Assistant expert system for inverters corrective maintenance

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Abstract. The paper presents a prototype of an assistant expert system whose purpose is to help the specialized personnel in solving issues that involve inverters in PV systems. Thus, the expert system based on the data given by the user, i.e., the inverter model and the error code, offers a troubleshooting guide and repair actions. In this way, the inverter's malfunction or failure-solving time is decreased. As the aim of the research was to test the feasibility of this kind of application, the expert system was developed in CLIPS-IDE, and considered only two models of inverters, i.e., Huawei and Sungrow, and a limited number of errors. The expert system was tested using a qualitative approach, so every possible input data was introduced, and the results were verified. The findings of the validation underlined the feasibility of an assistant expert system for inverter corrective maintenance regarding voltage, grounding system, cooling issues, etc.

1 Introduction

The number of PV (photovoltaic) systems, both large and small, is increasing rapidly, as the importance of generating electricity using renewable energy has been highlighted in the context of climate change. Additionally, the accessibility and the efficiency of these systems, plus the favorable legislation and electricity price, have made these systems especially attractive as investments (large PV plants) and for household and small companies' PV systems (prosumers). Indeed, in Romania, in 2025, according to ANRE (National Regulatory Authority in the Field of Energy) data, the installed photovoltaic power exceeded the threshold of 3 GW in large PV power plants, and the number of prosumers, with smaller PV systems, reached over 200,000, with an installed capacity of about 2.44 GW (at the beginning of 2025) [1].

PV systems consist of several components; however, the inverter plays a key role by converting the DC output of the PV array into AC power while ensuring compliance with grid voltage, frequency, and power quality requirements. However, it was acknowledged that it has been the primary source of corrective maintenance and downtime in PV plants [2, 3]. PV inverters are vulnerable to various factors, such as electrical surges, harsh environmental conditions, software bugs, and manufacturing defects, which can cause their failure. Studies on inverter malfunctions suggest that its electrical components are the primary cause [2 - 5].

An important aspect of a PV system is its grounding installation, as this element will affect the magnitude of the grounding fault current, temporary overvoltage, and protection against lightning strikes [6, 7]. Thus, the grounding installation has a direct relation with the safety and the stable operation of the PV system [8-10].

Corrective maintenance of PV inverters is carried out by qualified personnel following a structured procedure that includes fault identification, cause diagnosis, repair planning, execution of corrective actions, functional testing and verification, and comprehensive documentation of the intervention for future analysis and continuous improvement. The efficiency of this process is influenced by a combination of technical, human, organizational, and environmental factors. Thus, to enhance the corrective maintenance, the implication of an assistant expert system that would help the personnel is a smart approach.

This paper presents an expert system that can be used to assist the qualified personnel in their task to perform the corrective actions in PV inverter maintenance. The expert system was built as a prototype ready to be tested. It was built in CLIPS, which gives the advantage of rapidity in development, as the inference engine is predefined, along with the user interface.

The remainder of the paper contains a literature review that provides the state-of-the-art in the research theme in the second section and the contributions of the study in relation to similar research. The third section describes the methodology, that is, the development and characteristics of the expert system. The fourth section presents the expert system implementation in CLIPS. The next section shows and discusses the results of the expert system's primary stages of testing and validation. The last section concludes the research and its findings, along with future works.

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2 Literature review

The maintenance activities regarding the inverters from PV systems are divided into five classes: preventive, prescriptive, condition-based, predictive, and corrective, as the authors present in their review paper [11].

The corrective maintenance refers to the process of fixing equipment after it breaks down or malfunctions, restoring it to operational condition. This strategy is not the most effective, but it is often used due to several factors, primarily because of the lack of personnel and financial resources. Thus, a critical aspect is to reduce the response time, in addition to the incorporation of fault acknowledgement, intervention, and repair activities data for the intervention personnel [12, 13]. In the literature, there are studies that aim to make this process more efficient [14]. In this paper, the authors propose an operation and maintenance decision support system for the corrective maintenance of large-scale PV plants. The proposed system operates entirely on the field measurements and considers technical and financial aspects. The extended version of the same research is described in [15]. The conclusion of the study, based on the results, showed the financial advantages of performing the corrective maintenance near zero power production.

The inverters' malfunctions that are the cause of corrective maintenance have been studied before and presented in the literature [16-20]. The study described in [16] uses the Wavelet transform to identify the faults that occur in the circuit of an inverter. According to [17] and [18], the inverters' elements most likely to malfunction are cards and boards, the transistor matrix, fans or the cooling system, and capacitors. In [17], the authors made a qualitative analysis of diverse types of inverters considering the five criteria enumerated earlier. They concluded that there is limited data on practices to measure and predict component failures, and that a validation is needed for inverter failure prediction. [19] presents the use of machine learning to evaluate the most common failures of PV inverters. The 12 subsystems (ground fault detection, breakers, capacitors, IGBTs, transducers, inductors, frequency filters, surge protectors, heat management system, power supply, communications, and printed circuit boards) of an inverter are considered, and their malfunctions are studied from data to determine patterns. For example, the authors concluded that communications tend to cause problems in spring and autumn when the humidity is high. Popescu and el. extensively describe the faults and causes of a single-phase inverter. The paper specifies 14 inverter symptoms with their characteristics (faults and causes) that are coded appropriately, which, according to the authors, are the starting point for an expert system that can support the personnel during the inverter's operation.

The use of expert systems and knowledge-based systems in maintenance is proposed in the literature. For example, [21] presents the development of a knowledge-based system for predictive maintenance. In the last 5 years, the use of expert systems in the field of corrective maintenance has been very limited. Considering the studies from the literature, the contributions of the paper are:

- Framework for developing an expert system dedicated to corrective maintenance.
- Fault analysis of two models of inverters, both in single-phase and three-phase types.
- Stages of the proposed expert system building in CLIPS.
- Prototype of an assistant expert system for the corrective maintenance of PV inverters.

3 Methodology

The proposed expert system was developed using the framework illustrated in Figure 1. The three phases (conceptualization, implementation, and validation) of the framework were considered in accordance with [22].

The conceptualization phase aims to define the fundamentals for development of the expert system, i.e., its structure and key objectives. Further, the implementation phase supposes the translation of the conceptual elements into practice using the chosen software, which in this research is CLIPS.

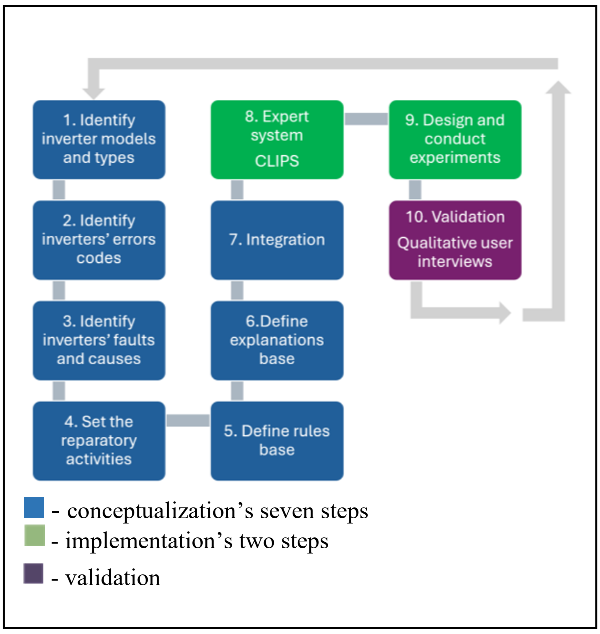


Fig. 1. Framework of the proposed expert system.

The methodology begins with the identification of the inverter models and types. In the research, single-phase and three-phase Huawei and Sungrow inverter models were considered, as these are the most used in Romania. For each inverter model, the manufacturer gives error codes and the troubleshooting guide. For example, the error codes of Sungrow inverters are four-digit numbers as 0002…0016, and three-digit numbers like 039 and 205 [23]. Table 1 enumerates six of the error codes and the information given by the manufacturer.

Table 1. Sungrow error codes, faults, and actions [23].

Code	Fault	Instruction
0002	The grid voltage exceeds the inverter's allowable upper limit.	Check the voltage of the grid. If the grid voltage exceeds the permissible range of inverter protection parameters, ask the utility grid company for a solution.
0003	Grid transient voltage exceeds the permissible range	This is a short-term fault due to grid conditions. The inverter should fix itself.
0004	The grid voltage is below the inverter's allowable lower limit.	Check the grid voltage. If the grid voltage exceeds the permissible range of inverter protection parameters, ask the utility grid company for a solution.
0010	Islanding	Check whether the AC circuit breaker is triggered, and the cables are firmly connected. Check whether the grid is not in service.
0012	A failure current is detected.	Check the PV strings for a ground fault.
0036	The temperature of the radiator is too high.	Check whether the placement of the inverter is correct. Check whether the inverter operating ambient temperature is more than the range. Check whether the AC output power exceeds the nominal power.

The third and fourth steps are done together, based on the information given by the manufacturer. More knowledge about the inverters' symptoms, faults, and repair actions was acquired from the specialized personnel, who are represented by experts and personnel that realize the corrective maintenance. The knowledge was achieved through interviews and observations. An example of the final form of data that was used in the rules base is:

Error code – 0036.

Symptom – Overtemperature (OT). When the temperature alarm sounds, the inverter reduces power or stops.

Possible causes – Insufficient ventilation, dust, and/or faulty fans.

Troubleshooting steps – Clean fans and case, check airflow.

Solution - Cleaning, improving ventilation, and/or replacing the fan.

Using the results obtained in the previous steps, the rules and explanation bases are built. All these are integrated into a whole, the result being the assistant expert system sketch. Figure 2 illustrates the structure of the proposed expert system and its interaction with the personas that have a type of connection with it.

The components of the expert system are the knowledge base that contains the rule base, fact base, and the context (data used in the rules), the inference engine, explanation module, and interface module.

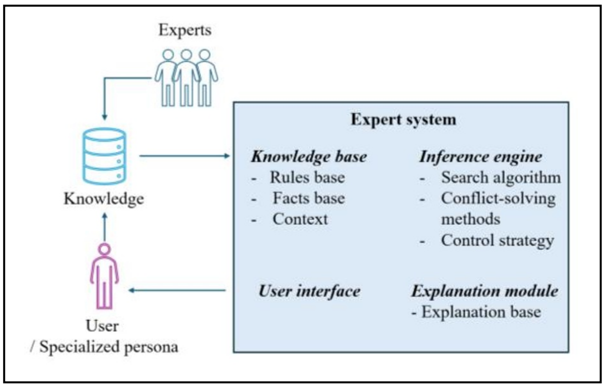


Fig. 2. Structure of the proposed expert system.

4 Expert system implementation

The expert system implementation was made using CLIPS IDE, a version of CLIPS that is an open-source expert system shell. This means that the user interface and inference engines are predefined. Table 2 contains a detailed description of the implemented expert systems. The modules' characteristics can be predefined (CLIPS IDE-defined), particular (specific to the proposed expert system), or predefined with particular aspects (using a predefined module and adding specific features).

Table 2. Expert system components characteristics.

Module	Characteristics
Knowledge base	*Particular* Knowledge representation using rules and simple objects, which are divided into two categories corresponding to the mentioned two inverter models (21 for Huawei and 26 for Sungrow)
Inference engine	*Predefined* Feedforward control strategy Rete algorithm Three conflict-solving methods - (1) the priority method – the rules with the highest priority (salience) will be used first, (2) if the applicable rules have the same priority, the rule that uses the most recent facts will be executed first, and (3) the first rule applicable method (order of introduction into the rule base).
Explanation module	*Particular* The explanations are defined as rules Contain information that helps the user to understand the faults, causes, and repair actions

User interface	*Predefined with specific aspects* A text-based interface that asks for input data specific to the proposed expert system

Figure 3 demonstrates the implementation of the proposed expert system with a capture from CLIPS-IDE, where the objects refer to the inverter, code, diagnosis, cause, troubleshooting, solution, and explanation.

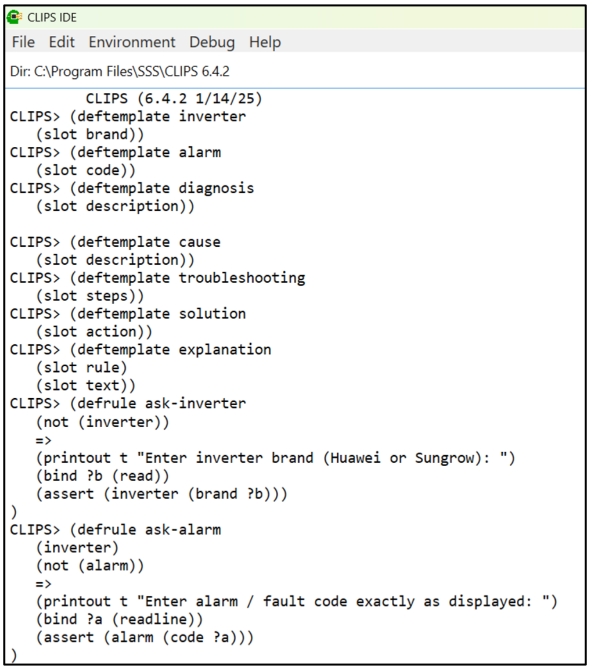


Fig. 3. Expert system implementation in CLIPS-IDE.

To increase the efficiency of the expert system, all knowledge was implemented as a single rule, as can be seen in the next paragraph.

```
(defrule huawei-overtemp
 (inverter (brand Huawei))
 (alarm (code "Inverter Overtemperature"))
 =>
 (assert (diagnosis (description "Thermal alarm; power derating or shutdown")))
 (assert (cause (description "Poor ventilation, dust, defective fan")))
 (assert (troubleshooting (steps "Check airflow, clean filters, inspect fan")))
 (assert (solution (action "Improve ventilation or replace fan")))
 (assert (explanation (rule huawei-overtemp)
        (text "Thermal protection prevents damage to power electronics.")))
)
```

The text-based interface interacts with the users, as the proposed expert system asks for the input data (facts) and shows the results, as solutions and explanations. As CLIPS-IDE works with rules, everything is implemented as displays the next paragraphs ((1) interface module and (2) explanation module).

(1)

```
(defrule ask-inverter
  (not (inverter))
  =>
  (printout t "Enter inverter brand (Huawei or Sungrow): ")
  (bind ?b (read))
  (assert (inverter (brand ?b)))
)

(defrule ask-alarm
  (inverter)
  (not (alarm))
  =>
  (printout t "Enter alarm / fault code exactly as displayed: ")
  (bind ?a (readline))
  (assert (alarm (code ?a)))
)
```

(2)

```
(defrule show-result
 (diagnosis (description ?d))
 (cause (description ?c))
 (troubleshooting (steps ?t))
 (solution (action ?s))
 (explanation (text ?e))
 =>
 (printout t crlf "===== INVERTER EXPERT SYSTEM =====" crlf)
 (printout t "Diagnosis: " ?d crlf)
 (printout t "Probable cause: " ?c crlf)
 (printout t "Troubleshooting steps: " ?t crlf)
 (printout t "Recommended solution: " ?s crlf)
 (printout t "Expert explanation: " ?e crlf)
)
```

It must be mentioned that, for research and explaining purposes, and to be easier to understand by the readers, the error codes for the inverters were implemented using text and not numbers. But the assistant expert system that works with the specialized personnel, the interaction text with the users should be more specialized.

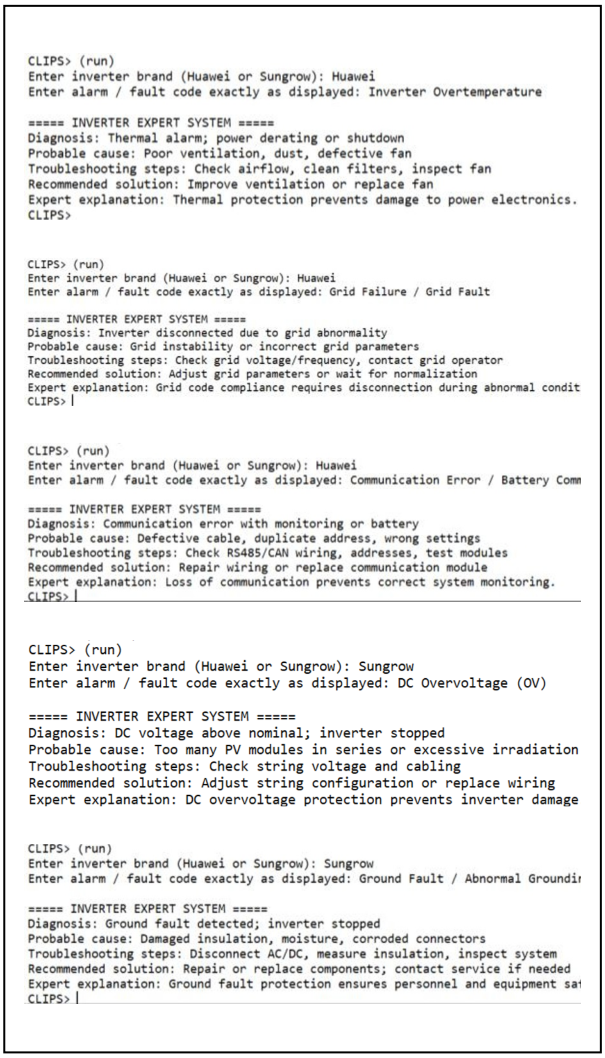
5 Validation and discussions

The validation of the proposed expert system was made using qualitative testing. Because the current version of the expert system is a prototype, the testing was limited and focused on the efficacy of the implemented expert system.

Thus, every possible input data was introduced, and the results were evaluated. Figure 4 illustrates the result given by the expert system for the following facts: inverter model "Huawei" and the error "Inverter Overtemperature", "Huawei" and the error "Grid Failure / Grid Fault", "Huawei" and the error "Communication Error / Battery Comm", "Sungrow" and the error "DC Overvoltage (OV)", "Sungrow" and the error "Ground Fault / Abnormal Grounding".

The results of the testing showed the efficacy of the expert system. Consequently, the advantages of the expert system are that it is a valuable and quick source of knowledge for the personnel who are employed in the corrective maintenance of inverters of PV systems.

The limitation of the current form of the expert system is that it is implemented in CLIPS-IDE, so the interface is not user-friendly.


```
CLIPS> (run)
Enter inverter brand (Huawei or Sungrow): Huawei
Enter alarm / fault code exactly as displayed: Inverter Overtemperature

===== INVERTER EXPERT SYSTEM =====
Diagnosis: Thermal alarm; power derating or shutdown
Probable cause: Poor ventilation, dust, defective fan
Troubleshooting steps: Check airflow, clean filters, inspect fan
Recommended solution: Improve ventilation or replace fan
Expert explanation: Thermal protection prevents damage to power electronics.
CLIPS>

CLIPS> (run)
Enter inverter brand (Huawei or Sungrow): Huawei
Enter alarm / fault code exactly as displayed: Grid Failure / Grid Fault

===== INVERTER EXPERT SYSTEM =====
Diagnosis: Inverter disconnected due to grid abnormality
Probable cause: Grid instability or incorrect grid parameters
Troubleshooting steps: Check grid voltage/frequency, contact grid operator
Recommended solution: Adjust grid parameters or wait for normalization
Expert explanation: Grid code compliance requires disconnection during abnormal condit
CLIPS> |

CLIPS> (run)
Enter inverter brand (Huawei or Sungrow): Huawei
Enter alarm / fault code exactly as displayed: Communication Error / Battery Comm

===== INVERTER EXPERT SYSTEM =====
Diagnosis: Communication error with monitoring or battery
Probable cause: Defective cable, duplicate address, wrong settings
Troubleshooting steps: Check RS485/CAN wiring, addresses, test modules
Recommended solution: Repair wiring or replace communication module
Expert explanation: Loss of communication prevents correct system monitoring.
CLIPS> |

CLIPS> (run)
Enter inverter brand (Huawei or Sungrow): Sungrow
Enter alarm / fault code exactly as displayed: DC Overvoltage (OV)

===== INVERTER EXPERT SYSTEM =====
Diagnosis: DC voltage above nominal; inverter stopped
Probable cause: Too many PV modules in series or excessive irradiation
Troubleshooting steps: Check string voltage and cabling
Recommended solution: Adjust string configuration or replace wiring
Expert explanation: DC overvoltage protection prevents inverter damage

CLIPS> (run)
Enter inverter brand (Huawei or Sungrow): Sungrow
Enter alarm / fault code exactly as displayed: Ground Fault / Abnormal Groundi

===== INVERTER EXPERT SYSTEM =====
Diagnosis: Ground fault detected; inverter stopped
Probable cause: Damaged insulation, moisture, corroded connectors
Troubleshooting steps: Disconnect AC/DC, measure insulation, inspect system
Recommended solution: Repair or replace components; contact service if needed
Expert explanation: Ground fault protection ensures personnel and equipment sa
CLIPS> |
```

Fig. 4. Expert system results.

6 Conclusions

The number of PV systems is increasing rapidly, and thus, more maintenance is needed. In the case of corrective maintenance, the time to solve the problem is essential. To achieve this goal, a feasible approach is to use an application available to all personnel involved in maintenance activities.

The objective of the research whose results are presented in this work was to develop an expert system that can assist the personnel in their activity of inverter corrective maintenance. The knowledge used to build the knowledge base of the assistant expert system was obtained from experts and specialized personas through interviews and observations. To develop the prototype of the expert system, the CLIPS IDE was used. The resulting expert system was validated through qualitative testing, which underscored the efficacy of the expert system prototype and answered the research question: the expert system is feasible as assistance for the corrective maintenance of inverters in PV systems.

To make the present prototype more efficient, it should have a user-friendly interface and the possibility for users to introduce new information.

As future work, more inverter models can be introduced.

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