POLITEHNICA
University of Bucharest

DOCTORAL SCHOOL OF
ELECTRICAL ENGINEERING

Ph.D. THESIS
SUMMARY

CONTRIBUTIONS REGARDING THE ANALYSIS OF NONLINEAR CIRCUITS IN PERIODIC REGIME, ASSOCIATED WITH PHOTOVOLTAIC SYSTEMS

Ph.D.: **Eng. Bogdan-Alexandru ONOSE**

Ph.D. Supervisor: **Prof. dr. eng. Ioan Florea HĂNȚILĂ**

BUCHAREST 2023

SUMMARY CONTENT

ACKNOWLEDGEMENT

I would like to express my unbounded thanks to Mr. Prof. Dr. Eng. Florea Ioan HĂNȚILĂ, the scientific supervisor of this doctoral work, for the guidance and involvement given with generosity and kindness both during the research period, as well as during the entire period of developing the thesis of doctorate.

I also want to thank the National Institute for R&D in Electrical Engineering ICPE-CA, for the support provided in the experimental testing part and the experimental validation of the obtained results. Thus, I would like to give special thanks to the team of the Photovoltaic Systems Laboratory, especially to Mr. Ion MURGESCU and Mr. Ștefan-Adrian ȘONTEA for their availability and involvement, throughout the duration of this doctoral thesis.

Last but not least, leaving the most important thing for last, I would like to express my utmost gratitude and thanks to my family, for all the support they have given me throughout the years of my studies to complete them successfully.

Bogdan-Alexandru Onose

1. INTRODUCTION IN RENEWABLE ENERGY SOURCES

The EU's interest in supporting renewable energy sources (RES) is justified for several reasons, one of which is the development of a more sustainable energy system, as RES contributes to the reduction of local pollutants and greenhouse gas emissions, which help mitigate climate change and improve air quality. The EU has a long-term policy to promote RES, and over the years, numerous legislative measures have been taken to support it. In addition to these policies, the EU has implemented a series of initiatives and specific objectives for the penetration of RES in the energy mix.

By creating the National Integrated Plan for Energy and Climate Change 2021-2030 (NIPECC), which will form the basis of the country's strategy in this field, Romania has already made significant progress in this regard and following the recommendations of the European Commission, the plan is being changed, and so Romania will raise its target for the share of renewable energy in gross final consumption to 30.7% by 2030. In addition, priority will be given to the installation of an additional capacity of 7GW of renewable energy by 2030 [17].

The Romanian Energy Strategy 2020-2030, with the perspective of 2050, foresees the growth and development of the competitiveness of the Romanian Economy, the quality of life and the protection of the environment are inextricably linked to the development and modernization of the energy system.

2. THE CURRENT STAGE OF DEVELOPMENT IN THE FIELD OF ANALYSIS

According to the data published by National Energy Regulatory Authority (ANRE) [25], there are currently 633 photovoltaic power plants (PPP), of which non-dispatchable <1MW are 356 PPPs (with a total installed capacity of 164MW) and between 1MW-5MW there are 217 PPPs (with a total installed capacity of 597MW), and dispatchable >5MW are 60 PPPs (with a total installed capacity of 637MW). Taking these elements into account, I performed an analysis of the existing situation for dispatchable photovoltaic plants based on the data provided by Transelectrica [26], and out of the 60 existing dispatchable PPPs, 36 PPPs were installed only in 2013, having until 2021 inclusive 8 years of operation.

In the period 2011-2013, in Romania, equipment was installed mainly based on the unique "lowest price" criterion, this being visible today through the prism of the performance of these photovoltaic systems. For this reason, we performed a global analysis on the production of dispatchable photovoltaic parks installed in Romania in 2013, they represent over 65% of the total dispatchable systems installed to date.

The presented results show a lower performance for 78% of the analyzed photovoltaic parks, this being attributed to the accelerated degradation of the equipment, but the causes of equipment interruption / non-functioning for other reasons cannot be excluded (equipment interruptions / non-functioning are to be avoided in photovoltaic systems).

The low performance of dispatchable photovoltaic parks is directly related to their income, more precisely the losses that occur as a result of the accelerated degradation of the equipment, and in some cases significant values can be reached.

According to the situation presented, there is a phenomenon of accelerated degradation of photovoltaic systems in Romania, which can mainly arise from two major causes: the poor quality of the installed equipment and the reduced level of maintenance or its lack.

By comparing the frequency and impact of the occurrence of equipment quality problems in photovoltaic parks, I can say that photovoltaic modules have a significantly greater influence both in number and impact on the operation of these systems. Efficiency is essential in the operation of a photovoltaic system, and simply installing a photovoltaic system is not the end of the story: regular maintenance is required to ensure that each solar panel produces the maximum amount of energy possible.

Although photovoltaic systems generally require little maintenance and can run smoothly for years, they are still fundamentally an electrical system with few moving parts that wear out over time, and this means operators must comply with legal regarding regular inspections and operational safety [27].

In general, a distinction can be made between four types of maintenance:

A. **preventive (or planned) maintenance:** includes checks and standard maintenance of the machines according to the instructions in their technical manuals, with a defined frequency, chosen according to the environment and the warranty clauses of the maintenance contract.

B. **corrective maintenance:** is the intervention that is usually carried out as a result of the findings during preventive maintenance, when it is discovered that an inverter is not working correctly.

C. **conditional maintenance:** real-time data from PV systems is used to predict failures and/or degradation of power generation performance, as well as to prioritize maintenance and resource allocation activities.

D. **reactive maintenance:** it is the one that is carried out after the equipment has stopped working. This differs from preventive maintenance, which is carried out according to a well-established schedule. Reactive maintenance (also known as "failure maintenance") is the process of returning equipment to normal operation after it has failed.

Taking into account the elements presented in this chapter, I found that a thorough analysis of the accelerated degradation of photovoltaic systems in Romania is necessary, taking into account only the poor quality of the installed equipment.

3. FUNCTIONING PRINCIPLE OF PHOTOVOLTAIC SYSTEMS

The operating principle of the solar cell is to convert the energy from the sun directly into electricity. Semiconductor materials such as: silicon, gallium arsenic, cadmium telluride, copper-indium selenite alloys are used in this process. The most common type of module in existence is crystalline silicon, and currently approximately 95% of modules in existence worldwide are of this type.

The typical crystalline silicon solar cell is composed of 2 differently charged layers, so in its construction the first layer is negatively charged with phosphorus atoms and the next layer is positively charged with boron atoms. An electric field is thus created at the p-n junction, which produces the separation of charges (electrons, vacancies) activated by solar radiation.

A non-linear circuit is an electrical circuit whose parameters vary depending on current and voltage. In other words, a photovoltaic module represents a non-linear circuit in which the circuit parameters (resistance, inductance, capacitance, waveform, frequency, etc.) are not constant.

A circuit operates in periodic regime if all currents and all voltages are periodic functions of the same period. If at least one current or voltage is not sinusoidal, the regime can be said to be non-sinusoidal or deforming. This regime appears as a permanent regime (asymptotic behavior when $t\rightarrow\infty$) in a usual circuit in which all excitations are periodic of the same period and are related to $t=0$ [29].

In order to achieve a more accurate mathematical modeling of PV modules, the equivalent circuit and the underlying equations of the single-diode, two-diode and three-diode mathematical model were exemplified. The two-diode model has seven unknown parameters compared to the five parameters of the single-diode model, thus being preferred in periodic-regime equivalent circuit analysis.

To obtain higher powers, several solar cells are interconnected, with two connection possibilities: connecting the solar cells in series or in parallel. In the case of photovoltaic modules, solar cells are generally connected in series to increase the voltage value of the module, and in the case of high-power photovoltaic modules, strings of cells are connected in parallel.

In order to be able to compare different solar cell technologies or even different types of photovoltaic modules, it is necessary that this comparison takes place under specified uniform conditions [32]. These standard conditions are based on the international standard IEC 60904 and are as follows [33]: solar radiation value = 1000 W/m2, module temperature = 25oC (with a tolerance of ±2oC), light spectrum defined (solar radiation spectrum distribution according to IEC 60904 -3) having air mass = 1.5.

In short, the curves are characterized by the following 3 points:

A. The MPP (maximum power point) is the point on the characteristic curve at which the solar cell operates at maximum power.
B. I_{SC} short circuit current is about 5-10% higher than I_{MPP}.
C. V_{OC} open circuit voltage has values of 0.5-0.6V for crystalline cells and 0.6-0.9V for amorphous type cells.

The efficiency of the photovoltaic mode is determined by the ratio of the electrical energy output of a solar cell to the incident energy in the form of solar radiation. The energy conversion efficiency (η) of a solar cell is the percentage of solar energy the cell is exposed to that is converted into electrical energy. This is calculated by dividing the energy produced by the module at the peak power P_{MPP} (W), by the received radiation R (W/m^2) and the surface of the solar cell S (m^2).

Over the entire lifetime of the equipment (25 years for photovoltaic modules), the annual amount of electricity produced varies, due to the gradual wear and tear of the photovoltaic modules and the consequent decrease in their efficiency. The vast majority of photovoltaic module manufacturers guarantee their products with respect to module wear over time, namely [34]: 10 years for 90% of production and 25 years for 80% of production.

4. INFLUENCE FACTORS OF PHOTOVOLTAIC ENERGY PRODUCTION

The first factor influencing the production of photovoltaic energy is solar radiation and opacity, since the sensitivity to the light spectrum describes the range of wavelengths in which a solar cell works most efficiently and the influence on the efficiency of the solar cell for different values of radiation. While crystalline solar cells are sensitive to the long wavelength of the solar radiation spectrum, thin film cells utilize visible light intensity better, and amorphous silicon solar cells can absorb short wavelengths optimally [43].

The second influencing factor is represented by the tilt angle of the photovoltaic module, so that the incident angle of the sun is as close to perpendicular as possible. The incidence of solar rays on an inclined photovoltaic module depends on the angle of inclination of the module measured from the horizontal β and the angle of elevation α.

In addition to the angle of inclination of the modules and the angle of incidence of the sun, there is another angle (azimuth) that affects the performance of a photovoltaic system. The azimuth represents the angle formed between the south direction and the perpendicular line that meets the photovoltaic module. It is found that for a variation of $\pm 5^o$ of the azimuth, the power loss is not significant, only for an azimuth greater than $\pm 25^o$ the efficiency of capturing solar rays drops to about 98%.

Dust is another factor of influence that is least taken into account in the case of the operation of a photovoltaic module, but which in certain cases can have a significant influence. Dust and dirt particles will accumulate on the photovoltaic modules over time, and in areas with heavy traffic, pollution, arid areas and with a low volume of precipitation, the losses due to the layer of dirt deposited on the modules can reach 10-15% [46].

Another important factor is the temperature, and in the case of crystalline silicon modules, the voltage is quite strongly affected by the temperature of the photovoltaic module, and the value of the current almost does not change with changes in the temperature of the modules, it increases slightly with the increase in temperature [47]. During the summer, the power reduction due to high temperatures can be as high as 35% compared to STC conditions, and to reduce power losses, the photovoltaic modules must release heat into the environment easily or have sufficient ventilation.

A final influencing factor is represented by shading, where crystalline modules, thin-film modules have an increased tolerance to shading, since in the case of standard modules with individual silicon cell structure shading of a cell in most cases leads to the limitation or failure of half of a module. In this case, the question arises how we can protect a photovoltaic cell or a photovoltaic module from the destructive effects of partial or complete shading.

A simple and effective way to protect photovoltaic cells against the destructive effects of shading is to connect a bypass diode across each photovoltaic cell of a series-connected string [51]. The implementation of bypass diodes helps preserve the performance of the series connected string by restricting the reverse bias voltage generated in any partially shaded cell and thereby reducing the electrical power that can be dissipated by that cell. When the cell is shaded or partially shaded, then the bypass diode becomes active and the shaded cell no longer produces electricity and behaves as a semi-conductive resistor.

5. ANALYSIS OF PHOTOVOLTAIC MODULES DEFECTS

There is a lot of discussion and there are different opinions about the quality and performance of photovoltaic modules as well as their lifespan. To put order in this dispute I took as a reference the definition given for a defective photovoltaic module expressed in Subtask 3.2 Review of Failures of Photovoltaic Modules; IEA PVPS Task 13 [52]: A PV module is defective if its power has irreversibly degraded under normal operating conditions or creates a safety problem. A purely cosmetic problem that has no consequences for power or operational safety is not considered a PV module defect.

Information on photovoltaic module failures has been available since the early 1970s. According to data reported by the National Renewable Energy Laboratory (NREL), the most common degradation modes in photovoltaic modules over the past 10 years were hot spots (33%), followed by ribbon discoloration (20%), glass breakage (12%), EVA film discoloration (10%), cell breakage (9%), and potential-induced degradation (PID, 8%) [54].

Photovoltaic modules are subjected, throughout their lifetime, to mechanical stress (mainly wind), solar radiation, humidity, heat, snow, hail, salt fog, acid rain, dust, wind that drives abrasive particles, etc., thus I presented the mechanisms of aging as well as failure mechanisms of non-linear circuits in periodic regime of photovoltaic modules.

The main phenomena that occur in photovoltaic modules and that lead to their failure and/or premature aging are: degradation of power, corrosion of electrical contacts, cell breakage, interruption of connections between cells, delamination of the EVA film, formation of air bubbles between the cell and the film EVA, discoloration of the EVA film and/or the backsheet film, snail marks, fracturing of the backsheet film (the film behind the module), degradation of the ribbon weld (interconnection tape) on the photovoltaic cell, burning of the encapsulant and the backsheet film due to the electric arc or the hot spot of the "hotspot", failure of the bypass diodes, breaking of the glass, degradation of the anti-reflective layer of the glass, degradation of the adhesive that fixes the junction box, falling of the aluminum frames.

The external factors listed, which act on the modules mounted in the PPP, obviously affect all photovoltaic modules. But the power degradation, for products manufactured with compliant materials, is below the limit of 0.8%/year [56]. This limit is imposed by the photovoltaic module performance guarantee offered by all manufacturers who have committed to manufacture in accordance with the IEC 61215 standard.

Defects occur predominantly in childhood and middle life. Infant defects generally occur due to non-conformities on the manufacturing line such as imperfect contacts, improperly fixed frames on the modules that come off during the winter, water ingress into the junction box and electrolytic corrosion of the terminal contacts, etc. Defects or premature wear that occur during the average life period are generally due to the use of non-compliant materials in the manufacture of the product.

Very common are the defects due to the EVA foil, the backsheet foil and the connection tapes of the cells: yellowing of the encapsulated, corrosion of the tapes, penetration of moisture through the protective film causing premature corrosion of the connections. Photovoltaic plants built in Romania, especially those built in 2013, suffer from these defects in a very large proportion [59]. If during the average life period the module complies with the product and performance warranty conditions, the probability of failure in the following years is very small, from here onwards only wear and tear intervenes.

Photovoltaic module defects can have external or intrinsic causes. Intrinsic causes are due to non-conforming materials and/or their non-conforming processing. But all this is generated by poor quality supervision throughout the manufacturing process, from procurement to delivery.

There can be a number of defects in photovoltaic modules that come directly from production, and if they do not affect the rated power or safety in operation, nor cause an acceleration of the degradation of power or safety, they are not considered major defects. Defects in the structure of the silicon crystal or striations on photovoltaic cells, as well as processes that take place in production, which leave visible traces and may appear as a defect to the uninitiated, but these are not considered defects.

6. CASE STUDY - ANALYSIS OF REPOWERING SOLUTIONS FOR A PHOTOVOLTAIC PARK

6.1 Measurements and input data validation

The case study analyzed in this Ph.D. thesis is based on the application of repowering solutions for the 0.97MWp EVO Photovoltaic Park, in Romania, where it is aimed to bring the performance back to a normal level, compared to its lifetime, following the analysis and determining the degree of accelerated degradation of the modules in the site.

The 0.97MWp EVO Photovoltaic Park, built in 2014, consists of 3,960 photovoltaic modules of 245Wp/pc (6 strings x 22 modules connected in series), connected to 30 inverters of 28.6kW/pc.

Taking into account the significant number of inverters that are part of the EVO Photovoltaic Park, I analyzed the evolution of the energy produced over a period of 2 weeks from March 2022. The analysis was based on the comparison of the total energy in direct current (DC) at the input to the inverters, for the same climatic and solar radiation conditions, to highlight the inverters with low performance. I found that there is a variation of about 5.4% between the energy supplied by the modules to the inverters of the EVO Photovoltaic Park, under identical daily weather conditions, so I did not find a pattern with either consistently lower energy or consistently higher energy.

In order to refine the analysis over the group of inverters in the EVO Photovoltaic Park, I selected a number of 3 days with stable atmospheric conditions and optimal solar radiation (over 800W/m^2), to be able to compare the energy provided by the photovoltaic modules on each of the inverter inputs at STC conditions, thus I was able to identify the energy variations between the DC inputs of the inverters, as well as the differences between the 2 MPPTs of the same inverter, with a comparison frequency of 15 minutes.

In addition to the analysis of each inverter, I also compared the average values of the energy provided by the photovoltaic modules in DC on all existing MPPTs in the EVO Photovoltaic Park, and following the analysis carried out, I centralized the inverters with a variation greater than 2% between MPPT1 and 2, in order to identify the causes of these variations during the measurement stage in the EVO Photovoltaic Park. Thus, 4 inverters with a variation greater than 2% and 2 inverters with a variation greater than 3% between MPPT1 and 2 were identified.

Moving from the analysis of historical data, to performing actual measurements in the field and laboratory, a methodology for measuring the nonlinear I-V characteristic was defined. Currently, there are ten standards, nine from the 60904 series and one from the 60891 series, applicable to the components and processes involved in the measurement of the characteristic for the non-linear equivalent circuits of the photovoltaic module [65], these elements are transposed into European norms through the European Committee for Electrotechnical Standardization CENELEC [66] and then to national standards.

In this context, the IEC 60904-9 standard defines a method for classifying solar simulators, which includes three quality indicators. Suppliers of solar photovoltaic power measurement simulators must specify the respective class for each indicator. Class AAA solar simulators are currently commercially available and are qualified by independent parties.

To measure the non-linear current-voltage characteristic (I-V) of the equivalent circuit for the photovoltaic modules in the EVO Photovoltaic Park, I used the existing infrastructure within the Photovoltaic Systems Laboratory (PVLAB) of INCDIE ICPE-CA. The Photovoltaic Systems Laboratory (PVLAB) is accredited by RENAR no. LI 1228 of 2020 for carrying out measurements on site in natural light and in the laboratory in simulated sunlight.

From the list of inverters with greater than 2% energy variation between MPPT 1 and MPPT 2, I performed on-site measurements for INV 8, 11, 22, 23 and 26, as well as for those with greater than 3% variation related to INV 12 and 27. On-site measurements were carried out for each string of photovoltaic modules to see if there are variations between them and to be able to identify any defects in order to perform a more thorough inspection at the photovoltaic module level, by prioritizing the strings with problems.

From the analysis of the on-site measurements for the 7 inverters selected in the preliminary report, with a variation greater than 2%, respectively 3% of the energy between MPPT 1 and MPPT 2 was determined, I made a classification of them according to the average value module degradation on each inverter. Based on this classification, INV 8 and INV 22 were eliminated because their performance was caused by external factors.

Table 0-1 Measured values on site for inverters classification

Name of inverter	Average degradation value of module / invertor measured	Causes identified by measurements
INV 8	**-14,22%**	Shading due to vegetation
INV 11	**-14,38%**	Low performance of some modules in the string
INV 12	**-14,87%**	Low performance of some modules in the string
INV 22	**-16,01%**	Module with cracked glass surface
INV 23	**-12,74%**	Low performance of some modules in the string
INV 26	**-15,29%**	Low performance of some modules in the string
INV 27	**-12,07%**	Low performance of some modules in the string

To verify the measurements made at the site of the EVO Photovoltaic Park, in order to apply the repowering solutions, I also performed measurements in the laboratory for a limited number of photovoltaic modules. The laboratory measurement of the current-voltage characteristics (I-V) of the photovoltaic modules in simulated light, carried out according to the procedure of the SR EN 60904-1 standard, art. 4.2. Measurements in simulated light.

I selected 6 photovoltaic modules from INV 26 from the EVO Photovoltaic Park, and the tests were carried out with the Pasan HighLIGHT LMT solar simulator, class A+. The results show both the real current-voltage curve (I-V) of the tested photovoltaic modules and the values of the main parameters that characterize a photovoltaic module. The resulting values for four photovoltaic modules showed values between 209-210W for each module tested, and two of them had values of 167W and 155W.

From the laboratory measurements made on the selected photovoltaic modules from the EVO Photovoltaic Park, I first confirmed the results of the site measurements and determined the real degree of degradation / accelerated aging of the photovoltaic modules, finding out their real power.

The fill factor was calculated for each photovoltaic module measured and this is essentially a measure of the efficiency of a photovoltaic module, however deviation from the expected value or changes in the fill factor can give an indication if a fault is present.

Using the photovoltaic simulation software - PVSyst, I made an estimate of the energy production, for the 7th year of operation of the EVO Photovoltaic Park, on a single inverter, which helps me highlight the energy gain in the case of implementing the proposed repowering solution. Thus, according to the technical sheet of Risen photovoltaic modules, the manufacturer guarantees an initial power degradation, occurring in the first year of 3% due to the "LID" light-induced degradation phenomenon, and in the 12th year the maximum power degradation must be up to value of 90%, resulting in an average linear degradation limit starting from year 1 to year 12, as having an average value accepted by the manufacturer of power degradation for photovoltaic modules of 0.63%/year.

Following the simulation, I determined that each inverter in the EVO Photovoltaic Park equipment should deliver to the network a quantity of energy equal to 40,851 MWh/year, taking into account the average radiation values of the last 20 years. This amount of energy represents the value without applying the degradation factor of 7.4% related to the 7 years, from where we calculated the reference value of 37,824MWh/year/inverter for the EVO Photovoltaic Park in the 7th year of operation. From the analysis of the historical data of the energy delivered to the network of the EVO Photovoltaic Park, the value for the 7th year of operation was an average of 35,019 MWh/year/inverter, which results in an average of 2,805MWh/year/inverter energy lost through the accelerated degradation of photovoltaic modules. This energy can be fully or partially recovered by applying appropriate repowering solutions.

During the inspection of the EVO Photovoltaic Park I discovered that a significant number of panels showed an advanced degree of degradation even though they had been installed since 2014. About 80% of the panels showed a change in the color of the central band of connection between the cells (copper band coated with Sn-alloy Pb) and approximately 3% of them had burns of the foil behind the panel (backsheet foil). The cause of the phenomenon discovered in the EVO Photovoltaic Park, later proven by the detailed analysis of the photovoltaic modules selected for measurements in the laboratory, is the corrosion of the interconnection strips of the photovoltaic cells under the action of acetic acid which is formed by the reaction between the compounds of the EVA encapsulating film (ethylene-vinyl- acetate) and water vapor penetrating through the backsheet.

After the analysis, I concluded that this process of degradation of the contact resistance is slow and occurs when the corrosion, produced by the acetic acid, takes place behind the strip, in the area of electrical contact with the cell. All the measured photovoltaic modules have powers below 210W, which means a power degradation of at least 11.2%, from which a power degradation rate of 1.6%/year results. The value of 1.6%/year of the power degradation rate for the EVO Photovoltaic Park is more than double compared to the maximum allowed value of 0.63%/year validated by simulation, for compliance with the performance condition of the photovoltaic modules according to the technical sheet.

If we take into account the value of the annual linear increase of the rate of 1.6%, we arrive that after 20 years of operation the photovoltaic modules in the EVO Photovoltaic Park equipment will present a maximum power of 129Wp, which would mean 52% of the initial power instead of 80% of what was guaranteed on delivery.

6.2 Repowering solutions for photovoltaic installations

Repowering is the process of replacing defective photovoltaic (PV) modules and/or modules showing premature power degradation with new photovoltaic modules, but of the same type and with rated powers equal to the rated power of the original module. The most common technical reason for repowering is the so-called degradation of the power of the modules, which produces over time, for each module, a loss of their power. The nominal power of a photovoltaic module is the power that it has written on the label and in its technical data sheet, this is also called peak power because it represents the power measured in standard STC reference conditions.

Repowering can mean replacing or partially rearranging modules or replacing inverters, so as to return the photovoltaic system to the initial parameters from the moment of commissioning. Regardless of the level of modifications made, the general objective of repowering is to increase the performance of the existing system, bringing it to the original parameters from the commissioning date.

The replacement or rearrangement of photovoltaic modules with major defects can only be decided on the basis of the visual inspection on site, the analysis of the operation of the photovoltaic modules with the thermal imaging camera and by carrying out a thorough campaign of measurements either on site or in the laboratory.

For inverters, a quick repowering solution is to perform corrective maintenance by checking and updating the software version used by them. Another solution would be to replace low-performing inverters (identified by an AC and DC inverter verification campaign), or based on a historical failure analysis. to discover which had the higher defect frequency.

In order to be able to take into account the option of rearranging the photovoltaic modules, the importance of "mismatch" losses (MML) must be highlighted. Mismatch losses are caused by the interconnection of photovoltaic cells or modules, which do not have identical properties or operate under different conditions. Mismatch losses are a serious problem because the power of the entire PV module is determined and limited by the lowest power solar cell.

Mismatch in photovoltaic modules occurs when the electrical parameters of a solar cell are significantly changed compared to those of the other solar cells with which it is connected. The impact and power loss due to mismatch mainly depends on the operating point of the PV module, the circuit configuration and the parameter (or parameters) that are different from the rest of the solar cells.

Researches on the MML phenomenon have been mainly carried out by using one of two methods: (I.) the comparison of the ideal maximum power of a photovoltaic array with the actual maximum power, calculated by progressively synthesizing the I-V curves of the arrayed modules until the end is reached to the complete photovoltaic module string; (II.) MML estimates of photovoltaic module strings, composed of modules with known or statistically generated I-V characteristics.

In the case of replacing the photovoltaic modules, this action is done only after the measurement campaign of the photovoltaic modules and the determination of their I-V characteristics, resulting in exactly how many photovoltaic modules need to be replaced for each individual string. The photovoltaic modules in the strings connected to the inverters with significantly lower production will be prioritized, the photovoltaic modules with defects will be identified, followed by their replacement with new ones or ones with optimal operating parameters.

The identification of the optimal solution for equipping the EVO Photovoltaic Park is based, on the one hand, on the opportunity to integrate a new and advanced solution to increase the production of photovoltaic electricity by rearranging or replacing the photovoltaic modules, and on the other hand, studying the behavior of the photovoltaic modules analyzed under site conditions proposed.

Based on the values obtained from the measurements made on site and in the laboratory, I classified the photovoltaic modules into three main categories, namely:

I. Photovoltaic modules with a significant power degradation (over 10%), well below the performance limit corresponding to the years of operation or defects that endanger their operation and/or the strings

II. Photovoltaic modules with average power degradation, at the limit of an acceptable level of degradation and showing no visual defects

III. Photovoltaic modules with minimal degradation, which have the output power within the normal degradation limit

In order to define the best repowering solution for the EVO Photovoltaic Park, I have proposed the following methods for repowering:

- For category I photovoltaic modules: the repowering solution is to replace them with new ones of similar power to the nominal power at EVO Photovoltaic Park commissioning and install them on dedicated rows of new photovoltaic modules.
- For category II and III photovoltaic modules: the repowering solution is to rearrange them in rows of equal powers after a prior selection, in order to maximize the performances of the rows of photovoltaic modules, by minimizing mismatch losses between the photovoltaic modules.

Analyzing all the measurements carried out on site, I defined an optimal repowering solution for the EVO Photovoltaic Park, by structuring it in three main directions of action according to the following table.

Table 0-2 Optimal repowering solution for EVO Photovoltaic Park

A.	**Keeping current configuration for inverters with normal power output** (power degradation within normal limits)	**5 inverters**	**660 photovoltaic modules**
B.	**Rearranging modules without defects** (power degradation within normal limits and medium / minor defects**)**	**10 inverters**	**1320 photovoltaic modules**
C.	**Module replacement for low energy output inverters** (accelerated degradation and major defects)	**15 inverters**	**1980 photovoltaic modules**
Total number of inverters in EVO Photovoltaic Park		**30 inverters**	**3960 photovoltaic modules**

The optimal repowering solution in the case of the EVO Photovoltaic Park is to replace the photovoltaic modules for the inverters with low energy production and rearrange the modules for the rest of the inverters.

6.3 Applying the repowering solution

Based on the results obtained after the analysis of the measured data for the 7 inverters, we defined a procedure for validating the repowering solution by identifying a pilot for the EVO Photovoltaic Park. Thus, **the pilot validation procedure represents the choice of 2 inverters: one with the best performance and one with the worst** (in the present case INV27 and INV26), for the physical application of the repowering solution on them and the determination of the real energy gain for case by case, as follows:

i. INV 26 – having the highest value of degradation, for this I proposed the replacement of all photovoltaic modules with new ones.
ii. INV 27 – having the lowest value of degradation, but still quite large differences between the strings, for this I proposed to replace only the photovoltaic modules with low performance determined on the basis of field measurements.

i. By completely replacing the photovoltaic modules at INV 26, with new modules having similar performance to the original ones, its power was brought back to the initial values, thus reducing the measured power degradation with a value of -15.29%.

ii. To determine the low-performing modules in the INV 27 arrays, I ran an extensive measurement campaign of each module in each array. Thus, to replace the modules with low performance, I used photovoltaic modules also from the EVO Photovoltaic Park, more precisely from INV 26, the inverter in which we completely replaced the photovoltaic modules. All replaced PV modules from INV 26 were measured and those with corresponding parameters were saved as spare modules.

Based on the on-site measurements made for INV 27, I identified the photovoltaic modules with problems and replaced a number of 12 photovoltaic modules with modules previously used in the EVO Photovoltaic Park at INV 26, inverter in which I completely replaced and saved the photovoltaic modules having the appropriate parameters.

By replacing the low-performing modules, we achieved a power gain of 477W (about 25.2% more than the replaced modules) for the INV 27, which can be correlated with a power gain equal to 2.4 photovoltaic modules with the current performances of those currently equipping the EVO Photovoltaic Park.

In order to apply the repowering solution for the EVO Photovoltaic Park, by rearranging the photovoltaic modules without defects, INV27 was selected, because it was subjected to a thorough measurement campaign for each photovoltaic module on all 6 strings connected to it. For the mentioned inverter I selected strings 1 and 6, where we found a significant dispersion of Isc, Voc and Pm parameters for both strings of the measured INV 27 and determined the dispersion losses for each.

I analyzed the resulting dispersions, from which I could conclude that there is no constant quality of the modules, so the method by which the power of the strings can be increased consists in rearranging the photovoltaic modules so that on each string there are modules with equal sensitive Isc, Voc and Pm parameters or power to differ by no more than 4W. Thus, the rearrangement eliminates mismatch losses and increases the efficiency of the park, by increasing energy production. As a working method, I proposed the selection of module pairs according to the I-V characteristic and rearranged the photovoltaic modules in row 1 and 6 of INV27, in increasing order of the measured power value for each individual module.

After the physical regrouping of the photovoltaic modules on the INV27 strings in pairs, a verification of the dispersion of the Isc and Voc parameters will be carried out between the modules of the same newly formed string. The role of this action is to avoid the dispersion of Ipm and Vpm parameters between photovoltaic modules which would lead to the dispersion of Pmeasured points in the string and implicitly to power losses.

Modules with large deviations from the average values of the mentioned parameters, from each group of values formed after rearrangement, are checked for defects. Each parameter Isc, Voc, Imp and Vmp indicates by its deviation from the nominal values a possible defect that must be detected and analyzed. The new groups of modules will be divided into strings of 22 pieces, mounted on the existing metal structures, connected to each other and connected to the inverters, thus forming the new optimized strings.

For the determination of mismatch losses (MML) in the case of the EVO Photovoltaic Park, I have selected the values of interest Imp and Ump for string 6 related to INV27. For string 6 from inverter 27, the MML losses are 2.6%, and the parallel connection of the 6 strings related to the inverter does not significantly change the MML losses, having the voltage dispersion Vpm in string 6 with a small value.

6.4 Energy gain after repowering

After applying the pilot validation procedure for the repowering solution on INV 26 and INV 27, we extrapolated the values from the measurement results for the application of the optimized solution, to determine the energy gain at the level of the entire EVO Photovoltaic Park. I started by analyzing the history of the energy delivered to the network by the EVO Photovoltaic Park and calculated the average value of the energy delivered to the network of 35,019MWh/year/inverter, a value considered constant for the 5 inverters in which there was no intervention, according to the optimized solution of repowering applied to the EVO Photovoltaic Park.

For the 10 inverters in which I proposed the elimination of MML losses, even after rearranging the photovoltaic modules in strings there will still be a small value of MML losses, this being considered 0.2%, thus resulted at an average value of the energy delivered to the network of 36,734MWh/year/inverter. This value represents a **gain of 4.7% by applying the repowering solution to rearrange the photovoltaic modules in the EVO Photovoltaic Park** to eliminate MML losses.

For the 15 inverters in which I proposed to replace the photovoltaic modules with new ones having similar characteristics, resulted the average value of the energy delivered to the network of 40,851MWh/year/inverter, being the one resulting from the INV26 measurement after applying the repowering solution. This value represents a **gain of 14.3% by applying the repowering solution of replacing the photovoltaic modules in the EVO Photovoltaic Park** with new ones having similar specifications.

Finally, I extrapolated the data obtained at the level of the entire park and the result was the value of the **energy gain of 104.65MWh/year for the EVO Photovoltaic Park**, by applying the optimized repowering solution, representing a total **combined energy gain of 9.9%** for the EVO Photovoltaic Park.

6.5 Financial indicators for repowering

The main objective of the financial analysis is to calculate the financial performance indicators of the project (its profitability). The analysis is carried out by the cost-benefit method, taking into account the updating technique. In the financial analysis, expenses and income are determined for the entire period of analysis. The project is considered profitable for positive NPV, IRR higher than the discount rate taken into account and above-unit PI.

The financial cost-benefit analysis was carried out taking into account the following premises:

- ✓ The financial discount rate taken into account is 5%, according to the latest regulations of the European Commission for energy projects;
- ✓ The investment value (without VAT) proposed to be realized is 99,00 thousand Euro, representing own sources;
- ✓ The annual operating costs were not taken into account, because the repowering solution of the EVO Photovoltaic Park does not bring additional operating costs compared to the existing situation;
- ✓ The energy price was calculated starting from a value of the bilateral contract concluded by the beneficiary in 2021 of 325 Lei/MWh (65.66 EUR/MWh), to which an indexation coefficient was applied that takes into account forecasts and information officials provided by ANRE;
- ✓ The income related to the implementation of the investment is constituted by the sale of the electricity gained against the situation in which the repowering solution is not implemented in the EVO Photovoltaic Park. Annual revenues were determined only for the amount of additional electricity delivered;

The results of the financial analysis show that the project is profitable, based on the financial indicators determined for the repowering solution related to the EVO Photovoltaic Park, as follows:

- ✓ Net Present Value - 97,37 thousand Euro
- ✓ Internal Return Rate - 14,2 %
- ✓ Profitability Index - 2,03
- ✓ Return Rate – 7,4 years

As part of the sensitivity analysis, the variation of the efficiency indicators, the updated net income and the internal rate of return, is determined when some critical parameters are changed. Based on the results obtained, we determined that the parameter "investment value" is not CRITICAL, while the Parameter "value of energy delivered to the network" is

CRITICAL, because the net present value and the internal rate of return vary by more than 1% at a variation of the value of the energy delivered to the network by ±1%.

7. CONCLUSIONS

The work is part of the research direction initiated by Prof. Dr. Eng. Florea Ioan HĂNȚILĂ, aiming to make significant contributions for the analysis of non-linear circuits in periodic regime, associated with photovoltaic systems. Some research results obtained in the doctoral thesis were used in national projects, presented in scientific events or scientific publications.

The original personal contribution of the author of the Ph.D. thesis includes:

C.2.1. A study of the main influencing factors of electricity production from photovoltaic sources, by identifying, cataloging and determining their influence in the day-to-day operation of the main elements of a photovoltaic system. I took into account all the identified factors and their influence, in carrying out the detailed analysis of the EVO Photovoltaic Park.

C.2.2. A study on the defects of photovoltaic systems, from the way they appear, continuing with their identification and cataloging according to the main causes, and finally I evaluated the causes of their appearance in correlation with the type of existing factors. The correct identification and the mode of occurrence of the defect in photovoltaic systems is the basis of photovoltaic repowering.

C.2.3. Elaboration of a detailed analysis plan regarding the historical data available for the EVO Photovoltaic Park in order to identify the real situation regarding the energy produced by it. I've analyzed the low-performing components from the perspective of comparing the recorded power and energy data of the 30 inverters, including their variation between MPPT 1 and 2, to perform ordering according to the recorded values and establish priorities for detailed on-site analysis.

C.2.4. Measurement of photovoltaic modules selected in the analysis to determine its main parameters and nonlinear I-V characteristics. The measurements were carried out both on site and in the laboratory, respecting the conditions for testing photovoltaic modules from the specialized standards. The results of the measurements show the real situation of the degradation of the photovoltaic modules in the EVO Photovoltaic Park.

C.2.5. A study on the repowering solutions related to photovoltaic systems installations, with the analysis of the main components for which repowering can be carried out. I've analyzed the ways of applying the existing repowering solutions according to their limitations as well as the real situation of the EVO Photovoltaic Park determined based on the analysis of historical production data.

C.2.6. Identifying the optimized solution for photovoltaic repowering by using three main directions of action, for the technical-economic optimization with a view to its application in the case of the EVO Photovoltaic Park. I've defined a pilot validation procedure, by choosing 2 inverters: one with the best performance and one with the worst (in the present case INV27 and INV26), for the physical application of the repowering solution on them and determining the real gain of energy for each individual case

C.2.7. Implementation of the pilot validation procedure for the photovoltaic repowering solution in the EVO Photovoltaic Park by applying the proposed methodology. I've applied the optimized repowering solution by rearranging modules to INV 27 to reduce mismatch losses (MML), in order to minimize the losses by rearranging the photovoltaic modules on each string and calculated the value of these losses.

C.2.8. Definition of the energy gain after applying the pilot validation procedure on the repowering solution defined for each of the 2 selected inverters. The results were extrapolated by applying the optimized repowering solution based on the 3 main directions defined, thus calculating the energy gain for the entire EVO Photovoltaic Park.

C.2.9. The evaluation of the feasibility of the optimized repowering solution for the EVO Photovoltaic Park from the economic perspective is based on the identification of the economic feasibility of this solution. I've determined the main financial and economic indicators for the application of the optimized repowering solution and analyzed their sensitivity to the variation of the main parameters. The result confirmed the economic-financial feasibility of the optimized repowering solution of the EVO Photovoltaic Park.

The results presented in the Ph.D. thesis can be developed in the following directions:

- Operation optimization the of photovoltaic systems and its main components throughout the life of the equipment;
- Development of improved procedures regarding the maintenance of photovoltaic systems to prevent the occurrence of defects;
- Testing of the main components on site and/or in laboratory to verify the main technical parameters;
- Evaluation of the real-life situation of photovoltaic parks and systems regarding their operating efficiency and the main components;
- Development of specialized services regarding the identification of defects in the main components of photovoltaic systems;

List of published scientific papers:

iii.1. B.A. Onose, I. Murgescu, Ș.A. Șontea "*Photovoltaic modules degradation and repowering solutions analysis",* International Symposium ISB-INMA-TEH 2022, pp. 466-473, ISSN 2537 – 3773.

iii.2 D. Cujbescu, C. Persu, L. Dumitrescu, I. Murgescu, B.A. Onose, Ş.A. Șontea, E.Mirea *"Intelligent equipment for maintenance of agricultural crops in protected spaces",* International Symposium ISB-INMA-TEH 2022, pp. 72-76, ISSN 2537 – 3773.

iii.3. S.I. Tiberiu, B.A. Onose, V. Rohat, T.C. Sava, I. Murgescu, S. Sontea, I.I. Bitir, "*Consumer and Prosumer comparative statistical analysis of load curves. Study Case: Romania*" 2021 16th International Conference on Engineering of Modern Electric Systems (EMES), 2021, pp. 1-9, doi: 10.1109/EMES52337.2021.9484111.

iii.4. B.A. Onose, I. Murgescu, Ș.A. Sontea, "*Hybrid RES Mobile Innovative System Optimized for DC-DC Applications*", 2020, In: Visa I., Duta A. (eds) Solar Energy Conversion in

Communities. Springer Proceedings in Energy. Springer, Cham, doi: 10.1007/978-3-030-55757-7_10.

iii.5. G. Rigatos, N. Zervos, P. Siano, M. Abbaszadeh, P. Wira & B.A. Onose, "*Nonlinear optimal control for DC industrial microgrids*", 2019, Cyber-Physical Systems, 5:4, 231-253, DOI: 10.1080/23335777.2019.1640796

iii.6. B.A. Onose, M.A. Hanek, G. Vătăşelu and L.N. Demeter, "*Advanced modular photovoltaic system for Plug-in Small Electric Vehicles (PsEV)*" 2017 Electric Vehicles International Conference (EV), 2017, pp. 1-4, doi: 10.1109/EV.2017.8242105, WOS:000427815000019.

iii.7. B.A. Onose, C. Boboc, M. Chefneux, "*Advanced monitoring and control architecture for lowering the energy consumption of non-residential buildings*", Electrotehnica, Electronica, Automatica (EEA), 2017, vol. 65, nr. 2, art. 1, pg 5-10, ISSN: 1582-5175

SELECTIVE BIBLIOGRAPHY

[17] Planului Național Integrat pentru Energie și Schimbări Climatice 2021-2030 (PNIESC).

[25] ANRE - RAPORT PRIVIND REZULTATELE MONITORIZĂRII PIEŢEI DE ENERGIE ELECTRICĂ ÎN LUNA DECEMBRIE 2021.

[26] https://www.transelectrica.ro.

[27] Best Practices in Operation and Maintenance of rooftop solar PV systems in India, 2018, GERMI.

[29] Sakaros Bogning Dongue,1Donatien Njomo,1and Lessly Ebengai1 "An Improved Nonlinear Five-Point Model for Photovoltaic Modules", *International Journal of Photoenergy,* Volume 2013 | Article ID 680213 | HYPERLINK "https://doi.org/10.1155/2013/680213" \t "_blank" https://doi.org/10.1155/2013/680213

[32] STC vs. PTC (and sometimes globally notated as NOTC), APsystems USA.

[33] IEC 60904-1:2020 - Photovoltaic devices - Part 1: Measurement of photovoltaic current-voltage characteristics.

[34] F. Prieto-Castrillo,, N.í Núñez and M. Vázquez, Warranty Assessment of Photovoltaic Modules based on a Degradation Probabilistic Model, Technical University of Madrid.

[43] https://en.wikipedia.org/wiki/Luminous_efficiency_function.

[46] Shaju, Anitha & Chacko, Rani. (2018). Soiling of photovoltaic modules- Review. IOP Conference Series: Materials Science and Engineering. 396. 012050. 10.1088/1757-899X/396/1/012050. .

[47] E.E. van Oyk*,B.J. Scott*t,E.L. Meyer• and A.W.R. Leitch, Temperature dependence of performance of crystalline silicon photovoltaic modules, South African Journal of Science 96, April 2000.

[52] IEA - Review of Failures of Photovoltaic Modules - Photovoltaic Power System Programme, Report IDEA-PVPS T13-01:2014.

[56] S. NYLUND, Z. BARBARI, STUDY OF DEFECTS IN PV MODULES, UV fluorescence and Thermographic photography for Photovoltaics (PV) Field Application, 2019, School of Business, Society and Engineering.

[59] Oliveira, Michele & Cardoso, Antônia & Viana, Marcelo & Lins, V.. (2017). The causes and effects of degradation of encapsulant ethylene vinyl acetate copolymer (EVA) in

crystalline silicon photovoltaic modules: A review. Renewable and Sustainable Energy R.

[65] IEC 60891:2021 - Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics.

[66] https://www.cencenelec.eu/.

CONTENTS OF THE Ph.D. THESIS