Prediction of the degradation process of mono-Si photovoltaic panels in Ukrainian and Czech conditions

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***Abstract*— This paper focuses on project studying the influence of various technical, meteorological, and specific local factors influencing power generation from photovoltaic plant. This problem is analysed on model PV plants installed in Ukraine and Czech Republic.**

The Fault tree analysis (FTA) method is applied on photovoltaic power plant damage tree. The most significant technical problems of PV modules and entire photovoltaic plants are identified and discussed. Also mathematical method computing coefficient of the total residual resource of the plant and to calculate predicted energy generation of the plant taking into account general degradation is discussed. Indicator coefficients describing abnormal PV modules operation are described. Structural diagram of the model of the coefficient of the residual resource of the PV module was developed

Basic data originate from measurements on monocrystalline Si PV panels installed in commercial plants commissioned in Ukraine and the Czech Republic. Data show important differences in behavior and operational conditions. It is evident that prediction the of technical condition of the plant, degradation of PV modules and actual electricity generation strongly depends on local conditions. Ignoring the gradual reduction of capacity leads to ertrors in assessment of the total energy efficiency, profitability, payback time and necessary power reserve to compensate the unstable RES generation.

Keywords*— *technical conditions; PV power plant; PV module, coefficient residual resources.

I. Introduction

Integration of renewable energy sources (RES) into power systems (PS) is a strong trend impacting many subjects in local specifics of particular countries. According of “REmap Energy Generation and Capacity” developed IRENA, Solar PV will play key role for green deal [1], also this noted in [2].

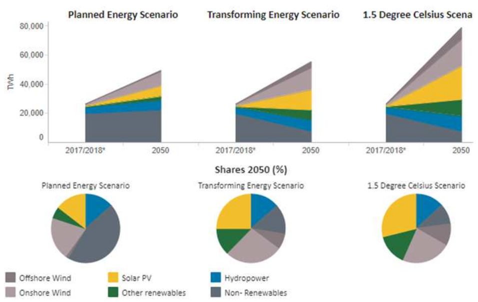

Fig. 1. Electricity generation in World [1].

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Effectively implementing and operating PV power plants depends on meteorological parameters and technical conditions [3, 4], which allow precictly control it with usage criterion optimality = maximum efficiency PV power plant + maximum effect power grid influence [5]. In [6, 7] authors noted that optimality criterion implementation RES taking into account a lot of parameters. Analyses of relevant references [8-10] allowed us designed in flow-chat the

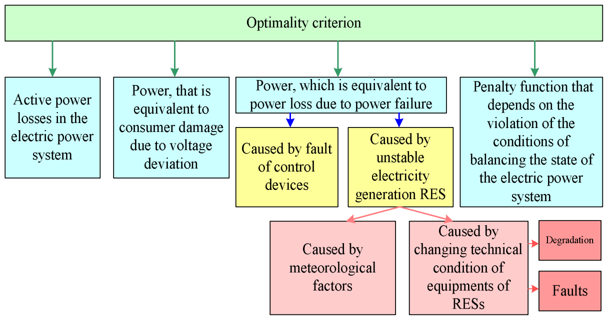

Fig.2. The optimality criterion implementation RES

optimality criterion implementation RES, which presented in Fig.2.

One of the ways increases the efficiency PV power plants is the correct determination of degradation and technical condition. Technical praxis shows that it is necessary to deeply assess the technical state of a photovoltaic plant. Very important influence gives the degradation of used photovoltaic modules.

During plant operation, we can easily identify a gradual decrease in the real electricity generation of the plant, if we assess the value to the initial state. It could bthe e result of all technical resources composing used modules, their technological features and many other random reasons. If we do not take into account the gradual reduction of PV modules capacity, it will lead to errors in prediction of their energy efficiency, profitability, payback time and power reserve for compensation for unstable RES generation [11].

Also very significant task nowadays is hourly electricity generation prediction for the next day and the power balance. So, it is necessary to determine precisely the actual generation of photovoltaic plants, to develop and improve appropriate methods, mathematical models, and tools. The initial step for this could be also the model of the software and hardware complex described in this paper. It helps to prepare a dataset to identify the dependences of the actual generation on actual technical conditions, meteorological conditions, and operating conditions. Fig. 3 shows sample degradation of photovoltaic plant.

Fig. 3. Degraded photovoltaic plant.

Fluctuations of plant functioning in real conditions including decarbonization strategy are investigated. The problems of generation and consumption balancing in power systems and grids are studied and basic technologies to provide balance are developed. Also influence of meteorological factors and technical conditions on electricity generation is studied as well as the possible participation of PV plants in the balancing of complex power systems. Mathematical method and models for understanding the technical condition of the plant while working in the balancing group have been developed. The most important defects of PV modules installed in the plant are determined. Also method for determining the coefficient of the total residual resource of the plant is proposed to understand and predict the actual generation of the plant while including actual degradation. A mathematical model of the residual resource coefficient the technical condition of the PV module has been developed. In a result, the proposed methods and tools for assessing the degradation of PV plants, their predicted power generation and balancing capabilities will allow more accurate planning of reserve capacity in the system and reduce penalties for PV plant investors [12].

II. Comparison of commercial photovoltaic plants commissioned in Ukraine and Czech republic

During the last years of the solar boom in Czech republic, sample new commissioned PV plants were investigated for initial degradation and technical problems. During 2009, in total 308 operated PV plants with installed power between 0,004 to 8 MW and during 2010 another 44 plants were analysed. The most important technical problems are displayed on Fig. 4.

Fig. 5 shows the same analysis made during 2020 on 98 PV plants and during 2021 on another 111 stations commissioned in Ukraine. Fig. 4 and Fig. 5 show, that relative amount of particular technical problems and defects in both datasets differs. It is probably result of common installations based on modern cheap panels from China production. Although these panels have usually better nominal values than older panels produced between 2009 and 2010, their resilience is usually lower. In accordance with the Law of Ukraine on the Electricity Market, the permissible deviation of the projected generation schedule from the actual generation for photovoltaic plants is 5 %. If the production differs for more than 5 % the producer must pay penalties.

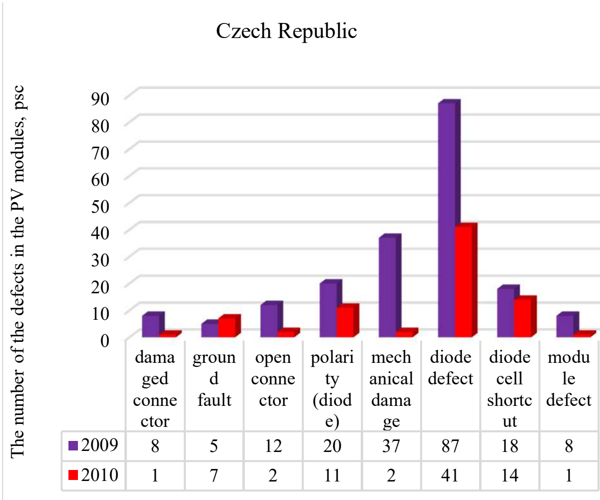

Fig. 4. Most important technical problems (Czech Republic, 2009-2010).

This means overproduction and underproduction as well. After studying the forecast of meteorological parameters and improving the interpretation of the obtained data of the generation schedule, there is a significant discrepancy between the forecast and the actual schedule of electricity generation. This phenomenon can also be explained by a large number of technological violations due to the failure of the main electrical equipment of the PV plants, namely power transformers, inverters, cable lines, etc. Within the operation of the studied PV plants, a detailed analysis identified the most significant technological problems and main reasons for the difference between expected electricity generation and real production. In the period of six monthe the hs, sample studied photovoltaic power plant in Ukraine, showed four different technological problems leading to the failure of power generation. That included also faithe lure of 2800 kVA block transformer.

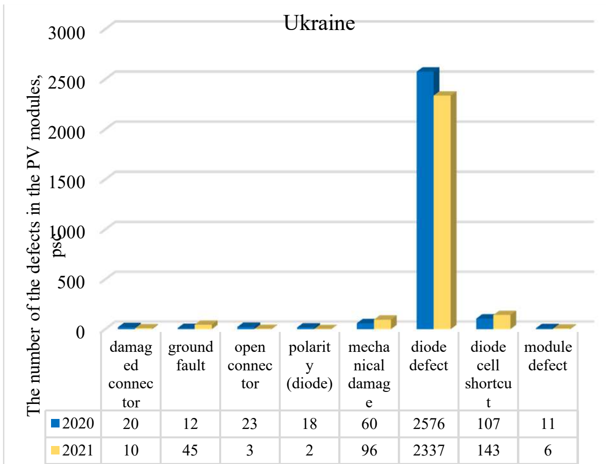

Fig. 5. Most important technical problems (Ukraine, 2020-2021).

Every problem happened at different day time and under different network conditions, which were not related to the problem. In contrast of that, another sample plants showed large number of gradual damage of the same equipment within one facility. It included network protections, testing and measurement instruments, supplementary electrical equipment, grounding devices and measuring transformers. Fig. 4 and Fig. 5 show differences between degradation curve of particular PV panel and whole PV system.

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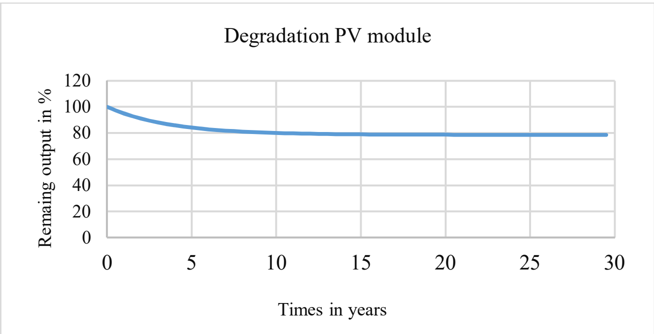

Fig. 6. Degradation curve of particular PV panel.

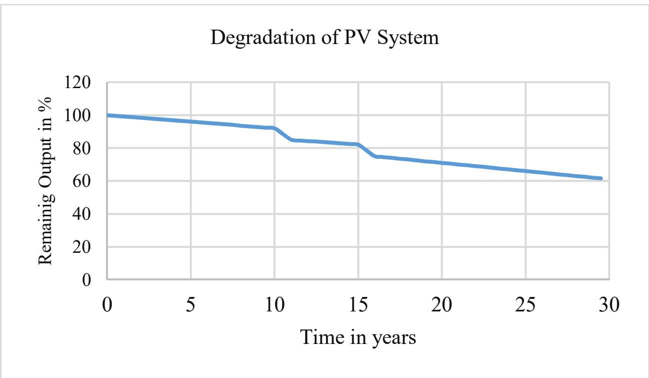

Fig. 7. Degradation curve of whole PV system.

III. PV SYSTEM FAULT TREE ANALYSES

The functioning of the PV plant as a complex system is influenced by a number of factors explained earlier. FTA of a common PV power plant is designed to take into account the data from Fig. 4-6, and Table 1 and references [13-15]. Structure of this FTA is presented on Fig. 8 [16, 17].

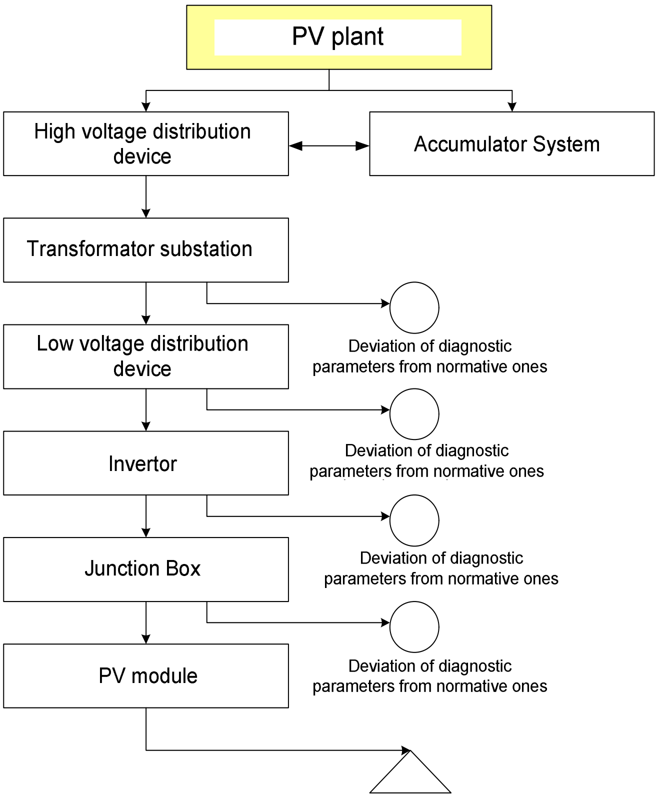

Fig. 8. PV plant FTA [18, 19].

Exact determination of technical condition of the PV module, electrical components and other parts is initial stage of this process. residual resources coefficients for each diagnostic parameter

Firstly, we need to define residual resources coefficients (RRC) for each diagnostic parameter for every element of the plant. It is necessary to follow from known values of diagnostic parameters to the corresponding values of RRC for each diagnostic parameter. Therefore, RRC for each diagnostic parameter can be mathematically defined as follows (6):

$$k_{i1} = \left| \frac{x_{i1,\lim} - x_{i1,current}}{x_{i1,\lim} - x_{i1,start}} \right| \qquad (1)$$

where $x_{i1,\lim}$ is limit value of the ith diagnostic parameter; $x_{i1,current}$ is the value of the ith diagnostic parameter at the time of detection; is the start value of the ith diagnostic parameter at the time of commissioning of new unit or after major or general repair [12].

The main view of the coefficient of the total residual resource of the equipment is determined by the expression:

$$K_{rr} = 1 - \sum_{\Theta=1}^{\zeta} \left\{ 1 - \left\{ \prod_{\chi=1}^{\psi} \left(k_{\Theta\chi}^{P\Theta\chi} \right) \cdot \prod_{\lambda=1}^{\phi} \left\{ 1 - \sum_{j1=1}^{m1} \left[\left(1 - k_{\Theta\lambda j1} \right) \cdot P_{\Theta\lambda j1} \right] \right\}^{P\Theta\lambda} \right\} P_{\Theta} \right\} \quad (2)$$

where $j1$ is the number of the blocks in the parallel part of the circuit that is collapsed; $m1$ is the number of blocks in the parallel part of the circuit that is collapsed; λ is number of the block in the serial part of the scheme, which consists of collapsed parallel blocks; φ is the number of blocks in the serial part of the circuit, which consists of collapsed parallel blocks; χ is number of the block in the sequential part of the scheme, which consists of uncollapsed; ψ the number of blocks in the serial part of the scheme, which consists of uncollapsed blocks; Θ is number of the block in the parallel part of the scheme, which consists of collapsed series-parallel; ζ is the number of blocks in the parallel part of the scheme, which consists of collapsed series-parallel blocks; $k_{\Theta\lambda j1}$ iscoefficient of the residual resource according to the controlled $\Theta\lambda j_1$ parameter in the corresponding group of parallel blocks that are later collapsed; $P_{\Theta\lambda j1}$ is is the probability of deviation of the controlled parameter from the norm in PV-module, which will be changing or reparing according to $\Theta\lambda j_1$ parameter in the corresponding group of parallel blocks which are subsequently collapsed; $k_{\Theta\chi}$ is the coefficient of the residual resource according to the diagnostic parameter in the block that does not collapse in the sequential part; $P_{\Theta\chi}$ is the probability of deviation of the controlled diagnostic parameter in the block that does not collapse in the sequential part; $P_{\Theta\lambda}$ is the probability of deviation of the group of controlled parameters from the norm in the collapsed group, which contains series-parallel blocks in the explosive, which is taken out for repair.; P_{Θ} is the probability of deviation of the group of controlled parameters from the norm in the collapsed group, which contains series-parallel blocks in the explosive, which is taken out for repair.

If we take into the account, that the failure or degradation of particular elements from Table 1 results in a failure of the PV module, then the total RRC of PV modules is calculated using equation (3):

$$k_{TRR} = \prod_{i=1}^{j} k_i^{p_i}; \quad (3)$$

where the total RRC of the PV module is evaluated on the ith diagnostic parameter. Many other ambient parameter (temperature, insulation, resistance, current, etc.) affects the RRC of the PV module elements as evident in the equation (4). Coefficients RRC of every element that influences the total RRC of the PV module. Number i is ith diagnostic parameter of elements of PV module, j is the number of diagnostic parameters and pi is the probability of deviations of the controlled parameter from the allowable limit value [8]:

$$p_i = \frac{y_i}{m}; \quad (4)$$

where y_i is the number of deviations of the controlled parameter from the allowable boundary of normalized value of this parameter. These deviations are detected by controlling the ith diagnostic parameter from the total number of detected deviations of controlled parameters from the allowable boundary of normalized values, while m is the total number of detected deviations of controlled diagnostic parameters

TABLE I. ANALYSED MALFUNCTIONS PVM ELEMENT

PVM element	Type of damage	Result	Parameter		Damage, units; Acting; %
Cell	breakdown of pn_junction	above the normalized increase of the photodiodes' resistance in the opposite direction - a increase in the resistance of the cell	Photodiode resistance, Ohm Current, A Temperature, °C	k_{cell}, r.u.	101 units; 0.034 r.u.; 3.36%
	breakdown silicon waffer	increased of the resistance of the cell			
	damage front-side contact	decreased conductivity of the contact			
	damage back-side contact	decreased conductivity of the contact			
Busbar	metal stripe	decreased conductivity of the contact current reduction, busbar heating heating	Temperature, °C Current, A	k_{busbar}, r.u.	43 units; 0.014 r.u.; 1.43%
	soldering points				
Junctionbox	casing	increased humidity	Temperature, °C Current, A Humidity, % Voltage, V	$k_{junctionbox}$, r.u.	2504 units; 0.833 r.u.; 83.3%
	sealing	increased humidity			
	by-pass siod	Increased conductivity; increased voltages			
Metall frame	deterioration of the tightness of the frame	heating, moisture inside the PVM	Temperature, °C Current, A	k_{metall_frame}, r.u.	54 units; 0.018 r.u.; 1.8%
Protective glass	deterioration of the tightness of the glass	heating, moisture inside the PVM	Temperature, °C Current, A	$k_{protective\_glass}$, r.u.	80 units; 0.027 r.u.; 2.66%
EVA foil	deterioration of the tightness of the EVA foil	heating, moisture inside the PVM	Temperature, °C Current, A	k_{EVA_foil}, r.u.	225 units; 0.075 r.u.; 7.48%
Rubber sealing	deterioration of the tightness of the rubber sealing	heating, moisture inside the PVM	Temperature, °C Current, A	$k_{rubber\_sealing}$, r.u.	
Cable connecting cells to the terminal	cable damage	insulation and resistance of the cable	Resistance of wires, Ohm Temperature °C	k_{cables_line}, r.u.	
	connectors	insulation and resistance of the connector			

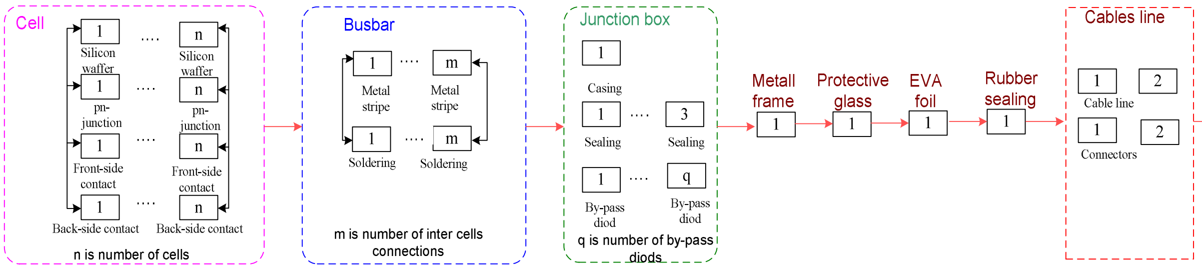

Fig. 9. Structural diagram of the PV-module the residual resource coefficient

allowable boundary of normalized values. Expanding the expression (7), total PV module RRC becomes (5) [17, 18]:

$$K_{rr} = k_{cell}^{p_{k\_cell}} \cdot k_{busbar}^{p_{k\_busbar}} \cdot k_{junction\_box}^{p_{junction\_box}} \cdot k_{metall\_frame}^{p_{metall\_frame}} \cdot k_{protective\_glass}^{p_{protective\_glass}} \times$$
$$\times k_{EVA\_foil}^{p_{EVA\_foil}} \cdot k_{rubber\_sealing}^{p_{rubber\_sealing}} \cdot k_{cables\_line}^{p_{cables\_line}}; \qquad (5)$$

where k_{cell} is RRC is for the relevant diagnostic parameters cell and determined using equation (6):

$$k_{cell} = 1 - \prod_{i=1}^{n} \begin{pmatrix} (1-k_{i\_silicon\_wafer}) \cdot p_{i\_silicon\_wafer} + \\ +(1-k_{i\_pn\_junction}) \cdot p_{i\_pn\_junction} + \\ +(1-k_{i\_front-side\_contact}) \cdot p_{i\_front-side\_contact}) + \\ +(1-k_{i\_back-side\_contact}) \cdot p_{i\_bank-side\_contact}) \end{pmatrix}; \qquad (6)$$

where $k_{i\_silicon\_wafer}$ is RRC of the silicon wafer of the cell, and $p_{i\_silicon\_wafer}$ is probability of deviations of the controlled parameter from the allowable limit value, which response for indicate the technical condition of the silicon wafer; $k_{i\_pn\_junction}$ is RRC of the pn-junction of the cell, and is the probability of deviations of the controlled parameter from the allowable limit value, which response for indicate the technical condition of pn-junction.

k_{busbar} is RRC is for the relevant diagnostic parameters busbar and determined using equation (7):

$$k_{busbar} = 1 - \prod_{i=1}^{m} \begin{pmatrix} (1-k_{i\_metal\_stripe}) \cdot p_{i\_metal\_stripe} \\ +(1-k_{i\_soldering}) \cdot p_{i\_soldering} \end{pmatrix}; \qquad (7)$$

where $k_{junction\_box}$ is for the relevant diagnostic parameters busbar and determined using equation (8):

$$k_{junction\_box} = 1 - \prod_{i=1}^{q} \begin{pmatrix} (1-k_{i\_ca\sin g}) \cdot p_{i\_ca\sin g} + \\ +(1-k_{i\_sealing}) \cdot p_{i\_sealing} + \\ +(1-k_{i\_by-pass\_diod}) \cdot p_{i\_y-pass\_diod}) \end{pmatrix}, \qquad (8)$$

where $k_{i\_ca\sin g}$ is RRC of the junction box casing; $p_{i\_ca\sin g}$ is is probability of deviations of the controlled parameter from the allowable limit value, which response for indicate technical condition of casing; $k_{i\_sealing}$ is of the junction box sealing; $p_{i\_sealing}$ is probability of deviations of the controlled parameter from the allowable limit value, which response for indicate technical condition of sealing; $k_{i\_by-pass\_diod}$ is RRC of the junction box by-pass diod; $p_{i\_y-pass\_diod}$ is probability of deviations of the controlled parameter from the allowable limit value, which response for indicate technical condition of by-pass diod.

Samples of simulations for summer, spring and winter are shown on Fig. 10., Fig.11 and Fig.12. Diagrams show power losses of diodes and losses of mismatched panels.

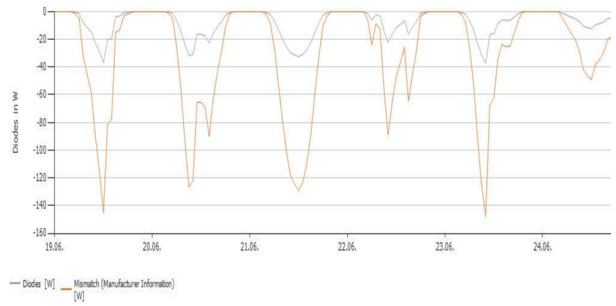

Fig. 10. Diagram of power losses of diodes and losses of mismatched panels the PV module (summer).

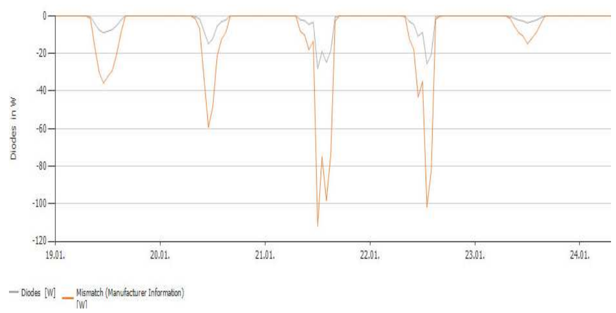

Fig. 11. Diagram of power losses of diods and losses of mismatched panels the PV-module (winter).

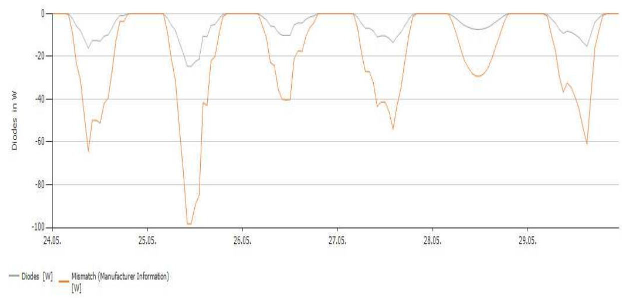

Fig. 12. Diagram of power losses of diods and losses of mismatched panels the PV module (spring).

All presented in Table 1 malfunctions negatively influence power generation PV-modules and decrease power generation. Problems with diodes are more common malfunctions, and more often indicated in the first year of operation. Fig. 10, 11, and 12 are presented simulated results of power losses of diodes and losses of mismatched panels of the PV module in summer with the usage of PVSOLPremium2023 in a 5-days period.

IV. CONCLUSION

In this article, various malfunctions of PV modules affecting power generation PV power plants have been investigated. The analyze of the malfunctions equipment in the PV power plant, was allowed to developed FTA PV power plant, and after that create a structural diagram of the PV module and the residual resource coefficient. For this purpose, various malfunctions have been grouped into categories namely, for influence on the degradation of elements for PV modules. For example, if just analyses the cell of the PV-panel, a minimum 4 faults can happen, namely breakdown of pn-junction; breakdown of silicon waffer; damage to front-side contact. In this case we see the increase of the photodiodes' resistance in the opposite direction - a increase in the resistance of the cell, which possibly reveals if time measures photodiode resistance, current, and temperature. The investigation of the set of events that can happen, then influence on the development of the process degradation PV-modules is crucial for the adaptation existed system online system diagnostic equipment of PV power plants and depend on the operational conditions of PV-modules.

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