e. the time constant of the high-pass filter, as the values of the filter time constant between 1 and 20 seconds fully meet the set requirements. The amplitude-frequency characteristic of the high-pass filter is shown in Figure 9.

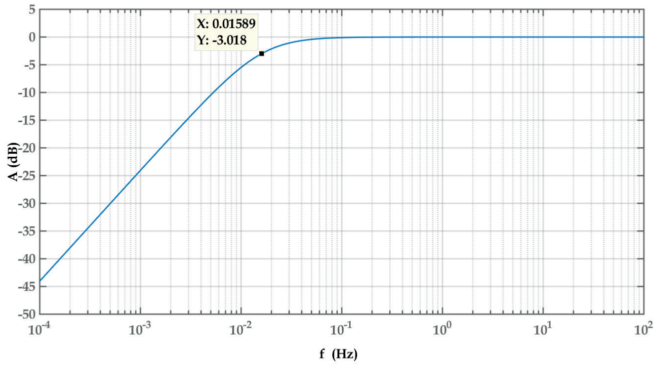

Figure 9 Amplitude-frequency characteristic of high-pass filter

3.4. DETERMINATION OF TIME CONSTANTS OF BLOCKS FOR PHASE COMPENSATION

As mentioned earlier, the elements in the excitation system introduce a certain phase delay into the stabilizing signal generated by the electromechanical oscillation stabilizer. In Figure 10, the phase-frequency characteristic of an excitation system is shown. At the frequency of electromechanical oscillations, which in this example is 1,94 Hz, the excitation system introduces a phase delay in the amount of 126,5°.

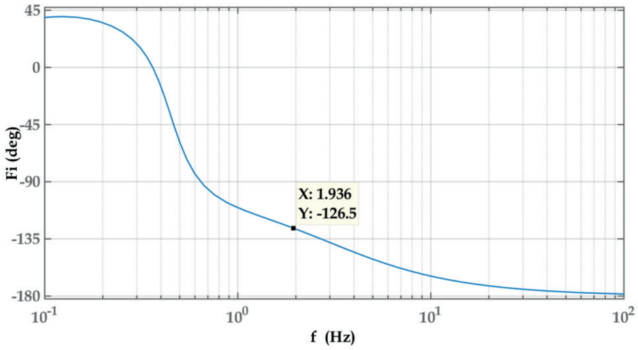

Figure 10 Phase-frequency characteristic of the excitation system before compensation

With correctly set phase compensation blocks, the phase delay at the frequency of electromechanical oscillations is almost 0 °, which allows the creation of »pure« damping torque on the rotor, which is in phase with the change of speed. The phase-frequency characteristic of the excitation system after compensation is shown in Figure 11.

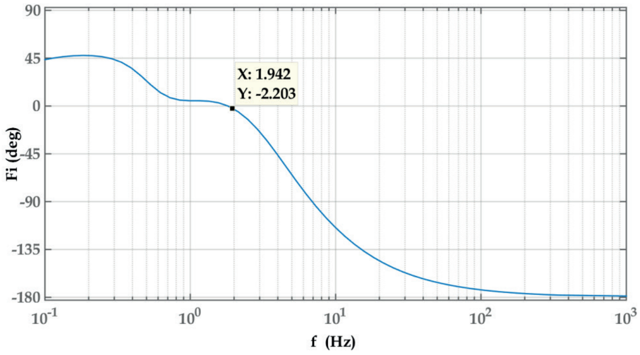

Figure 11 Phase-frequency characteristic of the excitation system after compensation

3.5. SIMULATION OF SYNCHRONOUS GENERATOR WITH AND WITHOUT AN ELECTROMECHANICAL OSCILLATION STABILIZER

In Figures 12-15, the responses of the characteristic variables of the synchronous generator during the abrupt change of the reference value of the active power from 0,5 p.u. to 0,6 p.u. and for cases with the electromechanical oscillation stabilizer turned off and on are shown.

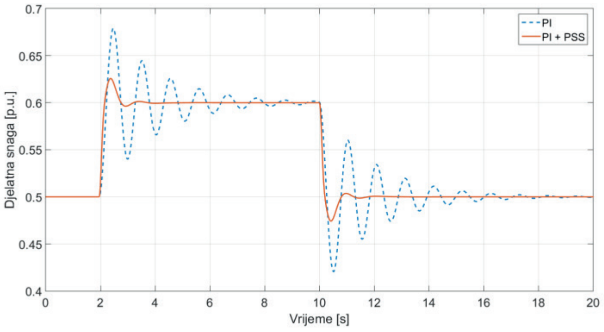

Figure 12 Active power response (Pe)

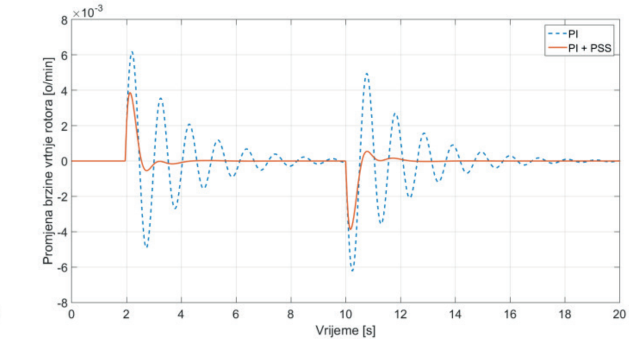

Figure 14 Load angle change (Δn)

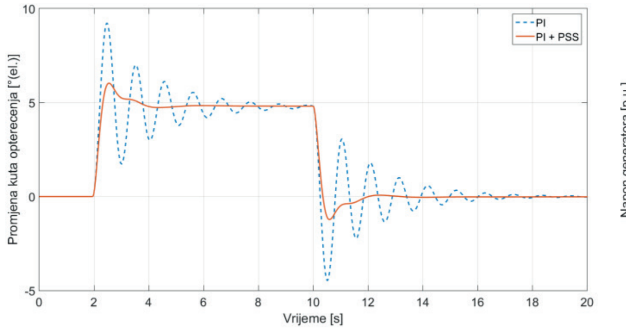

Figure 13 Change of rotation speed (Δδ)

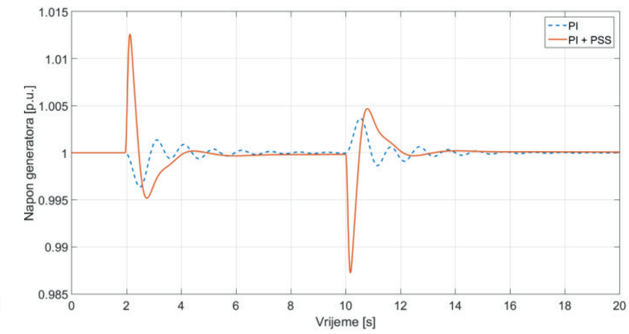

Figure 15 Voltage response (U_g)

4. CONCLUSION

The reliability of power supply is of paramount importance not only for the economy, but for the wellbeing of the entire society. The power system consists of countless elements that deliver electric energy in real time. Due to its gravity and size, it's vulnerable to a number of disturbances during its operation. In recent years, this problem is even more emphasized due to the increasing share of renewables. This paper deals with the problem of dynamic stability of synchronous generators in a power system. The literature review presented in the introduction segment revealed the existence of numerous techniques being applied for enhancing the dynamic stability of the power system. The notion of dynamic stability is related to the problem of low-frequency electromechanical oscillations that occur due to small driving disturbances and arise from the physical properties of synchronous generators. Namely, the eigenvalues of a synchronous generator occur in conjugate complex pairs, which indicate the oscillatory nature of the synchronous generator during network operation. The character of the eigenvalues determines the behavior of the synchronous generator after an operational disturbance. It is found that a synchronous generator is stable if the real parts of the eigenvalues are less than zero and that the generator begins to lose stability at the moment of a transition of eigenvalues from the left to the right side of the complex plane.

REFERENCES

[1] Butti, D., Mangipudib, S.K., Rayapudi, S.R. Design of robust modified power system stabilizer for dynamic stabilityimprovement using Particle Swarm Optimization technique. Ain Shams Engineering Journal 10, 769-783, 2019

[2] Dysko, A., Leithead, W.E., O'Reilly, J. Enhanced Power System Stability by Coordinated PSS Design. IEEE Transactions on Power Systems 25, 413-422, 2009

[3] Chatterjee, S., Ghosal, P., Mukherjee, V. Chaotic ant swarm optimization for fuzzy-based turning of power system stabilizer. International Journal of Electrical Power & Energy Systems 33, 657–672, 2011

[4] Shayeghi, H., Shayanfar, H.A., Safari, A., Aghmasheh, R.A. Robust PSSs design using PSO in a multi-machine environment. Energy Conversion Management 51, 696–702, 2010

[5] Mostafa, H.E., El-Sharkawy, M.A., Enary, A.A., Yassin, K. Design and allocation of power system stabilizers using the practice swarm optimization technique for an interconnected power system. International Journal of Electric Power Energy Systems 34, 57–65, 2012

[6] Olivas, F., Valdez, F., Castillo, O., Melin, P. Dynamic parameter adaptation in particle swarm optimization using interval type-2 fuzzy logic. Soft Computing 20(3), 1057–70, 2016

[7] Martínez-Soto, R., Castillo, O., Aguilar, L.T., Rodriguez, A. A hybrid optimization method with PSO and GA to automatically design - Type-1 and Type-2 fuzzy logic controllers. International Journal of Machine Learning and Cybernetics 6(2), 175–96, 2015

[8] Olivas, F., Amador-Angulo, L., Perez, J., Caraveom C., Valdez, F., Castillo, O. Comparative study of type-2 fuzzy particle swarm, bee colony and bat algorithms in optimization of fuzzy controllers. Algorithms 10(3), 101, 2017

[9] Valdez, F., Vazquez, J.C., Melin, P., Castillo, O. Comparative study of the use of fuzzy logic in improving particle swarm optimization variants for mathematical functions using co-evolution. Applied Soft Computing 52, 1070–1083, 2017

[10] Abido, M.A., Robust design of multi-machine power system stabilizers using simulated annealing. IEEE Transactions on Energy Conversion 15(3), 297–304, 2000

[11] Wang, Z., Chung, C.Y., Wong, K.P., Tse, C.T. Robust power system stabiliser design under multi-operating conditions using differential evolution. IET Generation, Transmission & Distribution 2(5), 690, 2008

[12] Karaboga, D., Basturk, B. A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. Journal of Global Optimization 39(3), 459–71, 2007

[13] Karaboga, D., Basturk, B. On the performance of artificial bee colony (ABC) algorithm. Applied Soft Computing 8, 687–97, 2008

[14] Amador-Angulo, L., Castillo, O. A new fuzzy bee colony optimization with dynamic adaptation of parameters using interval type-2 fuzzy logic for tuning fuzzy controllers. Soft Computing 22(2), 571–94, 2018

[15] Abido, M.A. A novel approach to conventional power system stabilizer design using tabu search. Int J Electric Power Energy Systems 21(6), 443–54, 1999

[16] Abdel-Magid, Y.L., Abido, M.A., Al-Baiyt ,S., Mantawy A.H. Simultaneous stabilization of multi-machine power systems via genetic algorithms. IEEE Transactions on Power Systems 14, 1428–39, 1999

[17] Kim, D. Hybrid GA-BF based Intelligent PID controller tuning for AVR system. Applied Soft Computing 11(1), 11–22, 2011

[18] Schleif, F., Hunkins, H., Martin, G., Hattan, E. Excitation control to improve power line stability. IEEE Transactions on Power Apparatus and Systems PAS-87, 1426–34, 1968

[19] Kundur, P »Power System Stability and Control«, McGraw-Hill, New York, SAD, 1994

[20] Rajeev, G. Robust non –dynamic multi –rate rate output feedback technique based power system stabilizer Ph.D Thesis. IIT Bombay; 2004

[21] Sambariya, D.K., Rajendra, P. Design of PSS for SMIB systems using robust fast output sampling feedback technique. 978-1-4673-0/12$31.00. IEEE; 2012

[22] Safie, S.I., Majid, S., Hasimah, A.R., Wahab, A., Yusri, M.H. Siding Mode control power system stabilizer (PSS) for Single Machine Infinite Bus (SMIB). No. PEcon 08, 122–126, 2008

[23] Magazoub Muawia, A., Saad Nordan, B., Ibrahim Rosasdiazli, B. Power system stabilizer for single machine infinite bus based on optimal control methods. In: 2014 IEEE 8th international power system engineering and optimization conference (PEOCON' 2014), Langkawi, The Jewel of Keah, Malaysia. 24–25 March 2014

[24] Ghoshal, S.P., Chaterjee, A., Mukherjee, V. Bio-inspired fuzzy logic based turning of power system stabilizer. Expert Systems with Applications 36, 9281–9292, 2009

[25] El-Zonkoly AM, Khalil AA, Ahmid NM. Optimal turning of lead-lag and fuzzy logic power system stabilizers using practical swarm optimization. Expert Systems with Applications 36, 2097–106, 2009

[26] Chaturvedi DK, Malik OP. Neurofuzzy power system stabilizer. IEEE Transactions on Energy Conversion 23, 887–96, 2008

[27] Talaat EA, Abdennour A, Al-Sulaiman AA. Design and experimental investigation of a decentralized GA-optimized neuro-fuzzy power system stabilizer. International Journal of Electrical Power & Energy Systems 32, 751–9, 2010

[28] Kundur, P. i dr »Definition and Classification of Power System Stability«, IEEE Transactions on Power Systems, Vol. 19, No. 3, pp. 1387-1401, 2004

[29] Vukić, Z.; Kuljača, Lj »Automatsko upravljanje – analiza linearnih sustava«, Kigen, Zagreb, Hrvatska, 2005

[30] de Mello, F.P.; Concordia, C »Concepts of Synchronous Machine Stability as Affected by Excitation Control«, IEEE Transactions on Power Apparatus and Systems, Vol. 88, No. 4, pp. 316-329, 1969

[31] Sumina, D.; Bulić, N.; Skok, S »Stabilization of Electromechanical Oscillations of Synchronous Generator«, Strojarstvo, Vol. 53, No. 3, pp. 209-219, 2011

[32] Ritonja, J »Analysis and Applicability of Heffron-Phillips Model«, Elektronika ir Elektrotechnika, Vol. 22, No. 4, pp. 3-10, 2016

(Footnotes)

1 Statements expressed in the paper are author's own opinions, they are not binding for the company/institution in which author is employed nor they necessarily coincide with the official company/institution's positions.

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Maintenance of Filter at The Gas Turbine Compressor Intake and Electric Transformer Connector Based on Operational Reliability

SUMMARY

The article analyzes the operational reliability of filter on the gas turbine compressor intake and the operational reliability of electric transformer connector. Empirical data (statistical sample) were collected to determine the failure density function f (t), the hazard function ω(t), and the expected value of mean time to failure MTTF. The numerical model was created in the Minitab 19 software tool. The Anderson-Darling test was used to accept or reject the hypothesi

KEY WORDS

compressor, filter, probability distribution, reliability

1. INTRODUCTION

Reliability is defined as a measure of a device's ability to operate without failure, and it mathematically predicts the behavior of a system or device under expected operating conditions [4]. The reliability of a system is divided into structural and operational. Structural reliability refers to the construction of the system, ie it is determined mathematically by the manufacturer, while operational reliability is determined from the operation of the system, and on the basis of empirical data [2].

The first part of the paper presents an analysis of the operational reliability of the filter on the gas turbine compressor intake. The intake air filtration system is crucial for the successful operation of a gas turbine. The filtration system protects the gas turbine from harmful impurities in the outside air, which can lead to problems such as output power fluctuations, erosion, dirt, and corrosion. The main cause of the problem is the dirt of the compressor. In such cases, operators often use compressor washing as a measure, for a quick repair and, and to restore output power and efficiency. The success of this measure is short-lived because cleaning simply washes away contaminants from the front blades to the inner blades of the turbine. Turning off the turbine allows for significantly more efficient washing, but causes costly downtime. In any case, the loss of production capacity is reversed due to contaminants that are continuously generated and damage the blades and other components. If the compressor suction filter is damaged or dirty, the power plant operation must be stopped and the filter replaced. The aim of this paper is to develop a model of preventive maintenance, in order to be able to predict the potential failure of the filter based on empirical data and to prevent the sudden exit of the power plant from the operation. Filters can also be purchased in advance and kept in stock, thus reducing the logistical maintenance time, which will speed up the return of the power plant to operation, or reduce financial losses due to production downtime.

The second part of the paper presents an analysis of the operational reliability of electric transformer medium voltage connector in the transformer substation system 20/0.4 kV with installed power of 630 kVA. Due to prolonged exposure to high current flows, over time, the cable head insulation may break. In this case the protection device will disconnect transformer from the distribution system and the consumers are left without electricity until the fault is repaired. The aim of this paper is to develop a model of preventive maintenance, in order to be able to predict the potential failure of the connector in transformer station based on empirical data and to prevent the sudden electric power failure that would left consumers without

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electricity and cause financial losses to electric energy seller. The main objective is to determine the optimal point for preventive replacement of the transformer connector subsystem.

2. MATHEMATICAL MODEL OF RELIABILITY ANALYSIS OF THE FILTER OF THE GAS TURBINE COMPRESSOR INTAKE

Researching the reliability of the technical composition is very important because in this way failures can be predicted, and financial losses resulting from the failure of the system or a device can be reduced [7]. The mathematical model of reliability analysis is determined with two functions, namely the reliability function R (t), and the failure intensity function ω(t) [8], [9]. Reliability expresses the numerical probability of a device operating without failure during a certain time interval and under the operating conditions for which the device is intended, while the failure intensity function shows how the failure intensity changes during the life cycle of the system or device [3]. The reliability of a system is calculated according to the formula:

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)\, dt \qquad (1)$$

where F (t) - a function of unreliability, and f (t) - function of failure probability density.

Another important quantity is the expected time to failure (MTTF), which represents the average time that the system or device works before the failure, and is calculated according to the formula [2], [13]:

$$MTTF = \int_0^\infty R(t) dt \qquad (2)$$

In order to determine the probability distribution function that describes the collected fault data, the following hypothesis is set:

H_0^0 - the statistical sample is equal to the three-parameter Weibull distribution at a significance level of 0,05

H_0^1 - the statistical sample is not equal to the three-parameter Weibull distribution at a significance level of 0,05

To accept or reject the hypothesis, the Anderson-Darling statistical test was used, which was made using the Minitab 19 program. The Anderson-Darling test is a statistical test that checks for a given sample of data on how well they match the selected theoretical probability distribution [14]. Anderson-Darling statistics (AD *) Anderson-Darling statistics measure how well the data track a particular distribution [4]. For a given data set and distribution, the more appropriate the distribution for the data, the smaller the statistics will be.

3. MATHEMATICAL MODEL OF RELIABILITY ANALYSIS OF TRANSFORMER CONNECTOR SUBSYSTEM

The main objective is to determine the optimal point for preventive replacement of the transformer connector subsystem. The optimal point for preventive replacement of the transformer connector subsystem should be determined taking into account the minimum costs of preventive maintenance c_p, costs of corrective maintenance ck, failure intensity function $\omega_{k,Re}(t)$, preventive maintenance intensity function $\lambda_{p,Re}(t)$ and operational reliability function $R_e(t)$ [1], [15].

The function of relative maintenance costs is described by the following relation:

$$c_{u,Re,rel}(T_R) = \frac{c_{p,Re,rel}}{100} \cdot \lambda_{p,Rel}(t) + \frac{c_{k,Re,rel}}{100} \cdot \lambda_{p,Rel}(t) \qquad (3)$$

where $c_{p,Re,rel}$ i $ck_{,Re,rel}$ represent the relative costs of preventive and corrective maintenance.

Optimal time for replacement of the cable head subsystem could be obtained by minimizing relation (3).

Relative costs of preventive and corrective maintenance could be obtained by following relations:

$$c_{p,Re,rel} = \frac{c_p}{c_p + c_k} \cdot 100 \qquad (4)$$

$$c_{k,Re,rel} = \frac{c_k}{c_p + c_k} \cdot 100 \qquad (5)$$

The costs of corrective maintenance are described with the following relation:

$$c_k = c_M + c_R \cdot E_{KA}(T) + c_N \cdot E_K(T) \qquad (6)$$

where c_M is estimated material cost (3700 kn) , c_R is cost of labor (210 kn/h) , c_N is estimated cost due to undelivered electricity (348 kn/h), $E_K(T)$ is time needed for corrective maintenance and $E_{KA}(T)$ is active time needed for corrective maintenance [12].

The costs of preventive maintenance are described with the following relation:

$$c_p = c_M + c_R \cdot E_{KA}(T) \qquad (7)$$

The function of preventive replacement of a part of the transformer connector subsystem is described by the following relation:

$$\lambda_{p,Rel}(t) = \frac{1}{T_R} \qquad (8)$$

The failure intensity function of the transformer connector subsystem is described by the following relation:

$$\lambda_{k,Rel}(t) = \frac{T_R - \int_0^{T_R} R_e(t)dt}{T_R \cdot \int_0^{T_R} R_e(t)dt} \qquad (9)$$

The operational reliability of $R_e(t)$ is described by the following relationship:

$$R_e(t) = 1 - \int_0^t f_e(t)dt \qquad (10)$$

where $f_e(t)$ is fault probability function.

4. RESEARCH RESULTS

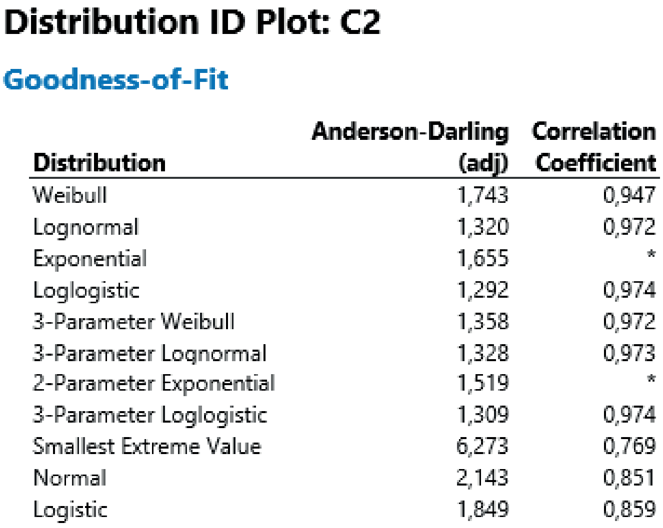
4.1. RESEARCH RESULTS OF THE OF RELIABILITY ANALYSIS OF THE FILTER OF THE GAS TURBINE COMPRESSOR INTAKE

The empirical data used in the analysis are given in the following table:

Table I. Operating time between failures and ordinal number of failures

Ordinal number of the fault	Operating time to failure [h]
1	35
2	44
3	114
4	92
5	163
6	113
7	115
8	197
9	44
10	258
11	532
12	114

The results of the research show that the collected empirical data best follow the log-logistic function, ie for it, the value of the Anderson-Darling test is the lowest, although the three-parameter Weibull distribution and the three-parameter log-normal distribution are very close to the Anderson-Darling test values. Therefore, the hypothesis is rejected, and the hypothesis is accepted. In reliability theory, the Weibull distribution is the most commonly used distribution because it can be applied to model many different data sets, that is, it is very flexible [1], [10]. The log-normal distribution is typically used for model system or device failures caused by corrosion or chemical reactions. Log-logistic distribution is used in various fields, such as survival analysis, hydrology, economics, etc [11]. Also, log-logistic distribution well approximates normal and log-normal distribution. Although the values of the Anderson-Darling test are close for these three distributions, the log-logistic distribution was selected, and it is used for further calculations.



Distribution ID Plot: C2

Goodness-of-Fit

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	1,743	0,947
Lognormal	1,320	0,972
Exponential	1,655	*
Loglogistic	1,292	0,974
3-Parameter Weibull	1,358	0,972
3-Parameter Lognormal	1,328	0,973
2-Parameter Exponential	1,519	*
3-Parameter Loglogistic	1,309	0,974
Smallest Extreme Value	6,273	0,769
Normal	2,143	0,851
Logistic	1,849	0,859

Figure 1. results of the Anderson-Darling test for the collected empirical data

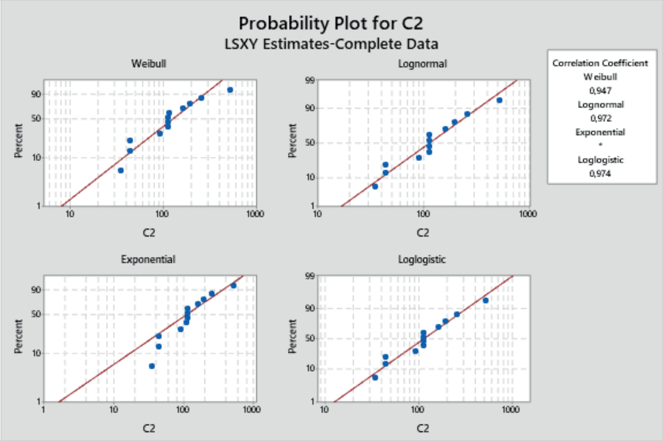


Figure 2. Hypothesis testing

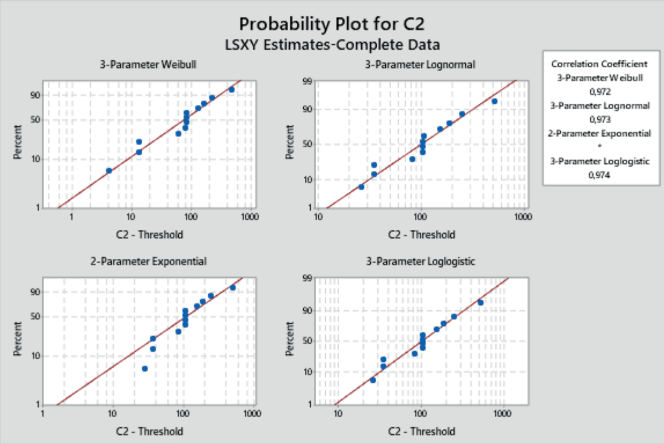


Figure 3. Hypothesis testing

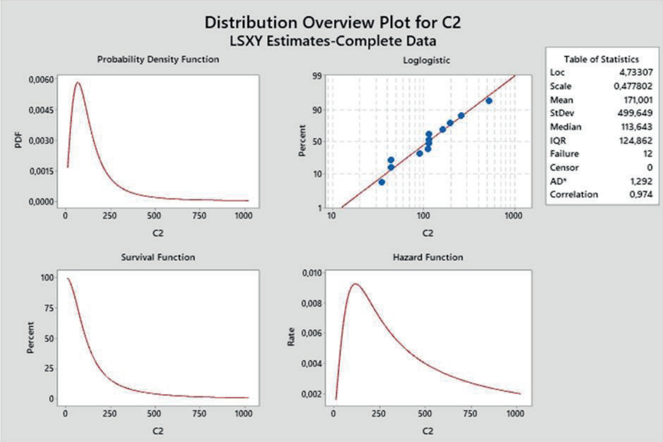


Figure 4. Hypothesis testing

The density function of the log-logistic distribution is given by the formula:

$$f(t) = \frac{e^{z}}{\sigma t(1+e^{z})^{2}} \qquad (11)$$

where:

$$z = \frac{t' - \mu}{\sigma} \qquad (12)$$

$$t' = ln(t) \tag{13}$$

The values of these parameters were selected based on the results obtained by analysis, and they are as follows: $\mu = 0{,}4778$; $\sigma = 4{,}733$; t = 171 h.

It follows that: t› = ln(171) = 5,142, z = 0,9855.

From the results of the analysis it can be read that the expected failure time is: MTTF = 171 hours.

The failure rate for the expected time of failure-free operation according to the above formula is:

$$\lambda(t) = \frac{e^z}{\sigma \cdot t \cdot (1+e^z)} \tag{14}$$

It follows that:

$$\lambda(171) = \frac{e^{0{,}9855}}{4{,}733 \cdot 171 \cdot (1+e^{0{,}9855})} = 8{,}9974 \cdot 10^{-4}\,\frac{failure}{hour} \cong 8\,\frac{failure}{year\ of\ work}$$

Also, the unreliability function for the expected time without failure is:

$$F(t) = 1 - R(t) = \frac{1}{1+e^z} = 0{,}728 = 72{,}8\ \% \tag{15}$$

The unreliability function shows that for MTTF = 171 hours the unreliability is as high as 72.8%. Cumulative Hazard (Cumulative Hazard) is calculated according to the formula:

$$(T) = \int_0^T \lambda(t) d = \int_0^T \frac{e^z}{\sigma \cdot t \cdot (1+e^z)} dt = \frac{e^z}{\sigma \cdot (1+e^z)} \cdot ln\,(T) \tag{16}$$

For the value of cumulative risk Λ (T) = 0,5; time T is: 0,154 · ln (T) = 0.5 → T = 25,7 h. For MTTF = 25.7 h, the unreliability is 64.24%. Given that power plants require a high degree of operational safety, the unreliability should not exceed 30%.

$$F(t) = 1 - R(t) = 0{,}3\ \rightarrow\ t \cong 88\ h \tag{17}$$

Given the high required degree of safety of 30%, the required time of preventive maintenance of the filter is t = 88 h of operation.

4.2. RESEARCH RESULTS OF THE OF RELIABILITY ANALYSIS OF THE TRANSFORMER CONNECTOR SUBSYSTEM

Table II. shows the empirical data used for analysis. Fault and duration data are displayed for connector failures in different transformer stations in which the electric connector operates under the similar conditions.

Table II. Empirical data used for analysis

Number of the connector	Operating time to failure $K_i = S_{KOi}$		Logistic time of corrective maintenance	Active time of corrective maintenance	Duration of corrective maintenance
	T_{Ri} [years]	T_{Ri} [hours]	T_{KLi} [hours]	T_{KAi} [hours]	T_{Ki} [hours]
1	38,64	338718	8,25	1	9,25
2	42,45	372117	9,9	1	10,9
3	37,28	326797	4,82	1	5,82
4	38,66	338894	0,22	0,23	0,45
5	29,23	256230	2,37	1	3,37
6	23,98	210209	0,11	0,12	0,23
7	18,75	164363	0,45	0,45	0,9
8	46	403236	4,82	1	5,82
9	35,88	314524	3,17	1	4,17
10	51,44	450923	0,75	1	1,75
11	40,1	351517	0,44	0,44	0,88
12	48,83	428044	2	1	3
13	44,65	391402	4,77	1	5,77

Statistical data processing was performed using the Minitab 19 software tool, based on the data from Table II. The results show that the collected empirical data for operating time to failure best follow the Weibull distribution function because for it, the value of the Anderson-Darling test is the lowest, although the log-logistic distribution is very close.

Although the values of the log-logistic Anderson-Darling test is close, the Weibull distribution was selected, and it is used for further calculations.

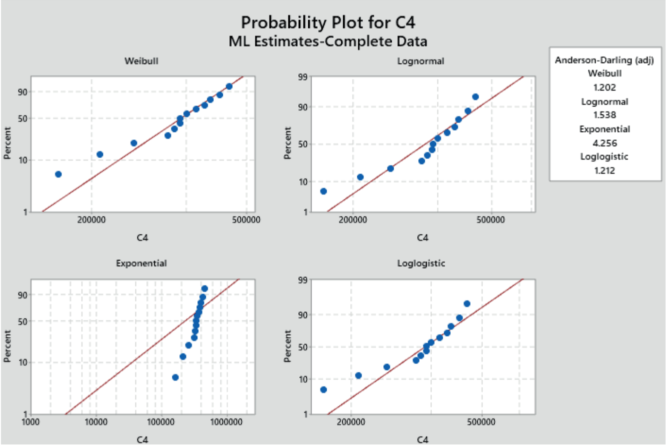


Figure 5. Different distributions for failure probability

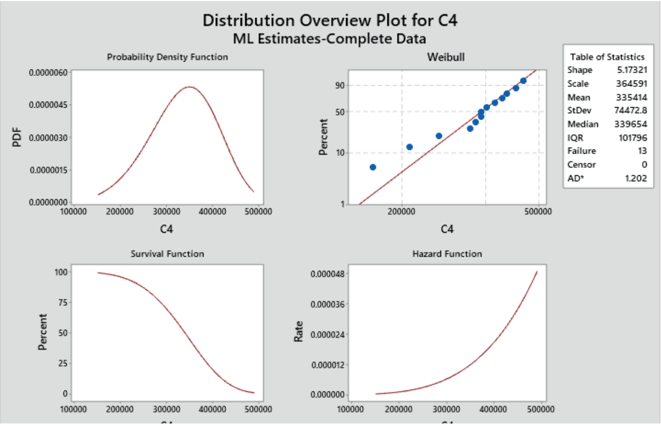


Figure 6. Weibull distribution parameters for failure probability

The density function of the Weibull distribution is given by the relation:

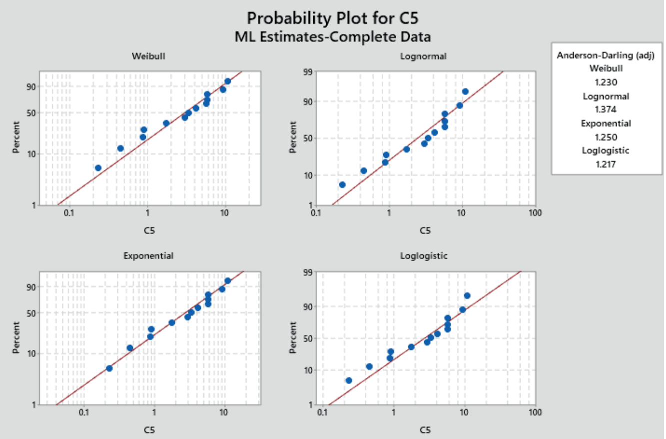
$$f(t)=\frac{c}{a}\cdot\left(\frac{t}{a}\right)^{c-1}\cdot e^{-\left(\frac{t}{a}\right)^{c-1}} \quad (18)$$

where *c* is shape parameter and *a* is scale parameter of Weibull distribution.

The values of these parameters were selected based on the results obtained by analysis in Minitab, and they are as follows: c = 5,17321 ; a = 364591 . If we insert it in equation (18) we get:

$$f_e(t)=1{,}419\cdot 10^{-5}\cdot\left(\frac{t}{364591}\right)^{4.17321}\cdot e^{-\left(\frac{t}{364591}\right)^{5{,}17321}} \quad (19)$$

Statistical data processing was repeated with collected data about time for corrective maintenance, logistic time for corrective maintenance and active time of corrective maintenance. The results are shown on Figures 7-12. The results show that the for all three cases collected empirical data best follow the loglogistic distribution function because for it, the value of the Anderson-Darling test is the lowest, although for two cases the Weibull distribution is very close.



Anderson-Darling (adj)
Weibull
1.230
Lognormal
1.374
Exponential
1.250
Loglogistic
1.217

Figure 7. Different distributions for maintenance time probability

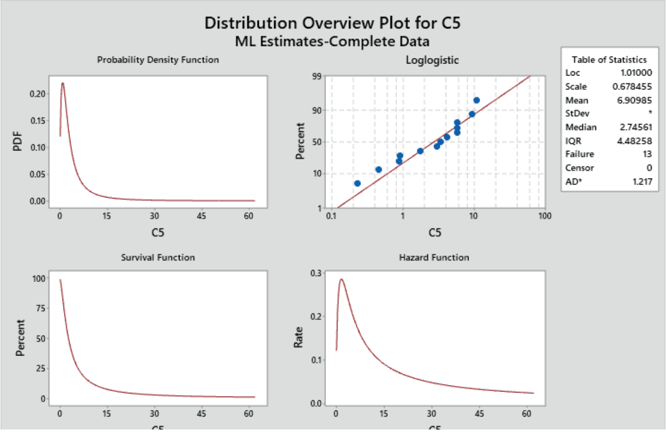


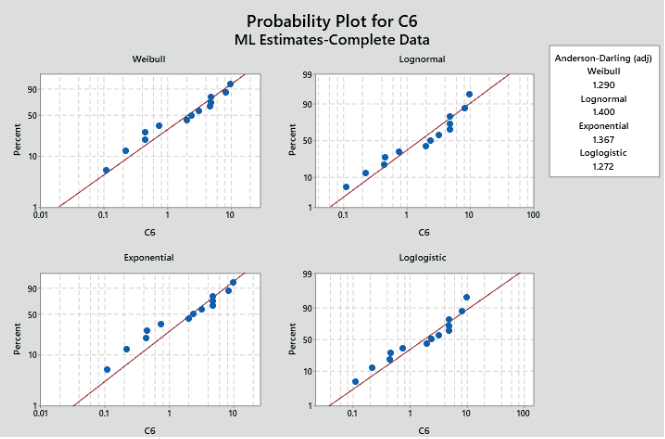
Table of Statistics

Loc	1.01000
Scale	0.678455
Mean	6.90985
StDev	*
Median	2.74561
IQR	4.48258
Failure	13
Censor	0
AD*	1.217

Figure 8. Loglogistic distribution parameters for maintenance time probability

The second statistical processing was made with corrective maintenance times. Figure 8. shows that the expected logistic time for corrective maintenance of E_K (t) = 6,91 hours.

The third statistical processing was made with logistic corrective maintenance times. Figure 10. shows that the expected logistic time for logistic corrective maintenance of E_{KL} (t) = 9,76 hours.



Anderson-Darling (adj)
Weibull
1.290
Lognormal
1.400
Exponential
1.367
Loglogistic
1.272

Figure 9. Different distributions for logistic maintenance time probability

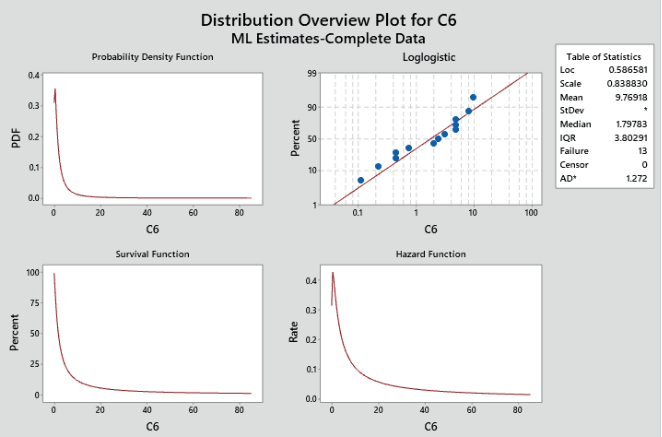
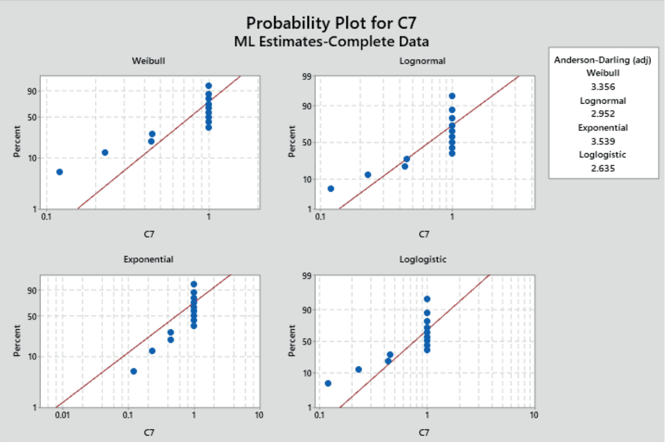


Table of Statistics

Loc	0.586581
Scale	0.838830
Mean	9.76918
StDev	*
Median	1.79783
IQR	3.80291
Failure	13
Censor	0
AD*	1.272

Figure 10. Loglogistic distribution parameters for logistic maintenance time probability

The fourth statistical processing was made with active corrective maintenance times. Figure 12. shows that the expected active time for active corrective maintenance of E_{KA} (T) = 0,95 hours.



Anderson-Darling (adj)
Weibull
3.356
Lognormal
2.952
Exponential
3.539
Loglogistic
2.635

Figure 11. Different distributions for active maintenance time probability

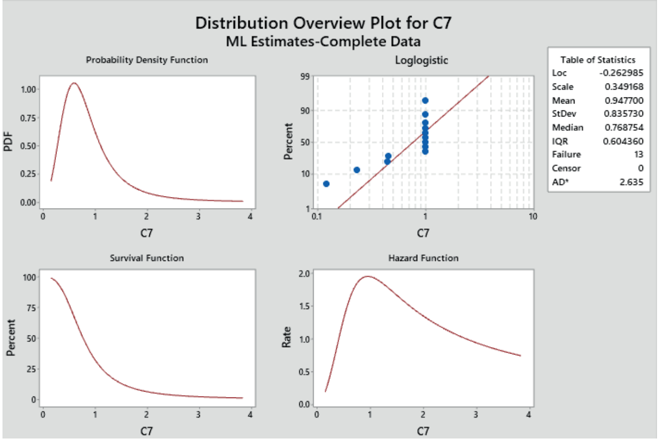


Figure 12. Loglogistic distribution parameters for active maintenance time probability

Table III. shows the numerical models for all four statistical processings.

Table III. Numerical model - presentation of theoretical function of the probability density of characteristic events and the expected time to their of origin

Event / times	Theoretical probability distribution	Numerical model (probability density function)	Expected time
Fault (K=S_{K0})	**Twoparameter Weibull distribution** Shape parameter c=5,17321 Scale parameter a=364591	$f_e(t) = 1{,}419 \cdot 10^{-5} \cdot (\frac{t}{364591})^{4.17321} \cdot e^{-(\frac{t}{364591})^{5.17321}}$	E_R(T)= 335414 h
Corrective maintenance time, T_K	**Loglogistic distribution** Location parameter l=1,01 Scale parameter a=0.678455	$m_K(t) = \frac{e^{(\frac{\ln(t)-1{,}01}{0{,}678455})}}{t \cdot 0{,}678455 \cdot (1+e^{(\frac{\ln(t)-1{,}01}{0{,}678455})})^2}$	E_K(T) =6,91 h
Logistic corrective maintenance time, T_{KL}	**Loglogistic distribution** Location parameter l=0,586581 Scale parameter a=0,838830	$m_{KL}(t) = \frac{e^{(\frac{\ln(t)-0{,}586581}{0{,}838830})}}{t \cdot 0{,}838830 \cdot (1+e^{(\frac{\ln(t)-0{,}586581}{0{,}838830})})^2}$	E_{KL}(T)=9,76 h
Active corrective maintenance time, T_{KA}	**Loglogistic distribution** Location parameter l=-0,262985 Scale parameter a=0,349168	$m_{KA}(t) = \frac{e^{(\frac{\ln(t)+0.2629851}{0.349168})}}{t \cdot 0{,}349168 \cdot (1+e^{(\frac{\ln(t)+0.262985}{0.349168})})^2}$	E_{KA}(T)=0,95 h

If we insert times for corrective maintance E_{KA}(T) and E_K (T) from Table III. into relations (6) and (7), we get costs of preventive maintance 3899,5 kn and costs of corrective maintenance 6304,18 kn.

If we insert costs of preventive and corrective maintance into relations (4) and (5), we will get relative costs of preventive maintance =38,2 and relative costs of corrective maintenance .

In order to determine the optimal point for preventive replacement of the transformer connector subsystem, it is necessary to determine the function of relative maintenance costs.

The operational reliability R_e (t) is described by the relation (10). If we insert the function of the probability density of the fault f_e(t) from Table III. in relation (10) we get:

$$R_e(t) = 1 - \int_0^t 1{,}419 \cdot 10^{-5} \cdot (\frac{t}{364591})^{4{,}17321} \cdot e^{-(\frac{t}{364591})^{5{,}17321}} dt \quad (20)$$

By integrating relation (20) we obtain the operational reliability of the transformer connector subsystem:

$$R_e(t) = e^{-(\frac{t}{364591})^{5.17321}} \quad (21)$$

By inserting parameters of maintenance distribution and costs as well as operational reliability of the transformer connector subsystem into the relation (3) we get the function of the relative costs of maintenance for transformer connector subsystem:

$$c_{u,Re,rel}(T_R) = 0{,}382 \cdot \frac{1}{T_R} + 0{,}618 \cdot \frac{T_R - \int_0^{T_R} e^{-\left(\frac{t}{364591}\right)^{5.17321}} dt}{T_R \cdot \int_0^{T_R} e^{-\left(\frac{t}{364591}\right)^{5.17321}} dt} \qquad (22)$$

A graph of the function of relative maintenance costs was drawn in program Mathcad 15 and shown in Figures 13., 14.

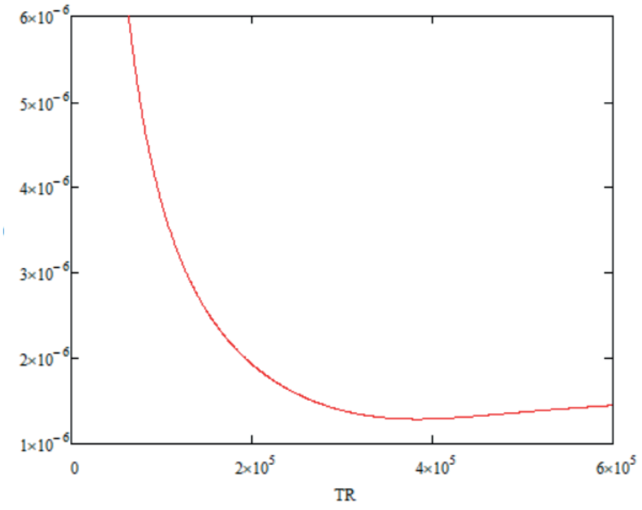


Figure 13. Graph of the function of relative maintenance costs cu,Re,rel(TR) for MV transformer connector subsystem

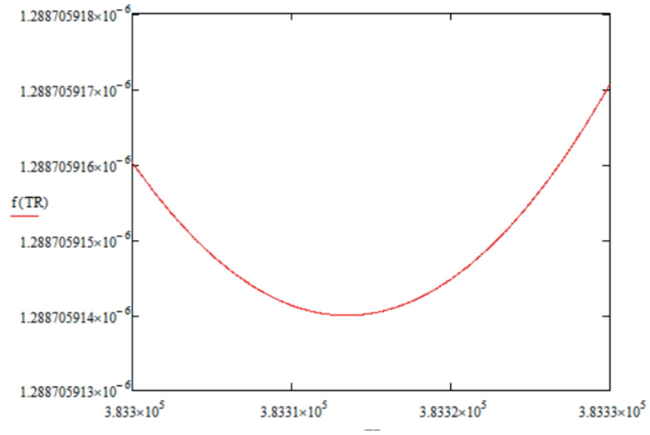


Figure 14. Minimum of the function of relative maintenance costs cu,Re,rel(TR) for MV transformer connector subsystem

Using the program Mathcad 15, the minimum of the function shown in Figure 14. was determined. In accordance with the obtained minimum, the optimal time of preventive maintenance of the medium voltage transformer connector subsystem is obtained. The optimal time for preventive maintenance is 383313 hours or 43,73 years.

5. CONCLUSIONS

First part of the article presents the results of the analysis performed on the empirical data of filter failure at the gas turbine compressor intake, obtained from the power plant in HEP's portfolio. The Minitab 19 software package was used for the analysis, and a three-parameter log-normal distribution was determined with a high level of significance, and the hypothesis was accepted. The expected uptime of the MTTF and the required time of preventive maintenance of the filter in relation to the required safety were also determined. The results obtained by the analysis can be used as a basis for making decisions related to the maintenance strategy, in order to prevent or minimize plant downtime caused by failure and thus losses. As said in the introduction of this paper, when the compressor suction filter is damaged or dirty, the power plant operation must be stopped and the filter replaced, so the aim of this paper is to develop a model of preventive maintenance, in order to be able to predict the potential failure of the filter based on empirical data and to prevent the sudden exit of the power plant from the operation. Data used for these calculations were collected during an extensive period of time, and they are empirical, i.e. they were collected from one of the powerplants from the HEP portfolio. Results of the analysis shows that the required time of preventive maintenance of the filter is t = 88 h of operation. That means that after 88 hours of operation of the powerplant, there is a good chance that the malfunction will occur on the filter. Knowing that, filters can be purchased in advance and kept in stock, and speed up the return of the power plant to operation, or reduce financial losses due to production downtime. Second part of the article presents the results of the analysis of the empirical data performed in order to determine optimal time for preventive maintenance of the medium voltage transformer connector subsystem. The results obtained by the analysis can be used as a basis for making decisions related to the maintenance strategy in order to prevent the sudden electric power failure that would left consumers without electricity and cause financial losses to electric energy seller. The analysis showed that the optimal time for preventive maintenance of transformer connector subsystem for the observed case is 43,73 years, which means that this is not a failure that happens often, and therefore it is not necessary keeping of spare parts in stock, or monitoring this part of equipment particularly. As shown in this paper, reliability analysis is very useful for determing time period after which a failure may occur. Knowing that time period is very important because it allows preparation for failure (planned maintenance, keeping spare parts in stock, etc.), which can significantly reduce the financial losses causes by failure.

REFERENCES

[1] J. Batelić: Contribution to increasing the reliability of the mill system of TPP Plomin 2 / doctoral thesis, Rijeka, Faculty of Engineering, 2019.

[2] D. Matika, J. Batelić: Determining the operational reliability of the Plomin 2 thermal power plant for the purpose of evaluating critical national infrastructure; III. International scientific-professional conference: »New security threats and critical national infrastructure«, pp. 218-227.UDK 351.751: 504, Zagreb 2013

[3] J. Batelić, D. Matika, K. Griparić: Maintenance of hydraulic cylinders based on the achieved level of operational reliability, Polytechnic and design, Vol. 7 No. 4, str. 281-288, 2019.

[4] A. Birolini: Reliability Engineering, Theory and Practice, Fifth edition, Springer, 2006.

[5] Minitab software tool: https://support.minitab.com/en-us/minitab/18/help-and-how-to/statistics/basic-statistics/supporting-topics/normality/the-anderson-darling-statistic/

[6] Mathcad software tool: https://www.mathcad.com/en/

[7] R. E. Barlow: Engineering Reliability, Society for Industrial and Applied Mathematics, University of California, Berkeley, 1998.

[8] B. S. Dhillon: Reliability engineering in systems design and operation, Van Nostrand Reinhold, 1983.

[9] T. R. Chandrupatla: Quality and Reliability in Engineering, 1st edition, Cambridge University Press, 2009.

[10] A. J. Hallinan Jr.: A Review of the Weibull Distribution, Journal of Quality, Volume 25, 1993 - Issue 2, Pages 85-93, Published Online: 21 Feb 2018.

[11] A. A. AlShomrani, A. I. Shawky, O. H. Arif, M. Aslam: Log-logistic distribution for survival dana analysis using MCMC, SpringerPlus 5, 1774 (2016)

[12] C. Stenström, P. Norrbin, A. Parida, U. Kumar: Preventive and corrective maintenance – cost comparison and cost–benefit analysis, Structure and Infrastructure Engineering, Volume 12, 2016 - Issue 5, Pages 603-617, Published online: 13 May 2015.

[13] C. D. Lai, G. D. Lin: Mean time to failure of systems with dependent components, Applied Mathematics and Computation, Volume 246, Pages 103-111, November 2014.

[14] T. W. Anderson: Anderson–Darling Tests of Goodness-of-Fit, International Encyclopedia of Statistical Science, Springer, Berlin, Heidelberg, 2011.

[15] C. C. Chang: Optimum preventive maintenance policies for systems subject to random working times, replacement, and minimal repair, Computers & Industrial Engineering, Volume 67, Pages 185-194, January 2014.

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Influence of Composition of Power Plant Fleets and Ownership of Transmission and Distribution Networks to Incumbent Company's Business Success in Some Former Socialist EU Countries

SUMMARY

By joining the EU, companies from eastern countries, which until then had largely operated in regulated circumstances, had to adapt to the open market. Liberalization and deregulation were imposed on them as new mantras, in contrast to ensuring the supply at all costs and addressing social issues. How these companies flourished in new circumstances is a legitimate topic for managerial research. This article researches the impact of the »hard assets« composition, that those companies operated, on their expected business success after a multi-year adjustment period. Positivistic research philosophy, »case study«, and the deduction approach are used. The data were collected mainly from secondary sources. 3 research goals were selected with 3 relevant research questions. An attempt was made to respond to them on the example of 7 Central European countries and 11 companies, direct successors of original incumbents. The property is grouped into 3 groups: classical power plants (nuclear, hydro, coal), renewable power plants (wind, solar, bio mass) and lines (transmission and distribution). Criteria for success are selected according to usual praxis, but also adjusted to accessible data, predominantly from the company's annual financial statements. Contrary to the developed intuition, and based on cases of companies analyzed, there was no significant correlation between the selected criteria of success and the observed asset classes, serving as independent variables. The biggest problem in the research was access to data. This paper is an extraction from an MBA dissertation.

KEY WORDS

assets valuation, success prediction, incumbents, deregulation, liberalisation

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1. INTRODUCTION

There are different business strategies which companies use to grow business or profitability, one of them being internationalisation. Once many middle and eastern European countries opened their borders to the west, they encountered new competition. Western companies in their pursuit of internationalisation strategy, operating in many different fields of activity, felt the sudden business "vacuum" of the east, a myriad of unsatisfied consumer needs offering opportunities. For sure they had more money, more knowledge and much more experience in the competitive environment, as eastern companies were mostly used to operate in regulated circumstances. The power of the eastern competitors was here perceived as weaker and markets as prone to entering.

How the companies originating from the east coped with the new situation, is for sure an interesting subject for research in managerial or strategic fields. When it comes to energy business in this context, and more specifically electricity business, it has its particularities. Energy is a "condition sine qua non" for modern society. The same is true for electricity. It is essentiality different to some other goods/products such as certain type of shoes or bananas, which come from a variety of sources and have a much higher demand price elasticity. The value of the GDP lost, if there is a reduction of supply, is couple of hundred times more than the price of the same amount of electricity. Another reason for the special status of electricity is the size and complexity of its infrastructure. Electricity systems, comprising of generation, transmission and distribution systems, are the biggest systems in the world, spreading across continents, built through decades, necessarily interconnected to politics in many ways. Clearly these systems are too big and too important to fail for any country. However, is it out of the question that some specific company operating in some or more parts of electricity value chain in one country fails totally or diminishes substantially? Would the politics or some other factors find a way to "intervene" and help a seemingly irreplaceable domestic energy subject which found itself in troubled waters? Would national governments take a role of an observant bystander and let the markets play their role as it is intended by the market economy paradigm where decisions are made based on price signals? Finally, are there some already recognisable patterns in the structure of the "eastern companies" that can lead to a prediction of their future success?

These and similar question are relevant. As the electricity business is long established and quite old, not much organic growth is happening in Europe. Energy efficiency is generally politically promoted, lately even more so as there is a universal recognition of the greenhouse effect danger. Consumption is mostly stagnant and for (former) western companies, push to the east was and still is a logical move.

Latest example where one can observe the development in the electricity market after its deregulation and liberalisation is Croatia. Here, an interesting phenomenon occurred recently in the retail business. Namely, after the initial entry of numerous new electricity retail companies, the market is lately getting more and more consolidated and the number of players is declining (Bičak 2018). It is a counterintuitive situation since one would expect that once markets open to competition, more and more players will emerge. By early 2018, HEP practically succeeded in surviving in the open markets, now for more than 5 years, against many challengers. It also succeeded in keeping more than 90% of the retail market for itself, not to mention the generation market where its position is unchallenged. Consequently, this also means that most of the early entrants into the Croatian electricity market failed.

So, which characteristics of HEP and the Croatian market are the ones relevant for this outcome? How did HEP manage to keep a high percentage of the market against private or international competition? Is it possible to define these characteristics and use them to compare HEP to other incumbents that found themselves in similar situation as HEP, after the market opening when their countries entered the European Union? Clearly, the situation in Croatia is not unique, as other countries also went through the same process of negotiations before entering the EU, with implementation of the EU legislative, deregulation in energy business being a part of the process. An attempt to find a western company with similar success was made, resulting in identifying SSE (Scottish and Southern Electric). SSE was practically the only continuously profitable energy company among the "big 6" in the UK in the 2009-2012 period. One of the theories explaining the good SSE performance was that it is inherently difficult to manage all parts of the production-transmission-distribution-retail chain for electricity and energy, and ownership of all parts helps in achieving better results, whatever the underlying root cause of this may be. SSE clearly states in its annual report (SSE p.l.c. 2012, p.31) that "*customers benefit from lower exposure to wholesale price volatility and from price stability through "smoothing"*". This general difficulty of management can be viewed maybe as a natural characteristic or a problem of the electrical system, originating from its complexity. If this is accepted as such, than the vertical integration of some portions or all of business can be considered as a „cure" or solution. Yet, on the example of electricity market in Sweden (Tang 2018), it was discovered that "*multi-plant firms on average have one percentage-point lower return on total assets, than single – plant counterparts*" implying that additional complexities, in this particular market, bring additional costs.

The other feature describing electricity infrastructure is its costs. For example HEP owns more than 2000 MW of hydro power stations, as well as 50% of the Krško nuclear power plant. HEP also owns all the transmission and distribution lines in the country. The best locations for hydro power plants are always built first meaning that every new location is on average less and less advantageous. Nuclear power plants are very difficult to build because of huge costs and also NIMBY phenomenon. These types of power plants, once built, have relatively low operating costs. They bring in a lot of profits.

Unlike hydro, nuclear or suitable lignite power plants, the ownership of wind, solar as well as gas power stations does not fall into this „difficult to get or develop" category, as the barriers to entry for these electricity sources are substantially lower. Thus, it is not such an enduring competitive advantage for anyone to operate a gas fired power station with its investment costs of less than 1000 Euro/kW.

Finally, the important factor describing and distinguishing between different electrical industries infrastructure is whether the assets, or combination of assets, is easy to replicate for companies coming late into a market. HEP has a very similar combination of hard to replicate, expensive hard assets related to electricity, present in the whole electricity value chain, same as SSE. The question to consider is whether this composition of factors is relevant for HEP's success, and an attempt of answering this can be made for similar eastern countries, which had their own incumbents upon entring the EU.

1.1 AIMS, OBJECTIVES AND QUESTIONS

After describing the context and some possible factors explaining the future performance of incumbents, it is necessary to define the research question. First, a choice of the countries to be observed needs to be made. The chosen countries are: **Croatia, Poland, Czech Republic, Slovakia, Hungary, Bulgaria and Romania**. These 7 countries have a similar "energy past". The timing of entrance into the EU being similar. Following upper discusion, the aim of this study is to: analyse common characteristics behind the performance of incumbent electricity companies in seven designated countries, with a special focus on ownership structure of power plants and lines.

Furthermore, this general aim is broken down into three more specific objectives. These objectives are directly translated further into research questions, shown in table I.

Table I. Research objectives and questions

Research Objectives	Research Questions
To evaluate if the ownership of hydro power plants, nuclear power plants, lignite/coal power plants by incumbent companies, can influence future success of these companies, observed on the example of the last 10 years	Q1: Can the ownership of hydro power plants, nuclear power plants and lignite/coal power plants by incumbent companies influence the future success of these companies, observed on the example of the last 10 years?
To evaluate if the ownership of „new" renewables or development of „new" renewables such as wind, solar and bio mass by incumbent companies, can influence future success of these companies, observed on the example of the last 10 years	Q2: Can the ownership of „new" renewables or development of „new" renewables such as wind, solar and bio mass by incumbent companies influence the future success of these companies, observed on the example of the last 10 years?
To evaluate if the ownership of transmission and distribution networks by incumbent companies can influence future success of these companies, observed on the example of the last 10 years	Q3: Can the ownership of transmission and distribution networks by incumbent companies influence the future success of these companies, observed on the example of the last 10 years?

Source: author

1.2 RATIONALE FOR THE STUDY – WHO CAN BENEFIT FROM IT

This research deals with the assessment of the influence of the combination of hard assets for some companies to the future success they will eventually have in the market. It is important to the management of these companies, as it will help them understand some part of the value adding process. It has its meaning to the existing competitor companies and potential competitors as well. It also has merit for policymakers, regulators and different energy agencies. In this regard, it can be considered as „integrated research and consultancy project" for incumbent companies, possible new entrants and other subjects mentioned. If found that possession of some combination of hard assets benefits the business performance of a company, it would be an example of a rather rare strategic situation, as, *„it is unusual for competitive advantage to be explainable by differences in tangible resources of organizations, since over time they can usually be imitated or traded*" (Johnson, Scholes and Whittington 2005, p.103).

An addition to the theoretical knowledge can be expected e.g. in the context of 5 forces, as described by Porter. The 5 forces are: Supplier power, buyer power, threat of new entry, threat of substitution, competitive rivalries (Johnson, Scholes and Whittington, 2005). The results of this research can clearly bring an additional insight in electricity markets after deregulation, providing new insight particularly for the force of "threat of new entry".

For the purposes of refining the research question, checking its initial validity, and better understanding the research rationale, literature review must be done. The goal of the literature review is shortly to "*map and assess the existing intellectual territory*" (Saunders, Lewis and Thornhill 2009, p.60).

1.3 SHORT DESCRIPTION OF THE RESEARCH APPROACH

The chosen research philosophy is positivism. Positivist approach "*adopts the stance of the natural scientist*" where the end product of the research can be "*law-like generalisation similar to those produced by physical or natural scientist*" (Saunders, Lewis and Thornhill 2009, p.113). Collection of data and quantitative analysis relate to this choice.

The chosen research approach is deduction, having "*its origins in research in natural sciences*" (Saunders 2009, p.126). The purpose of the research is to be descriptive and even more explanatory. The research strategy is "case study", as it provides "*rich understanding of the context of the research*" by Morris and Wood from 1991, as cited by (Saunders, Lewis and Thornhill 2009, p.146). The case study strategy also has the ability to provide answers to "why", "how" and "what" questions, which is a purpose of the research. Both qualitative (e.g. reading the scientific literature, examining secondary and tertiary documents) and quantitative methods (using sheet balances for analysis of success criteria for incumbent companies) will be used for data collection and data analysis. This can be referred to as "*mixed-model research*" as described by (Saunders 2009, p.183). Originally planned as longitudinal, time horizon of the study changed to end also as a "snapshot" or "cross–sectional" which was added during the course of the study. So, average phenomena in the chosen time period were observed but additionally also in the last available year so as to be able to compare the two.

2 LITERATURE REVIEW

2.1 INTRODUCTION

The role of the literature review is to find out what is already known on some subject. It is necessary to acquire the *„awareness of the current state of knowledge on a subject, limitations, and how one research fits into a wider context*" (Saunders 2009, p.59), raising also subjective knowledge in the process. Unlike in academic discipline, *„business and managerial research makes use of wide range of literature*" (Saunders 2009, p.61). This wide screening was used for current research as well. Introductory reading was done on SSE in an attempt to find a possible source of its success. From stated sources, it would appear that SSE's ownership of tangible, hard to replicate power infrastructure was exactly the cause (among others) which helped it achieve good business results. Interesting to note, similar factors exist in the case of HEP, which eventually lead to the final research question. RWE, another electricity company active in more parts of the electricity chain, was also analysed thoroughly, as it, contrary to SSE, operates in Middle European countries, a part of the former eastern bloc. What was observed here was the fact that it was very difficult for RWE to differentiate from other companies in the energy markets. There exists a condition of inertia among customers, with brands *„that are little more than labels on otherwise near-identical service*"(Beech 2016). Clearly, it was difficult for new entrants to differentiate in all new markets as well, and eventually, many of the biggest independents went broke in e.g. Germany, similar to Croatian condition today.

2.2 DEREGULATION AND LIBERALISATION

Until a couple of decades ago, *„the entire electricity sector in Europe was organized as a state-owned and controlled monopoly*" and in every country there was one *„vertically integrated company*", *„responsible for the generation, transmission, distribution and supply of electricity*" – an incumbent (Beus at al. 2018). In 1996 with the first EU directive on electricity, electricity sector started to open or deregulate. The goal of this process was to *„enable competition through restructuring of the entire power sector*" (Đogić 2018, p.79), as deregulation originated from the idea that *„public companies do not have proper incentives to optimize and reduce their costs*" (Đogić 2018, p.80). As eastern bloc disintegrated in early 90's, former Warsaw pact countries, among others, started entering the EU from 2004 until 2013.

By (Schneider & Jaeger 2001), electricity sector liberalisation is part of the wider trend toward liberalisation and the withdrawal of the state from involvement in infrastructure industries. Namely, up until the last quarter of the 20th century, most of them were governed by monopolistic structures tightly controlled by the state (Schneider & Jaeger 2001, p.4). By many observers, this reduction of the role of the state in infrastructure, is a part of an even wider trend, a *„manifestation of the process of globalization and its negative effects on the erosion of state sovereignty*" (Schneider & Jaeger 2001, p.4). Regulation originally was imposed by state, trying to reduce negative economic effects such as: child labour, monopolies, pollution, excessive working hours, frauds etc. Usual consequences of excessive regulation were not something that would fit well with the concept of „perfect competition", traditionally described as:

> *"they are made up of a very large number of firms, each with negligible proportion of the market;*
> *industry products are perfectly homogenous;*
> *entry and exit from the industry are totally unimpeded*"
>
> (Bailey & Baumol 1984).

Deregulation wave starting in the 70's spanned different industries in different entities, but usually was confined to: Airline or transportation in general, gas and electricity, telecom, financial, post and similar. The process did not progress without on-going controversy, also for electricity industry. So, according to (Beder 2003) "*Electricity deregulation was supposed to bring cheaper electricity prices and more choice of suppliers to householders*". Instead it has brought "*wildly volatile wholesale prices and undermined the reliability of the electricity supply*" (Beder 2003).

One of the proclaimed goals of liberalisation is *„to increase the market size*", and to establish *„the perfect competition in the market, where the most efficient producers have the largest market share*" (Đogić 2018). Benefits are then *„passed on to customers and the economy in the form of lower price and costs*" (Jamasb & Pollitt 2005).

Expected consequences of liberalisation were: reduction in electricity price, improvement in the level of service, reduction in the price differences among countries, the option for each customer to choose a supplier, and an increase in the efficiency of the sector by reducing the need for the construction and maintenance of reserve capacities (Tominov 2008). These are the „pros" of the liberalisation.

At present, current EU electricity market liberalisation represents *„the world's most extensive cross jurisdiction reform of the electricity sector involving integration of distinct state-level or national electricity markets*" (Jamasb & Pollitt 2005). It is centrally driven by the European Commission, with the long term objective of *„a single European energy market*" (Jamasb & Pollitt 2005). Without this support, the reform *„would have been considerably slower*" (Jamasb & Pollitt 2005). Namely, after electricity crisis in California in 2000-2001, *„restructuring process has slowed down significantly and many states have put their reform plans on hold*" (Jamasb & Pollitt 2005). It was observed that the consequences of blackouts were quite severe, which was a materialisation of a worst case scenario, an example of the „cons" of liberalisation. The original intention of the introduction of the „cost-of-service model of regulation" in 1920's was exactly an insurance against *„market manipulation, volatile prices and outages in exchange for a relatively small penalty in inefficiency*" (Duane 2002).

The role of incumbents' market power and its deterrent role to new entrants is recognised and also analysed, e.g. in banking industry. One of the examples is Italian banking market after opening. The experiences observed seem to be relevant for some other industries as well.

The existence of a „*relatively small potential up-side benefit in the form of moderately reduced rates and improved efficiency at the risk of huge downside costs and decreased reliability*“ coming from deregulation, (Duane 2002) is only one of the specifics of the electricity system and challenges for the deregulation process. The other are the physical characteristics of the system.

Three most distinguished features describing electricity system are:

- Huge sunk costs connected to physical infrastructure and corresponding functions: power plants-generation, lines-transport and distribution, connections to consumers - sales;
- Necessity of vertical integration of the indicated functions, with each function having „different economies of scale“;
- Synchronicity of the physical phenomena in the system. The storage of electricity is still practically not possible on the large scale even lately, so the balance between production and consumption needs to be preserved in all nods all the time (Jamasb & Pollitt 2005).

2.3 LIBERALISATION AND DEREGULATION OF ELECTRICITY SECTOR IN CEE COUNTRIES

Generally, despite formal liberalisation of the electricity market, „*changes in the power sector in many European countries were rather slow*“ (Đogić 2018). In regard to former eastern countries, there are some specifics. By (Đogić 2018) it is recognised that the process of adaptation for new countries remains far more difficult for electricity utilities, as there is a significant negative legacy. The first difference is that electricity was mostly traded as a commodity, which needed to be available to „*all customers regardless of the price*“ (Đogić 2018). The result was that the prices were very low, leaving utilities without investment potential. The development was nevertheless pursued through various types of state intervention. Other difficulties were “*surplus of employees with low efficiency, lack of managerial skills and inferiority of economic development of the related countries*“ (Tominov 2008).

After deregulation, incumbent utilities „*wanted to retain their market share*“ and „*exploit their positions of formerly vertically integrated state-owned monopolies as well as their connections to the governments and regulators in order to influence market entry and secure their positions*“ (Đogić 2018). It considering indicators such as ability of customers to switch suppliers, possibility of entrance, absence of excessive concentration of asset ownership, decoupling of transmission and production etc.. It was observed that progress in „*opening networks and markets was slower in SEE compared to others*“ because „*region's utility sectors are burdened with the legacy of inefficiency, underinvestment and a lack of customer focus, all inherited from the former communist regime*“ (The Economist 2010).

2.4 PERFORMANCE INDICATORS FOR COMPANIES IN ELECTRICITY INDUSTRY

The debate on objectivity of company's performance measurements is extensive and on-going. According to (Leković & Marić 2015), for big companies, with publicly accessible financial statements, this theoretical aspect is somewhat neglected, and success is expressed via means of „*financial indicators, as the total income per employee, profit per employee or the period to return investment, etc.* “. For objective measures, this is not surprising and it is also expected, as e.g. by (Novak & Sajter 2005), „*financial ratio analysis is the alphabet of the economic analysis of enterprises*“. Out of five **profitability ratios** mentioned by (Loth 2018), for the sake of simplicity and focus of the study, only Profit Margin and Return on Assets are used. **Efficiency ratios** described by (Loth 2018) are: Fixed-Asset Turnover, Sales/Revenue Per Employee, Operating Cycle, of which the first two are chosen. With the „fixed asset turnover“ the choice is made to use total assets for the calculation. The other possibility would be to use strictly „fixed assets“, also known as „capital assets or property, plant, and equipment“ (Loth 2018).

The chosen 4 ratios for incumbents are investigated for the last 10 years from all the possible sources, starting from aggregate sites. Then they will be brought into correlation with hard assets.

2.5 ASSET VALUATION

During research it proved difficult to establish market or even book value of some power equipment. In praxis, the regulatory book value of an asset has little to do with its economic value. As some companies provide only for total asset value, it is not possible to distinguish between value of assets in generators or lines. For the purpose of this research, this is yet necessary. For the purpose of replacement-cost valuation, it is necessary to have a recent source, on investment costs related to European electricity market. An attempt to find such values was successful with identification of Levelized Cost of Electricity Issue 2015 (VGB Powertech 2015), where typical values for power equipment costs for the year 2015 were provided, which was used.

3. METHODOLOGY

Research philosophy is a general term describing “*the development of knowledge and the nature of that knowledge*” (Saunders 2009, p.107). Here, positivism, “*working in a tradition of natural scientist*” is chosen as the philosophical concept. The research strategy is generally a plan of “*how the researcher will go about answering the research question(s)*” (Saunders 2009, p.600). Here, the research strategy will be a case study. Case study namely helps in: ”*understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research*” (Yin 1994, p.23). Research approach is a general term used for “*inductive or deductive research approach*” (Saunders 2009, p.600). Here, deductive approach was chosen.

Primary data is defined as “*data collected specifically for the research project being undertaken*” (Saunders 2009, p.598), while secondary data is originally collected for some other purpose. Because of the longitudinal aspect of the study, collecting primary data would not be feasible. Most data will be extracted from secondary and tertiary sources available on line, an example beeing annual reports. When it comes to the question of qualitative and quantitative analysis both will be used. Clearly an attempt will be made to use quantitative parameters for the description of “business success”, mostly from company's yearly financial statements, or sites that aggregate such data. Qualitative analysis is needed for incumbents' identification. Upon obtaining data from various sources, they were all put into an excel table. Different tables were produced based on this excel data and an attempt to find correlations was undertaken. In parallel, data were shown drawn on diagrams, so as to visually establish correlations. Mathematically, two kinds of correlations were analysed: Pearson's and Spearman's. As no sample was used, there was no need for sample analysis techniques. Among others, because of a relatively small number of companies, sensitivity analysis was performed by including/excluding some of incumbents.

4. FINDINGS/RESULTS

4.1 Incumbents – identification

Identification of incumbent companies was not straightforward. As an explanation of the rationale for the choice performed, a reminder of basic physical and economic logic of electricity is needed. There are 4 different lines of business. If one covers generation, transmission, distribution and sales in one country, all mayor parts of electricity chain are covered. Clearly, this division, description and scope are not perfect and total. There are other functions in each company, like economical, HR, telecommunications, informatics and many others. For sure in the 7 countries, some of these functions were split forming new, different companies, but such companies, although incumbents, although maybe operating in some parts in electricity business, are not the subject of this research. In some countries regulators also originated from incumbents, they keep working in electricity business, but such companies were also not persued. Even an attempt to identify them was not tried. Eventually, after rejecting also e.g. single power plant companies, single business companies etc.., 11 companies were identified: BEH, CEZ, HEP, MVM, Enea, Energa, PGE, Tauron, Electrica, Hidroelectrica and Slovenske elektrane.

4.2 BASIC DESCRIPTION OF SELECTED COMPANIES

The highest level description of individual incumbents is performed by grouping them by number of businesses they operate in. For this purpose they are shown split into 3 groups, by scope of integration of different core electricity businesses.

Only in Croatia is the situation very similar to the one before deregulation. The company HEP still owns all 4 electricity businesses, (generation, transmission, distribution and retail). The next group is the one where one of the businesses is missing from company's portfolio, typically transmission.

Table II.: Incumbents with 3 businesses

Country	Poland				Bulgaria	Hungary	Czech Republic
Company	PGE	Tauron	Enea	Energa	BEH	MVM	Cez
Functions	Production	Production	Production	Production	Production	Production	Production
	Distribution	Distribution	Distribution	Distribution	Transmission	Transmission	Distribution
	Retail	Retail	Retail	Retail	Retail	Retail	Retail

The last group of incumbents is the one that went through most changes. In Slovakia, Slovenske Elektrane does not possess any networks anymore. In Romania, the situation is the most complicated.

Table III. Incumbents with 2 businesses

Country	Slovakia	Romania	
Company	Slovenske Elektrane	Electrica	Hidroelectrica SA
Functions	Production	Distribution	Production, Hydro
	retail	retail	retail

4.3 INCUMBENTS – CAPACITIES, GENERATION AND GRIDS

After incumbents' identification, short description and grouping, next step in answering research question is identification of incumbent's assets in the area of generation capacities and networks. In table IV incumbents' power plants and networks are shown:

Table IV. Incumbents' assets

		HEP	ČEZ	PGE	Tauron	Enea	Energa	Slovenske elektrane	BEH/NEK	Electrica	Hidroelectrica	MVM
Power plants capacity installed (MW)	Nuclear	348	4290	0	0	0	0	1940	2000	0	0	2000
	Hydro	2.115	1985	1600	18	58	365	1653	2713	0	6444	0
	Coal/lignite	330	7754	10890	4572	5910	681	486	1620	0	0	0
	Wind	0	770	529	72	70	211	0	0	0	0	23
	Solar	0	125,1	1	1	0	5	2	0	0	0	0
	Biomass	4	30	69	237	159	1	0	0	0	0	0
Total NHC (MW)		2793	14029	12490	4590	5968	1046	4079	6333	0	6444	2000
Total WSB (MW)		4	925	599	310	229	217	2	0	0	0	23
Total company (MW)		4385	15720	12750	5574	6200	1340	5739	6333		6444	2023
Total Country (MW)		4878	21989	38104	38104	38104	38104	7742	10739	23580	23580	8750
Company generation 2016 (TWh)		12,5	61,1	53,7	16,8	13,6	4,0	19,0	n.a.	0	n.a.	16,4
Country generation 2016 (TWh)		12,8	83,3	166,6	166,6	166,6	166,6	27,1	45,3	65,1	65,1	31,9
Grid (1oookm)	HV grid (km)	7.69	9.85	0	0	0	0	0	15.1	0	0	4.84
	M&LV grid (km)	140	154	288	258	122	185	0	0	117	0	0
Percentage of generation (%)	NHC	64	89	98	82	96	79	71	100	0	100	99
	WSB	0,1	5,9	4,7	5,6	7,2	16,2	0	0	0	0	1,1

Source: author, based on Annual reports, corporate web pages, European Commission

Power plants are aggregated into 2 groups, so as to correspond to research questions. The first one is „NHC" group, consisting of nuclear, hydro and coal. The second is wind, solar, biomass, designated as „WSB". Third is lines. Corresponding values are shown in table V. An example of calculated values for one research question is shown in table VI. Success criteria are shown as well in figure 1, so as to visualy establish correlation.

Table V. Non-depreciated average asset class values for incumbents

	HEP	ČEZ	PGE	Tauron	Enea	Energa	Slovenske elektrane	BEH/NEK	Electrica	Hidroelectrica	MVM
Nuclear (MW)	348	4290	0	0	0	0	1940	2000	0	0	2000
Hydro (MW)	2.115	1985	1600	18	58	365	1653	2713	0	6444	0
Coal/lignite (MW)	330	7754	10890	4572	5910	681	486	1620	0	0	0
Company's NHC value (10^6 Euro)	9078	35540	21775	6919	9062	2263	14109	19654	0	21909	8000
Wind	0	770	529	72	70	211	0	0	0	0	23
Solar	0	125,1	1	1	0	5	2	0	0	0	0
Biomass	4	30	69	237	159	1	0	0	0	0	0
Company's WSB value (106 Euro)	7	2292	1450	610	461	532	5	0	0	0	58
Company's line value (106 Euro)	2770	3100	4030	3610	1710	2590	0	1590	1630	0	508
Company's 2016 total assets book value	5190	23347	15290	7560	5560	4243	9490	8804	1850	4150	4650
NHC value/Asset ratio (%)	175	152	142	92	163	53	149	223	0	528	172
WBS valus/asset ratio (%)	0,13	9,81	9,48	8,07	8,29	12,54	0,05	0	0	0	1,25
Line value/asset ratio (%)	53,4	13,3	26,4	47,8	30,8	61,0	0	0	88,1	0	10,9

Source: author, based on Annual reports 2007-2017 of 11 companies

Table VI. Companies by NHC value/asset ratio, average success criteria

	Hidroelectrica	BEH	HEP	MVM	Enea	ČEZ	Slovenske elektrane	PGE	Tauron	Energa	Electrica
NHC value/Asset ratio (%)	528	223	175	172	163	152	149	142	92	53	0
Profit margin (%)	10,8	0,5	6,9	6,0	7,4	17,5	11,1	12,2	3,8	4,7	5,8
ROA (%)	1,9	0,2	2,7	3,8	4,2	7,0	3,7	5,5	2,4	3,3	3,8
Asset turnover	0,15	0,40	0,38	0,69	0,56	0,38	0,32	0,44	0,61	0,67	0,64
Trunover/ Employee (1000 Euro)	155	129	145	318	200	264	512	145	155	235	108

Source: based on Annual reports 2007-2017 of 11 companies

4.5 ASSESSMENT OF CORRELATIONS

To assess correlation between NHC, WBS and line values to 4 success indicators, corelations using excell were calculated. Correlation coefficient enables to „*quantify the strength of linear relationship between two ranked or numerical variables*" (Saunders 2009, p.459), only an example is given in Figure 1.

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \tag{1}$$

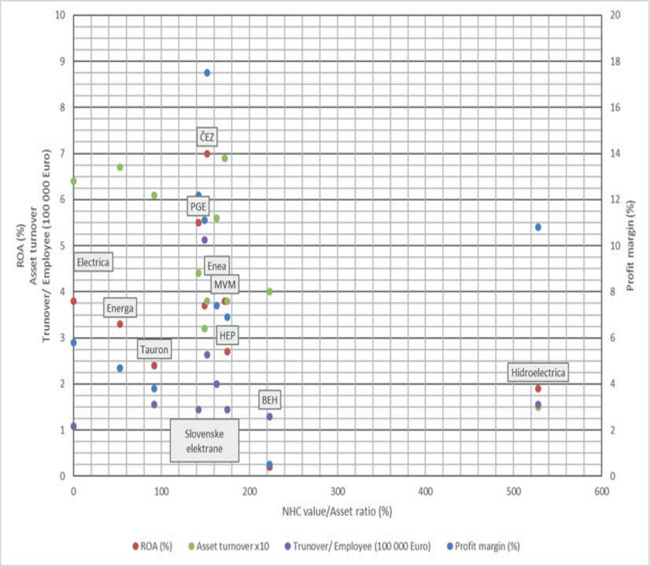

Figure 1. Average values, NHC assets linearity, shows corelations between parameters.

5. CONCLUSIONS

The first research question was: "can the ownership of hydro power plants, nuclear power plants, lignite/coal power plants by incumbent companies influence the future success of these companies, observed on the example of the last 10 years".

To try to summarise the answer to the first question: It seems that for the chosen 11 companies, when taking into account even rudimental sensitivity analysis in the described way, by omitting companies without any NHC sources or Hidroelectrica, which is more than 2 sigma away from the nearest other entry, there is no possibility to predict success of the companies observed through the chosen 4 success criteria, related to NHC value/asset ratio. The only clear, not changing correlation is the negative correlation of the NHC value/asset ratio to asset turnover. The interpretation of this is that with rising percentage of NHC assets, it gets more and more difficult to turn around assets.

The second research question was: "Can the ownership of "new" renewables or development of "new" renewables such as wind, solar and bio mass (WBS) by incumbent companies, influence the future success of these companies, observed on the example of the last 10 years".

As a conclusion to the second question: As the percentage of WBS sources was found to be rather low, in comparison to total assets, all conclusions must be taken with caution. More than a half of the observed companies have less than 1% of their total assets in such sources. If one takes average values, for the 2007-2017 period, most success criteria have positive correlations. The more WBS the company has, the higher the average success. But this fact changes lately. In 2016, most correlations are getting negative, meaning that success related to the same input diminishes with time. There is one exception. Turnover/Employee is negative in all cases, meaning that the higher percentage of WBS assets, the lover Turnover/Employee gets.

The question 3 was: "Can the ownership of transmission and distribution networks by incumbent companies influence the future success of these companies, observed on the example of the last 10 years".

Possession of lines had a negative correlation to profitability, but recently picture somewhat changed towards rising profit ratios. The same is true for ROA. Asset turnover is positive, but Turnover/Employee clearly negative.

Additionally, taking into account all stated considerations, it seems that no conclusions on success can be drawn based on division of incumbent companies according to number of main electricity businesses they operate.

Finaly, it can be observed that profit margin is negatively correlated to year of entry. The longer the company is in the EU, the lower the profit gets. ROA also falls during time. Asset turnover falls, meaning that the longer the company operates in the EU, the higher the asset turnover gets. Finally, there is a clear sign that the longer the company operates in the EU, the less employees it needs to earn the same amount of money.

REFERENCES

[1] Bailey, EE 1984, Deregulation and the theory of Contestable Markets, Yale Journal on Regulation, Volume 1, Issue 2

[2] Beech, M 2016, Comment: Repairing the NPower brand, Utility week, Faversham House Ltd., UK

[3] Beus, M, Pavić, I, Štritof, I, Capuder, T & Pandžić, H 2018, Electricity Market Design in Croatia within the European Electricity Market recommendations for Further Development, MDPI, Basel, Switzerland

[4] Bičak, D 2018, RWE od HT-a preuzeo poslovanje strujom, Večernji List, d.d. Styria Media Group AG

[5] Đogić, M 2018, GROWTH STRATEGIES OF ELECTRIC UTILITIES IN CONTEXT OF DEREGULATION AND LIBERALIZATION OF ELECTRICITY MARKET, Management: Journal of Contemporary Management Issues, University of Split, Croatia

[6] Energetika-Net 2016, HERA izdala certifikat HOPS-u, Energetika marketing d.o.o., Zagreb

[7] Jamasb, T & Pollitt, GM 2005, Electricity Market Reform in the EU, The Energy Journal, Vol. 26

[8] Johnson G, Scholes, K and Whittington, R 2005, Exploring Corporate Strategy, Prentice Hall, London

[9] Leković, B & Marić, S 2015, Measures of small business success/performance – importance, reliability and usability, Industrija, Vol.43, No.2, 2015, Ekonomski institut, Beograd

[10] Loth, R 2018, Financial Ratio Tutorial, Investopedia, New York

[11] Novak, B & Sajter, D 2005, Financijski omjeri, trans, Ekonomski vjesnik br. 1 i 2 (18) 89-96, Sveučilište J.J.Strossmayera u Osijeku, Ekonomski fakultet u Osijeku, Osijek, Hrvatska

[12] PWC 2016, The Future of Power Utilities in Central and Eastern Europe Disruptive global trends versus regional particularities, PriceWaterhouseCoopers Magyarország Kft, Budapest

[13] Saunders, M, Lewis, P and Thornhill, A 2009, Research methods for business students, Prentice Hall

[14] Schneider, V, & Jaeger, A 2001, The Privatisation of Infrastructures in the Theory of the State, workshop on Regulatory Reform at the 29th Joint Sessions of Workshops, Grenoble, France

[15] SSE plc. 2012, Annual report 2011, SSE plc., Inveralmond House, 200 Dunkeld road, Perth UK

[16] Tang, A 2018, Firm Dynamics and competition in the electricity market, Orebro studies in Economic 39, Orebro University, Orebro, Sweden

[17] The Economist 2010, Changing Direction: Reform of energy utility sectors in Central Europe, The Economist Intelligence Unit Ltd., New York, USA

[18] Tominov, I 2008, Liberalisation of the electricity market – is it meeting expectations, Journal of Energy: Energija, Ulica grada Vukovara 37, 10 000 Zagreb, Croatia, Vol.57 No.3 June 2008

[19] VGB Powertech 2015, LCOE, Issue 2015, VGB PowerTech e.V. | Deilbachtal 173, Essen, Germany

[20] Vlahinić Lenz N, Rosanda, A and Jakovac, P 2015, ELECTRICITY SECTOR IN SOUTHEAST EUROPE: CHALLENGES OF EUROPEAN INTEGRATION, Proceedings of ADVED15 International Conference on Advances in Education and Social Sciences, 12-14 October 2015-Istanbul, Turkey

[21] Yildiz, S & Karakas 2012, A, Defining methods and criteria for measuring business performance: a comparative research between the literature in Turkey and foreign, Procedia – SBS, Volume 58

[22] Yin, RK 1994, CASE STUDY RESEARCH Design and Methods, 2nd edition, Thousand Oaks, Calif. : Sage, 2455 Teller Rd, Thousand Oaks, CA 91320, USA

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