IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 26, 2018, accepted February 27, 2019, date of current version May 6, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2907199

Modeling and Verification of a Reliable Multi-Agent Solution Promoting the Autonomy and Self-Sufficiency of Microgrids in an Isolated Location

MONCEF BEN SMIDA[1,2,3], KHAOULA MILED[1,3], MOHAMED KHALGUI[1,3], (Member, IEEE), GEORG FREY[4], (Senior Member, IEEE), AND ZHIWU LI[5,6], (Fellow, IEEE)

[1]School of Electrical and Information Engineering, Jinan University (Zhuhai Campus), Zhuhai 519070, China
[2]LSA Lab of Polytechnic School, University of Carthage, Tunis 1080, Tunisia
[3]National Institute of Applied Sciences and Technology, University of Carthage, Tunis 1080, Tunisia
[4]Chair of Automation and Energy Systems, Saarland University, 66111 Saarbrücken, Germany
[5]Institute of Systems Engineering, Macau University of Science and Technology, Macau 999078, China
[6]School of Electro-Mechanical Engineering, Xidian University, Xi'an 710071, China

Corresponding authors: Mohamed Khalgui (khalgui.mohamed@gmail.com) and Zhiwu Li (systemscontrol@gmail.com)

This work was supported in part by the National Key R&D Program of China under Grant 2018YFB1700104, and in part by the International Scientific Partnership Program ISPP, King Saud University, under Grant ISPP#0079.

ABSTRACT This paper deals with microgrids in an islanded location where only local generator sources are deployed. However, microgrids in isolated mode are susceptible to unplanned meteorological changes. The defy is to improve the autonomy of these microgrids; thus we start first by checking the required availability of power in the microgrid after unexpected hardware conflicts, characterizing the faults in production sources by probabilistic distributions and modeling their occurrences by using a connection of Markov chains and Petri nets. We propose also a new multi-agent control strategy where agents are employed to check the availability of sources and supply power automatically to consumers in accordance with their priorities and power requirements. The whole architecture is modeled by a modeling and verification environment named ZIZO. The simulation and experimental results are based on data collected from a Tunisian petroleum platform. The availability of energy in the microgrid is increased to 99.68%, and it could be corrected up to 100%. Although this strategy can decrease the availability rate for the uncritical loads, it prevents the microgrid from any dangerous situation.

INDEX TERMS Microgid in islanded mode, Markov chain, Petri net, reliability, verification.

NOMENCLATURE

R-TNCES	Reconfigurable Timed-Net Condition/Event Systems
GR-TNCES	Generalized Reconfigurable Timed-Net Condition/Event System
PN	Petri Net
SPN	Stochastic Petri Net
GUI	Graphical User Interface
LTL	Linear Temporal Logic
CTL	Computation Tree Logic
PCTL	Probabilistic Computation Tree-Logic
FTA	Fault Tree Analysis
PV	Photovoltaic
WT	Wind Turbine
η_s	Extraction efficiency of component
n	Number of PV sources
Btt	Battery
DG	Diesel Generator
m	number of WT sources
p	number of Btt sources
s	number of DG sources
NCL	Non Critical Load
CLLP	Critical Load with Low Priority
CLHP	Critical Load with High Priority

The associate editor coordinating the review of this manuscript and approving it for publication was Aniruddha Datta.

S	Source (i.e., PV, WT, Btt, DG)
$P_{F.s}$	Failure probability of each source (S)
rs	Resource (i.e., sun, wind, charge, fuel)
$P_{F.rs}$	Lack probability of rs
C	Component (i.e., panel, wtc, bttc, dgc)
λ_c	Failure rate of C
R_s	Reliability of the microgrid
B	Circuit breaker
W_{PV}	Energy produced by PV
W_{WT}	Energy produced by WT
W_{Btt}	Energy produced by Btt
W_{DG}	Energy produced by DG
W_L	Energy required by loads
W_{sun}	Sun intensity
W_{wind}	Wind speed
W_{charge}	Battery charge level
W_{fuel}	Fuel level
$E_{pw.U}$	Probability of the power unavailability
E_i	Event-in
E_o	Event-out

I. INTRODUCTION

A microgrid is a small-scale power supply network that is designed for small energy generation units [8], [10], [13], [39]. It has been gaining ground with the growing concern on global environmental and social issues [4], [30], [43]. It is a new concept of power systems, dedicated to strengthening the grid resilience and helping mitigate the grid disturbances through the utilization of the heat generated from localized electricity production [47]. A microgrid is made up of intermittent sources such as renewable energy sources and controllable sources such as electrical diesel generators. It can run autonomously or with a connection to a larger grid. However, the productivity of renewable resources like photovoltaic sources and wind turbine generators highly depends on meteorological conditions. On the one hand, the productivity of photovoltaic sources is controlled by the intensity of natural light and temperature [31]. On the other hand, the productivity of wind turbine generators is subject to the variation of wind forces [32].

In an islanded mode, a microgrid works separately from the main grid, thus running the risk of being free from energy for a long period of time due to the nature of the intermittent sources. Since an isolated microgrid should be a self-sufficiency power system in many sectors such as offshore petroleum platforms and military bases, the service quality and mainly the power supply availability of a microgrid are regarded as paramount factors. Therefore, storage devices are implemented to support the microgrid energy productivity during sudden changes in generation or load. Still, the role of a storage device depends on the storage capacity of the microgrid [56]. To increase the system reliability and availability, the component sizing combination with the energy required by loads is considered as a high priority [52], [55], [57]. However, the increase of their capacity is economically expensive and inaccessible in some locations (i.e., offshore petroleum platforms). In addition, the microgrid cannot depend on the storage devices for a long period of time.

The microgrid investigated in this paper is an abstraction of an anonymous offshore petroleum platform located on the Tunisian coast. In bad weather conditions, the platform becomes inaccessible for refueling diesel generators. In this condition, the platform has to assure its energy self-sufficiency and has to avoid the total absence of electrical power supply. According to the historical production of the platform, nine total stops were registered between 2013 and 2017. These stops caused approximately two million dollars of losses for the Tunisian Government. The loss caused by stopping production of the platform per day is estimated at 200,000 dollars.[1] In this paper, we aim to solve the problem of reliability in this real Tunisian petroleum platform by creating a new control strategy based on the probabilities of failures in the sources and meteorological conditions. This strategy is a predictive solution of any malfunction that could happen in the system. It is based on real-time forecasting of meteorological factors taking into consideration a load shedding strategy. It increases the autonomy of backup sources and the system availability in unfavorable weather conditions. The control strategy will be verified by three methods: logic fault tree analysis [12], Markov chains [2], [7], [17], [28] and Petri nets [29] simulation and verification. In order to calculate the approximate value of availability and reliability [4], we study and implement a real model architecture of a microgrid system. It is used to control the reconfiguration process [86] and to guarantee the requested power in the grid. A mathematical approach is then needed to show the various relationships between the different components of a microgrid and the impact of the meteorological factors on them. The control strategy will be able to minimize the negative effect of the intermittent behavior of the renewable sources on the platform. The experimental tests of the implemented mathematical method are supported by ZIZO [45] which is a modeling and probabilistic-simulating software package of generalized reconfigurable timed net condition/event systems (GR-TNCES), a sub-class of Petri nets. The experimental simulation of this model shows a high improvement of the power availability in the microgrid.

This paper deals with a multi-source power system composed of wind turbine generators, photovoltaic panels, diesel generators and energy storage batteries. A hierarchical multi-agent [82], [84] control solution is presented, which aims to predict the availability of sources, and based on these predictive probabilities a load shedding strategy will be established if needed. The multi-agent reconfiguration is composed of three models, where the first deals with sources,

[1] Official statistics provided by CIPEM. Web: www.cipem.com.tn

the second manages tests, and the last model copes with decisions. The reconfiguration of such a system can culminate with a blocking problem that is sometimes unsafe or does not respect real-time properties [74], [76], [77]. We check a safe behavior of this reconfigurable architecture [78]–[80] after unexpected hardware conflicts using PRISM model checker [42]. It applies an exhaustive CTL-formal verification to ensure a safe reconfiguration [83], [85] of sources, tests, and decisions.

This paper is organized as follows. Section II presents the background. Section III describes the contribution of this paper which consists in the formalization and reconfiguration of the system. Section IV applies the contribution to a case study. Finally, Section V summarizes this paper.

II. BACKGROUND

This section presents the related work that deals with the microgrid reliability, control and supervision.

A. FORMALISMS

Petri nets provide a suitable and progressive framework for the representation and analysis of discrete event systems. They are appropriate to describe systems that involve competitive concerns, synchronization, sharing resources and parallelism [3]–[5]. Different classes of Petri nets can represent different types of systems. They can be used for control, performance analysis, simulation (step by step or automatically for a defined date or a number of transitions firing) and verification [21], [25], [37], [73], [87]. We choose ZIZO [45] and PRISM [42] as tools for formal modeling and analysis of system behavior. ZIZO is a software tool for modeling [41], analysis [50], control [1], [9], [15], [49], and scheduling [33], [38], [20], [54] of discrete event systems. It enables us to model, simulate and verify reconfigurable real-time control tasks sharing adaptive resources. PRISM (probabilistic model checker) is a tool for formal modeling and analysis of systems that exhibit random or probabilistic behavior. The verification of timed Petri nets is provided in PRISM with linear temporal logic (LTL) formulas [16], [18], [22], [23], computation tree logic (CTL) and probabilistic computation tree logic (PCTL) [11], [27]. The purpose is to check if the system respects the related functional and temporal constraints. ZIZO provides the possibility to export the created models to PRISM for the formal verification of the created model. This operation is guaranteed by generating a .pm file which is in PRISM language. The generated file is a randomized distributed algorithm that describes the whole model as a discrete time Markov chains [70], continuous time Markov chains [71], Markov decision processes [72], probabilistic automata and probabilistic timed automata [26]. Markov chains provide suitable and configurable graphs for the description and checking of several types of probabilistic models process [19], [24], [48].

B. STATE OF THE ART

The main problem in microgrids is that its availability is affected by the different deployed sources. As we are always limited by the spaces and the expense of these sources, researchers have been seeking for different strategies to adjust energy production in the cheapest and most efficient way, especially for the microgrid deployed in an islanded mode. Their main objective is to increase the reliability and availability in the grid [37], [52], [58]. Some researchers [35]–[37] find that the key element to improve microgrid efficiency is to coordinate between the different deployed sources, for example by maximizing the use of renewable energy resources and minimizing the utilization of diesel generators [34], [54]. In other words, the diesel generator should be used only when both renewable energy and batteries fail to meet load demands. The hybridization of the different deployed sources is considered as a new topology to control and supervise the operations of energy generation systems for certain researchers too [40]. The research in [51], [46] proposes that to maintain continuity of power supply in the grid, it is necessary to coordinate the load's behavior with the availability of energy in real-time, counting both on the stochastic fluctuation of the energy flow and the active demands of loads.

Although these strategies of control are in real-time, they do not allow us to have optimum availability. In this case, we come up with an original control strategy for a better energy management in a microgrid with an islanded mode. To put it more simply, the proposed strategy aims to combine both load forecasting and load shedding strategies [44]. We try to predict the availability of energy sources in order to decide the strategy of energy consumption by the loads according to their priorities. In a microgrid, the loads do not have the same importance, and in certain cases, the elimination of some non-critical loads increases the operating time of the critical loads without having any negative impacts on the main grid. Unfortunately, the performance of the forecasting control strategy depends on the accuracy of weather information on time. To overcome this problem, we use a mathematical model to calculate the failure probability of the sources according to environmental changes. Moreover, the control strategy will not only be based on the real states of sources, but it is also used to forecast the integration of the renewable energy sources by meteorological data and consequently to reduce the number of loads in action if needed so as to increase the autonomy of the backup sources. For this reason, we require the implementation of control agents [75] to manage the energy consumption and production where each agent needs to be related to the different components of the grid sources/loads and makes the appropriate decision according to the data information about weather and the state of sources. Thus, our system reconfiguration is composed of masters and slaves. The masters are the agents that make decisions according to the mathematical formalization developed later in this paper. The slaves will react according to

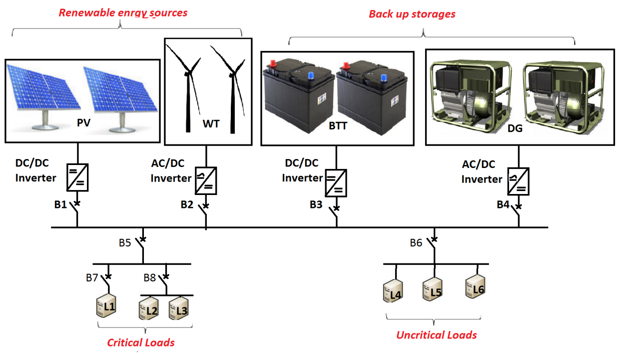


FIGURE 1. **The considered microgrid architecture.**

these decisions. The proposed control strategy can make the right decision on connecting the right sources instantly and on the use of the load shedding method according to integration probability of renewable sources.

To sum up, the availability of the electrical energy in an isolated grid is considered as one of the critical issues that needs to be solved on the spot. Improving performance of power grid (optimize power quality, cost, energy loss, etc.) urges a precise management and distributed control. Within this study, we try to evaluate the related works in order to eliminate the main problems of the existing control strategies which are designed to deal with the problem of system reliability and availability. However, most of them focus essentially on the increase of production by the sources oversizing [59]. Other solutions consider either side management of sources [60], [81] or side management of loads [61] and their forecasting methods are proved to be inadequate. As far as we are concerned, our choice of an approach with agents for the energy management provides the system with more flexibility in control. Besides, it is new in the sense that it facilitates the adaptation of the control strategy to any change in the microgrid topology. Also, the originality of this paper consists in a novel formalization of the problem in order to create a new control architecture to model, simulate and verify the proposed strategy. The developed control architecture is capable of assuring high power availability for critical and priority loads, thus improving the grid autonomy.

III. CASE TO BE STUDIED:TUNISIAN PETROLEUM PLATFORM

In this subsection, we present the microgrid investigated in this paper as well as its main problems.

A. MICROGRID ARCHITECTURE

The case to be studied is based on the microgrid of a Tunisian offshore petroleum platform located in the Gulf of Hammamet in Tunisia. The microgrid architecture (Fig. 1) of the adopted petroleum platform is composed of i) Sources: Two photovoltaic sources (PV), two wind turbine generators (WT), a storage device (two batteries: (Btt)), and two diesel generators (DG) with their fuel tanks; ii) Eight controllable circuit breakers (B1... B8); iii) Static converter for each source; and iv) Six loads (L1...L6).

In this microgrid, each renewable energy source is designed to be able to power all the loads and batteries in its charging phase. Each battery and each diesel generator is designed to be able to supply all loads. Battery and diesel generators are considered as back up sources in the microgrid. The autonomies of these back up sources (Btt and DG) depend respectively on the charge level of the battery and the fuel level of the diesel and both of them depend on the load consumption. Each energy source is characterized by its failure rate. The six loads are classified into two categories: critical loads (L1, L2, L3) and non- critical loads (L4, L5, L6). The critical loads (L1, L2, L3) have priority over the non-critical ones; L1 is a critical load with higher priority and L2 and L3 are critical loads with low priorities. The level of power supply priority depends on the power load criticality. The non-critical loads can be disconnected in some cases.

B. PROBLEM FORMULATION

In this subsection, we propose to calculate the availability A of the whole system. Thus, we define the real cause of failures in the system and we define the probability of failure of each source in the system to finally find the general equation of its availability by using the fault tree analysis method. The system is defined as follows:

$$System = (\mathcal{S}, \mathcal{L}, A, Crt)$$

where: i) $\mathcal{S}$ is a set of n PV sources, m WT sources, p Btt sources, and s DG sources, ii) $\mathcal{L}$ is a set of loads awaiting to be supplied with energy by taken into account the level of energy available and their priorities, iii) A is the availability of different sources, and iv) Crt is the controller of produced energy flow by each source. Knowing that the components and resource failures are mutually exclusive, the failure probability $F_{P.s}$ of each source is the sum of the failure probability of the resource $F_{P.rs}$ and failure rate λ_c of the component. The reliability R_s of sources depends on the failure probability $F_{P.s}$. We define the equation as follows:

$$R_s = 1 - F_{P.s} \tag{1}$$

$$F_{P.s} = F_{P.rs} + \lambda_c \tag{2}$$

According to Eq. (2), we determine the failure probability of each source as follows. i) For the PV source, we have

$$F_{P.PV} = F_{P.sun} + \lambda_{panel} \tag{3}$$

$$F_{P.sun} = 1 - P_{sun} \tag{4}$$

where $F_{P.sun}$ is the failure probability of resource (sun light), λ_{panel} is the failure rate of panel, and P_{sun} is the sunshine probability defined by

$$P_{sun} = \frac{hours\ of\ sunshine}{hours\ in\ a\ year} \tag{5}$$

ii) For the WT source, we have

$$F_{P.WT} = F_{P.wind} + \lambda_{wtc} \tag{6}$$

$$F_{P.wind} = 1 - P_{Wind} \tag{7}$$

where $F_{P.wind}$ is the failure probability of resource (wind force), λ_{wtc} is the failure rate of wind turbine component, and P_{Wind} is the probability of wind defined by

$$P_{Wind} = \frac{number\ of\ days\ with\ adequate\ wind\ speed}{number\ of\ day\ per\ year} \tag{8}$$

iii) For the DG source,

$$F_{P.DG} = F_{P.fuel} + \lambda_{dgc} \tag{9}$$

$$F_{P.fuel} = 1 - P_{fuel} \tag{10}$$

where $F_{P.fuel}$ is the failure probability of resource (fuel), λ_{dgc} is the failure rate of the diesel generator component (dgc), and P_{fuel} is the probability of refueling which is dependent of the wind probability defined by

$$P_{fuel} = \frac{periods\ wind\ is\ adequate}{periods\ of\ wind\ per\ day} \tag{11}$$

iv) For the Btt source:

$$F_{P.Btt} = F_{P.charge} + \lambda_{bttc} \tag{12}$$

$$F_{P.charge} = = 1 - P_{charge} \tag{13}$$

where $F_{P.charge}$ is the failure probability of battery charge, and λ_{bttc} is the failure rate of the battery component (bttc). The probability of the charged battery P_{charge} is defined by

$$P_{charge} = \frac{hours\ of\ autonomy\ of\ battery}{hours\ per\ day} \tag{14}$$

To ensure the continuity of power supply of loads in the microgrid, the power produced by sources should be greater than that required by loads (L) as follows:

$$max\{W_{PV}, W_{WT}, W_{Btt}, W_{DG}\} \geq L \tag{15}$$

where W_{PV}, W_{WT}, W_{Btt} and W_{DG} are the energy produced respectively by PV, WT, Btt and DG. The levels of energy in PV, WT, Btt and DG are respectively proportional to the level of energy of resources W_{sun}, W_{wind}, W_{charge} and W_{fuel}. They depend on the extraction efficiency of component η_s: η_{PV}, η_{WT}, η_{Btt}, and η_{DG}. They depend as well on the reliability of sources R_s: R_{PV}, R_{WT}, R_{Btt}, and R_{DG}. η_s and R_s are between zero and one. The energy of the sources is defined by

$$W_{PV} = f(W_{sun}, \eta_{PV}, R_{PV}) = W_{sun} * \eta_{PV} * R_{PV} \tag{16}$$

$$W_{WT} = f(W_{wind}, \eta_{WT}, R_{WT}) = W_{wind} * \eta_{WT} * R_{WT} \tag{17}$$

$$W_{Btt} = f(W_{charge}, \eta_{Btt}, R_{Btt}) = W_{charge} * \eta_{Btt} * R_{Btt} \tag{18}$$

$$W_{DG} = f(W_{fuel}, \eta_{DG}, R_{DG}) = W_{fuel} * \eta_{DG} * R_{DG} \tag{19}$$

C. MICROGRID AVAILABILITY CONDITION

In this subsection, we calculate the probabilities that characterize the failures on the platform using the fault tree analysis (FTA) [14]. The fault tree analysis structure decomposes the system levels of failures to determine the principal cause of the power unavailability in a microgrid. The reduced fault tree (Fig. 2) is deduced by using the cut set. It is used to calculate the probability of power unavailability $P_{pw.U}$, i.e.,

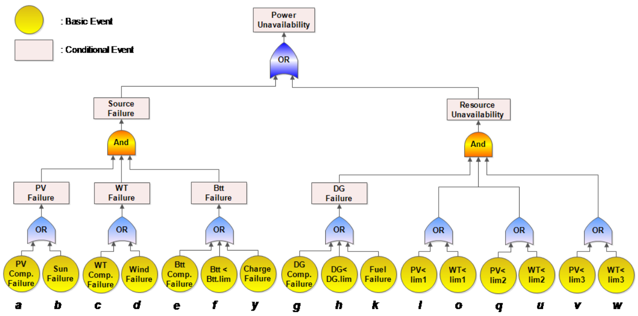


FIGURE 2. Microgrid availability conditions with fault tree analysis.

$$P_{pw.U} = [(a+b)*(c+d)*(e+f+y)] + [(g+h+k)*(l+o)*(q+u)*(v+w)] \tag{20}$$

where:
i) a and b are related to the photovoltaic sources cause of failure, a is the failure rate of PV panels and b is the failure probability of sun.
ii) c and d are related to the wind turbine generators, c is the failure rate of wind turbine component and d is the failure probability of wind speed.
iii) e, f and y are related to the batteries, e is the failure rate of batteries component, f is the probability of integration of batteries energy equal to Btt.limit $P_{Btt.limit}$ and y is the failure probability of batteries charge.
iv) g, h ank k are related to the diesel generators, g is the failure rate of the diesel generator component, h is the probability of integration of DG energy equal to DG.limit $P_{DG.limit}$ and k is the failure probability of the refueling.
v) l is the probability of integration of PV energy equal to limit1 $P_{PV.limit1}$ and o is the probability of integration of WT energy equal to limit1 $P_{WT.limit1}$.
vi) q is the probability of integration of PV energy equal to limit2 $P_{PV.limit2}$ and u is the probability of integration of WT energy equal to limit2 $P_{WT.limit2}$.
vii) v is the probability of integration of PV energy equal to limit3 $P_{PV.limit3}$ and w is the probability of integration of WT energy equal to limit3 $P_{WT.limit3}$.

Knowing that the events are mutually exclusive, and according to this reduced FTA, the expression of the power availability A in the microgrid is given by Eq. (21) as follows:

$$A = 1 - P_{pw.U} = 1 - [((\lambda_{panel} + F_{P.sun}) * (\lambda_{wtc} + F_{P.wind}) * (\lambda_{bttc} + P_{Btt.limit} + F_{P.charge})) + ((\lambda_{dgc} + P_{DG.limit} + F_{P.fuel}) * (P_{PV.limit1} + P_{WT.limit1}) * (P_{PV.limit2} + P_{WT.limit2}) * (P_{PV.limit3} + P_{WT.limit3}))] \tag{21}$$

D. PROBLEMS AND DISCUSSIONS

As shown earlier in this paper, the main problem of the petroleum platform is that it should be an autonomous power system as it operates in an islanded mode. The problem lies in the intermittent nature of all renewable energy sources. The availability of renewable sources (PV and WT) and refueling diesel generators are related to the meteorological conditions. The microgrid has to be connected only with the backup storage (batteries and diesel generators) until the weather condition improves. Backup sources are available for limited period of time. If backup storage stops and renewable energy is still inaccessible, then the electrical energy becomes totally unavailable and all the microgrid loads will be off-service. The unavailability of resources for a long period can cause several blackouts for the petroleum platform. Therefore, implementing a distributed management system for successful coordination, resources availability prediction, and network safety is imperative.

In this paper, the energy production by sources depends on the state of resources (sun, wind, battery charge and fuel), and the state of sources (PV, WT, Btt, DG). The national institute of the meteorology in Tunisia[2] supplies us with the necessary weather information. The data obtained for one year are utilized to estimate the sources availability. In this paper, the probability of availability of sources components is assumed as follows:

- i) Photovoltaic panels produce energy if the intensity of the sunlight is adequate. Otherwise, the photovoltaic panels does not produce energy. We have 2,804 hours of adequate sunlight per year. The estimated probability for the sun is 0.32 per year. The estimated failure rate of the PV components is $\lambda_{PV} = 10^{-6}$ [62].
- ii) The wind turbine generators do not produce energy if the speed of wind is inadequate. Wind speed should be between minimum 7 m/s (14 knots) and maximum 15 m/s (29 knots) [63]. The estimated probability for the adequate wind is 0.67 per year. The estimated failure rate of the WT components is $\lambda_{WT} = 5 * 10^{-6}$ [64].
- iii) The batteries have two functional modes; discharge mode if it is higher than 30% and charging mode if it is not at full charge and can only operate for 4 days at full load. The estimated probability for the batteries to stop producing energy is 0.62 per year. The estimated failure rate of the batteries is $\lambda_{Btt} = 3 * 10^{-6}$ [68].
- iv) The diesel generators can only operate for 9 days at full load and stop producing electricity if the fuel level is less than or equal to 10% (risk of cavitation). The fuel is available for refueling if the wind speed in the sea is between 7 and 10 m/s. The estimated probability for refueling is 0.21 per year. The estimated failure rate of the DG components is $\lambda_{DG} = 2 * 10^{-6}$ [69].

The availability of system components can be modeled as a Markov chains with four states for each component of the multi-source energy production system: WT, PV, DG and Btt (Fig. 3). Next, we present a control strategy and the main motivation of the contribution.

[2]www.meteo.tn

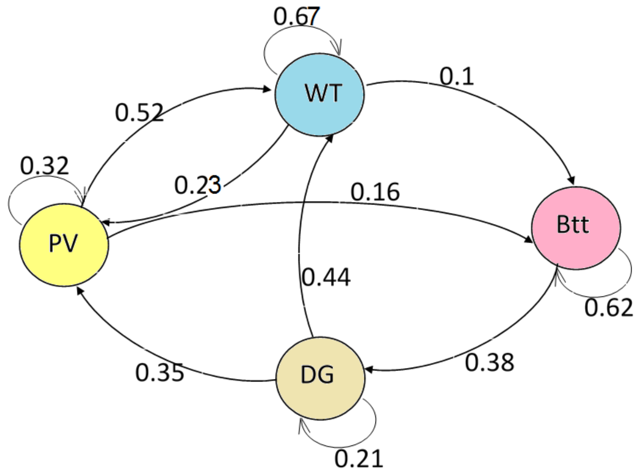


FIGURE 3. Probabilistic distribution of the microgrid sources with Markov chains.

IV. NEW SOLUTIONS FOR RELIABLE MICROGRIDS

In this section, we describe the paper contribution, formalization and motivation. We explain the multi-agent architecture and communication protocol using mathematical formulas.

A. MOTIVATION

The contribution consists in the development of a new control strategy in order to reach required availability and reliability of power in the microgrid. The control strategy is based on the study of the probabilities of failures in producing energy of each source. The study of this probability of failures will enable us to forecast the availability of sources over time within meteorological changes. A hierarchical multi-agent control solution is then presented, which aims to predict the availability of sources. Based on this forecasting probabilities, a load shedding strategy is established. This approach is original in the sense that it enables us to study the behavior of such systems under various meteorological conditions in order to predict their availability and fulfill energy demands for microgrid loads. The proposed model is composed of three parts: i) Producers, ii) Consumers, and iii) Masters. Producers and consumers are considered as slaves. The master plays the role of the system control kernel. It presents the system intelligence that makes several decisions according to the data information about resources and loads. It is able to detect the component malfunctions, enhance the performance and safety of the power supply and collect performance data. The master is linked to the producers and consumers by its circuit breakers in order to cut the selected slaves from the base architecture or to connect them according to the collected data information. There are three main masters: i) Super master, ii) Master agent for producers, and iii) Master agent for consumers. The super master agent is used to coordinate between the master agent for producers and the master agent for consumers and to exchange information between them. The master agent for producers is used to predict the probability of availability of each source and to select the sources with the highest probabilities to be the energy provider. The master agent for consumers decides if the load shedding strategy is needed based on the predicted probabilities coming from the super master.

B. MICROGRID CONTROL STRATEGY

In this subsection, we propose to control the loads and sources availability through their circuit breakers. The control of the platform component can be managed by their master agents. The master agents can control the sources and loads by its circuit breakers in order to cut them from the base architecture or connect them depending on the collected data information. The control of each circuit breaker depends on the availability of resources and the possibility of integration of renewable energy over time. In this paper, we aim to increase the availability of backup sources as well as the availability of the platform. Therefore, we focus mostly on the availability of power for critical loads. A shedding strategy is therefore required. The load shedding strategy aims to decrease the availability of power for the non-critical loads and to increase the availability of power for the critical ones by disconnecting the non-critical loads. This solution does not have negative impacts on the microgrid production. In the case of a short absence duration of renewable sources, the forecasting information helps the control strategy to avoid unjustified (unneeded) load shedding. B1, B2, B3 and B4 are the circuit breakers of the sources and B5, B6, B7, and B8 are the circuit breakers of the loads as shown in Fig. 1. The circuit breakers expression is presented as follows (the expression of $\lceil x \rceil$ represents ceiling(x)):

For PV, the circuit breaker *B1* is:

$$B1 = \left\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit3} \right\rceil \tag{22}$$

where $\sum_{v=1}^{n} P_{PV_v}$ is a set of PV sources going from $v = 1$ to $v = n$, $P_{PV.limit3}$ is the probability of integration of PV energy.

$$B1 = \begin{cases} 0 & \text{if } \frac{\sum_{v=1}^{n} P_{PV_v}}{n} < P_{PV.limit3} \\ 1 & \text{if } \frac{\sum_{v=1}^{n} P_{PV_v}}{n} > P_{PV.limit3} \end{cases}$$

For WT, the circuit breaker *B2* is:

$$B2 = (1 - B1) * \left\lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit3} \right\rceil \tag{23}$$

where $\sum_{j=1}^{m} P_{WT_j}$ is a set of WT sources going from $j = 1$ to $j = m$, $P_{WT.limit3}$ is the probability of integration of WT energy.

$$B2 = \begin{cases} 0 & \text{if } (B1 = 1) \text{ } or \text{ } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m} < P_{WT.limit3}) \\ 1 & \text{if } (B1 = 0) \text{ } and \text{ } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m} > P_{WT.limit3}) \end{cases}$$

For Btt, the circuit breaker *B3* is:

$$B3 = (1 - \overline{B1}) \vee (1 - \overline{B2}) \vee \left\lceil \frac{\sum_{z=1}^{p} P_{Btt_z}}{p} - P_{Btt.limit} \right\rceil \tag{24}$$

where $\sum_{z=1}^{p} P_{Btt_z}$ is a set of Btt sources going from $z = 1$ to $z = p$, and $P_{Btt.limit}$ is the probability of integration of Btt energy equal to limit.

$$B3 = \begin{cases} 0 & \text{if } (B1 = B2 = 0) \text{ } and \\ & \frac{\sum_{z=1}^{p} P_{Btt_z}}{p} < P_{Btt.limit} \\ 1 & \text{if } B1 = 1 \text{ } or \\ & \frac{\sum_{z=1}^{p} P_{Btt_z}}{p} > P_{Btt.limit} \end{cases}$$

For DG, the circuit breaker *B4* is:

$$B4 = (1 - B1) * (1 - B2) * (1 - B3) * \left\lceil \frac{\sum_{t=1}^{s} P_{DG_t}}{s} - P_{DG.limit} \right\rceil \tag{25}$$

where $\sum_{t=1}^{s} P_{DG_t}$ is a set of DG sources going from $t = 1$ to $t = s$, and $P_{DG.limit}$ is the probability of integration of DG energy.

$$B4 = \begin{cases} 0 & \text{if (B1=0 or B2=0 or B3=0) } or \\ & \frac{\sum_{t=1}^{s} P_{DG_t}}{s} < P_{DG.limit} \\ 1 & \text{if } (B1 = B2 = B3 = 0) \text{ } and \\ & \frac{\sum_{t=1}^{s} P_{DG_t}}{s} > P_{DG.limit} \end{cases}$$

For all the critical loads *B5* is:

$$B5 = (1 - \overline{B1}) \vee (1 - \overline{B2}) \vee (1 - \overline{B3}) \vee [(1 - \overline{B4}) *(\left\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit3} \right\rceil \vee \left\lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit3} \right\rceil)] \tag{26}$$

$$B5 = \begin{cases} 0 & \text{if } B1 = B2 = B3 = 0 \text{ } or \text{ ,} \\ & \text{if [B4=0} \\ & \text{and } ((\frac{\sum_{v=1}^{n} P_{PV_v}}{n}) <= P_{PV.limit3}, \\ & \text{or } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m}) <= P_{WT.limit3})] \\ 1 & \text{if } B1 = B2 = B3 = 1 \text{ } or \text{ ,} \\ & \text{if [B4=1} \\ & \text{and } ((\frac{\sum_{v=1}^{n} P_{PV_v}}{n}) > P_{PV.limit3}, \\ & \text{or } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m}) > P_{WT.limit3})] \end{cases}$$

For the non-critical loads, the circuit breaker *B6* is:

$$B6 = (1-\overline{B1}) \vee (1-\overline{B2}) \vee (1-\overline{B3}) \vee [(1-\overline{B4}) *(\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit1}\rceil \vee \lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit1}\rceil)] \quad (27)$$

$$B6 = \begin{cases} 0 & \text{if } B1 = B2 = B3 = 0 \; or \; , \\ & \text{if (B4=0} \\ & \text{and } (\frac{\sum_{v=1}^{n} P_{PV_v}}{n}) <= P_{PV.limit1}, \\ & \text{or } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m}) <= P_{WT.limit1}) \\ 1 & \text{if } B1 = B2 = B3 = 1 \; or \; , \\ & \text{if (B4=1} \\ & \text{and } (\frac{\sum_{v=1}^{n} P_{PV_v}}{n}) > P_{PV.limit1}, \\ & \text{or } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m}) > P_{WT.limit1}) \end{cases}$$

For the critical loads with the highest priority *B7* is: $B7 = B5$ For the critical loads with the least priority, the circuit breaker *B8* is:

$$B8 = (1-\overline{B1}) \vee (1-\overline{B2}) \vee (1-\overline{B3}) \vee [\,(1-\overline{B4}) *(\,\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit2}\rceil \vee \lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit2}\rceil\,)\,] \quad (28)$$

$$B8 = \begin{cases} 0 & \text{if } B1 = B2 = B3 = 0 \; or \; , \\ & \text{if (B4=0} \\ & \text{and } (\frac{\sum_{v=1}^{n} P_{PV_v}}{n}) <= P_{PV.limit2}, \\ & \text{or } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m}) <= P_{WT.limit2}) \\ 1 & \text{if } B1 = B2 = B3 = 1 \; or \; , \\ & \text{if (B4=1} \\ & \text{and } (\frac{\sum_{v=1}^{n} P_{PV_v}}{n}) > P_{PV.limit2}, \\ & \text{or } (\frac{\sum_{j=1}^{m} P_{WT_j}}{m}) > P_{WT.limit2}) \end{cases}$$

Thus the basic model is stated as follows:

$$Bi = \begin{cases} i=1 & \lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit3}\rceil \\ i=2 & (1-B1) * \lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit3}\rceil \\ i=3 & (1-\overline{B1}) \vee (1-\overline{B2}) \vee \lceil \frac{\sum_{z=1}^{p} P_{Btt_z}}{p} - P_{Btt.limit}\rceil \\ i=4 & (1-B1)*(1-B2)*(1-B3)* \lceil \frac{\sum_{t=1}^{s} P_{DG_t}}{s} - P_{DG.limit}\rceil \\ i=5,7 & (1-\overline{B1}) \vee (1-\overline{B2}) \vee (1-\overline{B3}) \vee [(1-\overline{B4}) * (\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit3}\rceil \vee \lceil \frac{\sum P_{WT_i}}{m} - P_{WT.limit3}\rceil)] \\ i=6 & (1-\overline{B1}) \vee (1-\overline{B2}) \vee (1-\overline{B3}) \vee [(1-\overline{B4}) * (\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit1}\rceil \vee \lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit1}\rceil)] \\ i=8 & (1-\overline{B1}) \vee (1-\overline{B2}) \vee (1-\overline{B3}) \vee [(1-\overline{B4}) * (\lceil \frac{\sum_{v=1}^{n} P_{PV_v}}{n} - P_{PV.limit2}\rceil \vee \lceil \frac{\sum_{j=1}^{m} P_{WT_j}}{m} - P_{WT.limit2}\rceil)]. \end{cases}$$

C. MULTI-AGENT ARCHITECTURE

In the previous subsections, we introduced a detailed mathematical formalization of the problem and the control strategy that we follow. In this subsection, we try to explain the multi-agent architecture, the motivation and the protocol of communication between the deployed agents. We have three categories of loads: i) Non-critical loads, ii) Critical loads, and iii) High priority loads. The multi-agent control solution is an attempt to predict the source availability based on weather information and to activate the list of loads according to their priorities. The power management is then provided by the three applied master/slave agents (Fig. 4). The master's role is divided into three parts: i) Control of resources (data information coming from the meteorological service indicating the probability of availability of sun/wind/refueling), ii) Control of the producers of energy based on the availability of its primary source (sun/ wind/ fuel/ charge), and iii) Control of the consumers by their priorities and the level of power production. The multi-agent architecture includes a super master, a master for producers and a master for consumers. The super master agent is in charge of making the decision

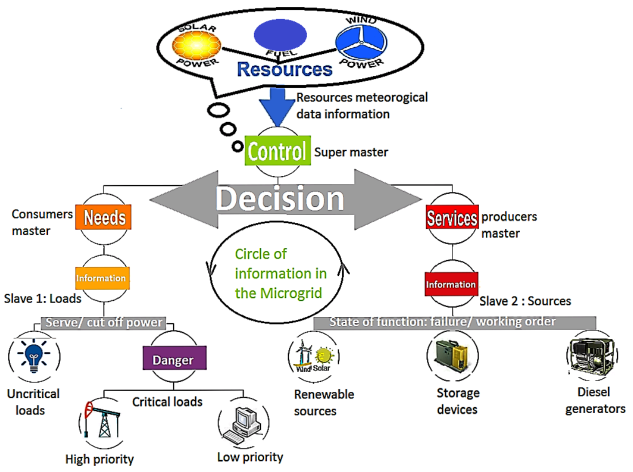


FIGURE 4. The multi-agent system communication protocol in the investigated microgrid.

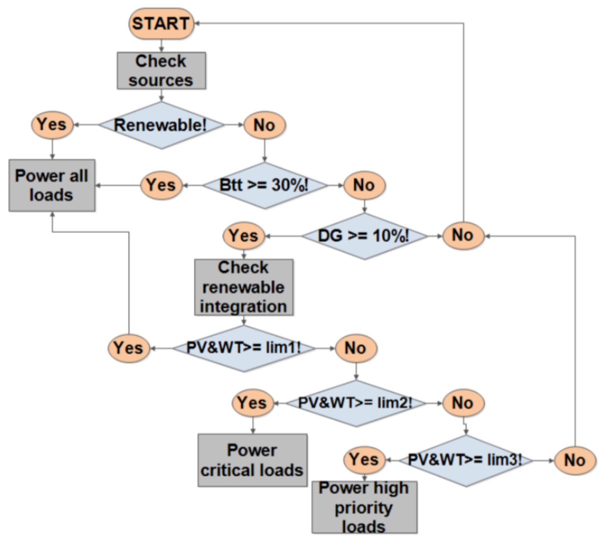


FIGURE 5. Organization chart of energy production.

of connecting one of the four sources and choosing between the three modes of the power supply by taking into account the meteorological information. There are three modes of supplying loads: Normal mode, degraded mode, and failure mode. The master agent for producers gives information about the functional state of each source. The master agent for consumers gives information about the functional state of loads and their priorities. In the normal mode, the super master gives an order to connect the renewable sources (PV, WT) with the highest availability to power all loads (critical and non-critical). In the case of unavailability of the renewable sources, the super master moves to the degraded mode by using batteries that will power almost all loads. In the event of battery failure (charge level is less than 30%), the super master switches to the diesel generators that will power almost all loads. In another case, the super master switches to load shedding control by disconnecting the non-critical loads and only power supply critical loads based on the probability of integration of the renewable resources: If it is less than $limit1$ and superior to $limit2$, only the critical loads should be connected; and if it is less than $limit2$ and superior to $limit3$, only the critical load with the highest priority should be connected to the microgrid. If the renewable sources are still not available ($< limit3$) over time and the storage sources are exhausted, the controller chooses the failure mode.

The system thus operates in three modes: i) Normal mode: either PV panels or WT are activated and produce electrical energy. In this mode, the batteries act as a load itself (charging mode). ii) Degraded mode: loads are supplied by batteries or diesel generator. iii) Failure mode: it is the critical mode that we are trying to avoid, where storage sources are exhausted and distributed energy sources are not available.

D. MULTI-AGENT COMMUNICATION PROTOCOL

The organization chart in Fig. 5 explains the communication between the master agent and the slaves in the microgrid controller. According to sources availability over time as described in the motivation subsection, the master gives order to the slaves to be in service or in a disconnected mode. The load shedding strategy depends on the possibility of integration of renewable sources when the system is working only with diesel generators.

Next, we model and verify the proposed control strategy using verification tools ZIZO and PRISM.

V. MODELING AND VERIFICATION OF RELIABLE MICROGRIDS

In this section, we describe the RTNCES [78] based model in mathematical terms. GR-TNCES is a network of R-TNCES which is an extension of the formalism TNCES with a specific function of self-reconfiguration. It is defined as a structure $G = \sum$R-TNCES $= (B, R)$, where R is the control module consisting of a set of reconfiguration functions, $R = r1, \ldots, rn$, and B is the behavior module that is a union of multi TNCESs, represented as follows: $B = (P, T, F, QW, CN, EN, DC, V,\ Z)$ where:

i) P (respectively, T) is a superset of places (respectively, transitions),

ii) $F \subseteq (PxT) \cup (TxP)$ is a superset of flow arcs,

iii) QW = (Q, W),

where $Q : F \rightarrow [0, 1]$ is the probability on the arcs and $W : (PxT) \cup (TxP) \rightarrow \{0, 1\}$ maps a weight to a flow arc. $W(x, y) > 0,\ if\ (x, y) \in F$, and $W(x, y) = 0$ otherwise, where $x, y \in P \cup T$

iv) $CN \subseteq (PxT)$ (respectively, $EN \subseteq (TxT)$) is a superset of condition signals (respectively, event signals),

v) $DC : F \rightarrow [l, h]$ is a superset of time constraints on output arcs. F is a flow arcs with $F \subseteq (PxT)$,

vi)$V : T \rightarrow \{\wedge, V\}$maps an event-processing mode (AND or OR) for every transition,

vii)$Z0 = (M0, D0)$, where $M0 : P \rightarrow 0, 1$ is the initial marking and $D0 : P \rightarrow 0$ is the initial clock position.

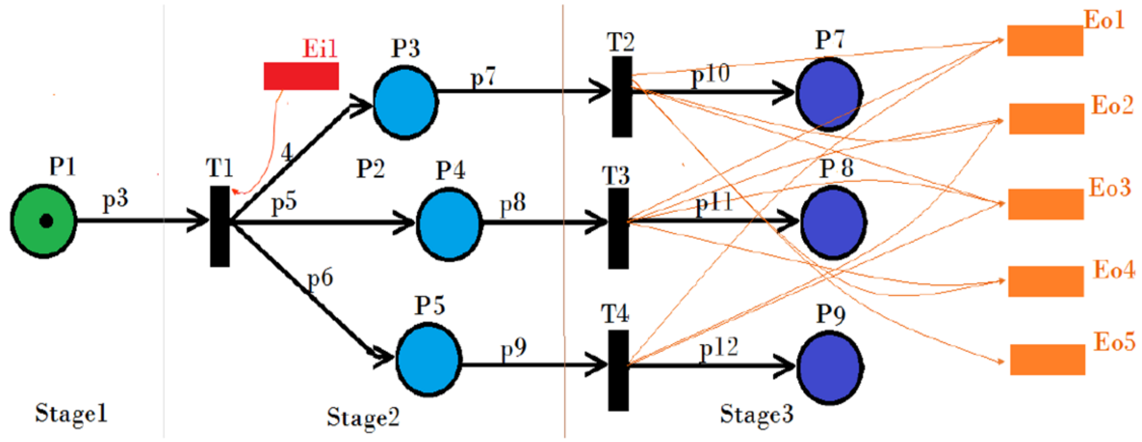


FIGURE 6. Petri net model.

We use an example to explain a GR-TNCES (Fig. 6), composed of seven places and four transitions. Fig. 6 represents the control of the diesel generator energy production that arrives by period Event-In (Ei1) representing the level of fuel in the diesel generators and leaves the system via condition Event-Out (Eo1, Eo2, Eo3, Eo4, Eo5) representing respectively the circuit breakers (B4, B5, B6, B7, B8) to be related. The energy production by diesel generators follows different stages. It starts at the place ('P1: check') to check the fuel level based on predicted data (Eq. 11), then fires T1 and chooses the corresponding stage. Each stage is represented by a token in the correspondent place. i) Stage1 predicates that the fuel level in the diesel generators is at its bounds and superior to 10%. ii) Stage3 represents the operating modes of the loads according to the integration probability of the renewable energy ($p4 = P_{WT.limit1} + P_{PV.limit1}$, $p5 = P_{WT.limit2} + P_{PV.limit2}$ and $p6 = P_{WT.limit3} + P_{PV.limit3}$), P3 for no load shedding, P4 for the first load shedding (only critical loads are active) and P5 for the second load shedding (only critical loads with the highest probability are active), and iii) Stage4 activates the corresponding circuit breakers according to the strategy of the required load.

A. PETRI NETS FRAMWORK

In the previous section, we have formalized the multi- agent energy management and provided a brief presentation of the Petri nets models. In the sequel, we model the real case study developed with Petri nets-based framework, since Petri nets have found many applications for the supervisory control [66], [67] and opacity verification [6], [65] of discrete event systems. In this paper, Petri nets are used for modeling the system behavior under the influence of various events (e.g. meteorological) according to the proposed control strategy, sources availability, and components failure. We choose the ZIZO software tool to model the control strategy and verify the system reachability. Thus, in a finite state machine, we say a system is reachable or co-reachable if and only if a set of markings is transferred from its initial marking to its finite places. The model of the control strategy studied and improved in the previous section using ZIZO is divided into three models that are connected by condition/event signals as shown in Fig. 7. Each model corresponds to a control master. The three models receive stochastic 'events' from each other about the resources predicted availability. These events contribute to deciding the reconfiguration process in order to guarantee the requested platform reliability. In fact, according to the resource availability, an 'event-out' is sent and an 'event-in' is created to activate the related source (sources side management relation 22 to 25). According to the source availability, an 'event-out' is sent and 'event-in' is created mutually to activate the related loads (load side management relation 26 to 28). In the sequel, we develop the three models as follows:

1) SOURCES

The first model "sources" is modeled as shown in Fig. 8. It starts at the idle state ('P1: idle') then fires T1 to choose the corresponding resources/places according to its probability of availability presented by its connecting arc. T2 will be fired only if P2 is marked, the same for T3, T4, and T5 will be fired only if their corresponding places are marked. P2, P3, P4, and P5 indicate the availability of the sun, wind, charge or fuel. At the moment when the token moves from T1 to T2, . . ., T5, an Event-Out is created to send the information to the next model. An Event-in is sent to the next model and is received by its corresponding transition, indicating the sources that shall be in action according to this data information.

2) TESTS

The second model "tests" is modeled as shown in Fig. 9. It starts at the check state ("P1: check"), then fires T1 to choose the corresponding sources to be in action and its corresponding strategy of energy demand/service side management. The different places of the network indicate various components of the system and shall be fired only if the related

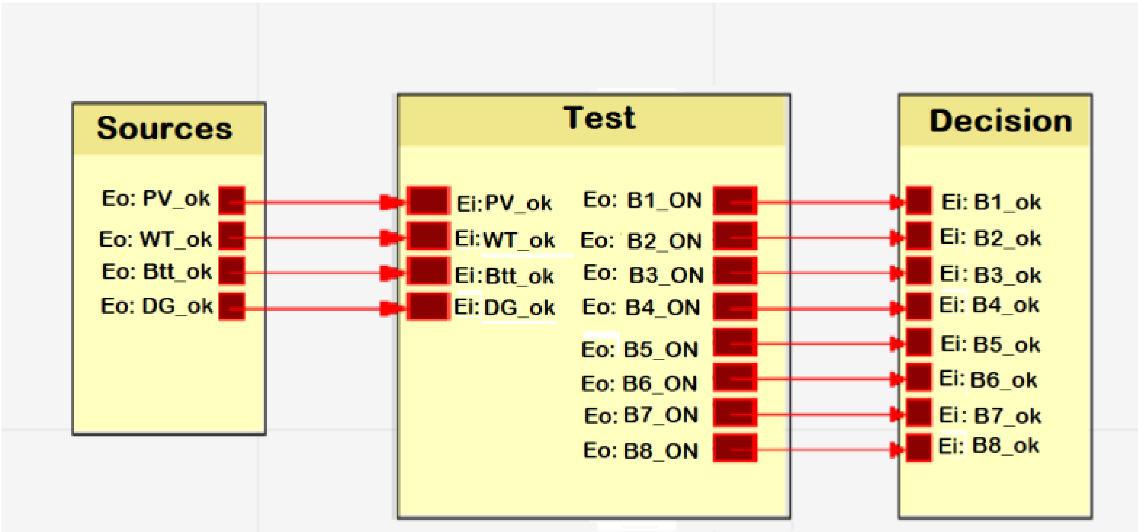


FIGURE 7. The main window of ZIZO shown the connection between the three petri nets models.

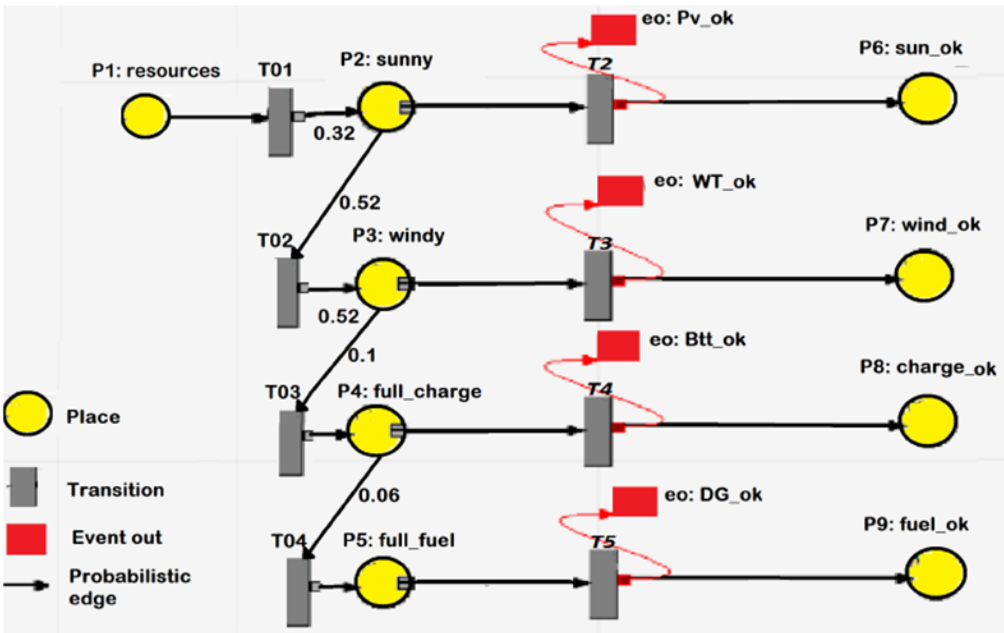


FIGURE 8. The sources modeling with petri net.

transition is fired and all its inputs are valid: Time parameters, Event-In and Condition-In. For example, T6 will be fired only if P2 is marked and P2 will be marked only if we receive a condition event as input indicating the availability of the sunlight. T10 will be fired only if P6 is marked. Knowing that, we are working with the diesel generator, and the possibility of integration of renewable resources is in their limit2, which is *Conditioned* by the arc related to it. All the places in this model so far end with a condition Event-out that will indicate the possibility of integration of each component (Event-out) to the networked devices according to the given conditions and arcs.

3) DECISIONS

The third model ''decisions'' is modeled as shown in Fig. 10. Similarly, it starts at the idle state (''P1: idle''), then fires T1 to choose the place (''P2: choose''). Place P2 has the task of choosing between the different deployed sources and the strategy of load shedding. Each component of the system is modeled by a place, transition, a conditional arc and an integrated Event-in as data information (coming from the previous model). The places on downstream shall be fired under the condition that the related transition is fired and all its inputs are valid: Time parameters, Event-In and Condition-In. If one place is fired, then it means that the corresponding

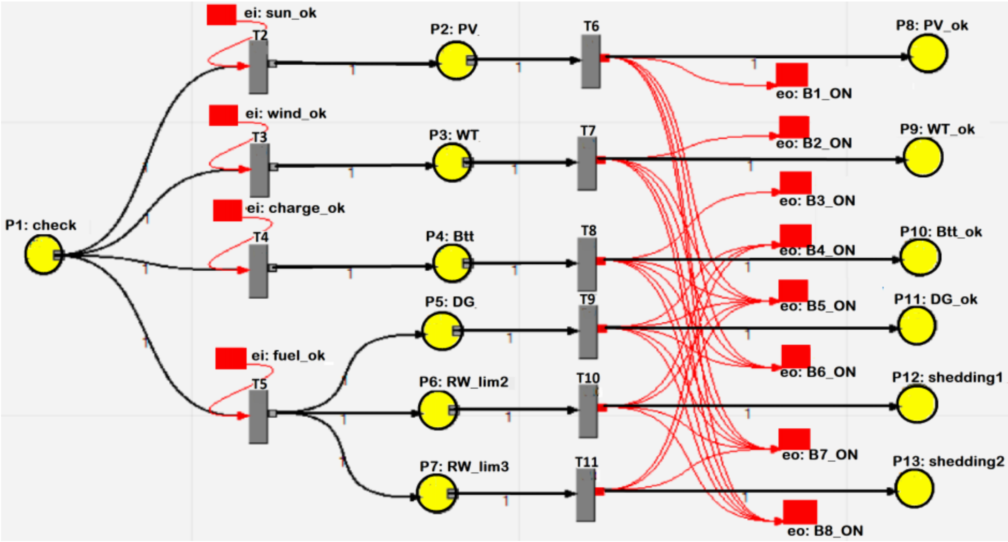


FIGURE 9. The tests of source modeling with petri net.

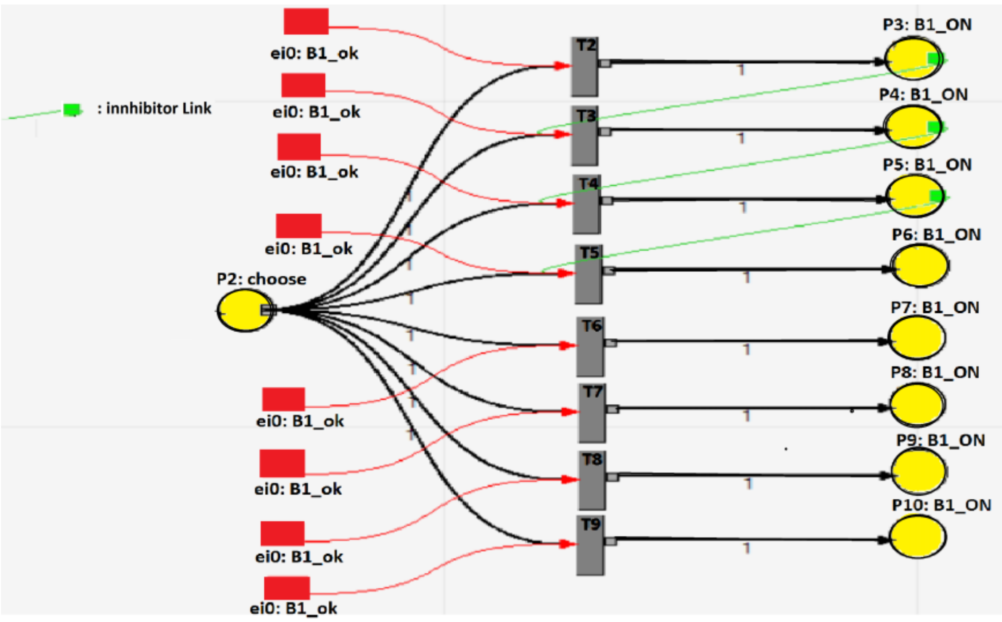


FIGURE 10. The connection decisions modeling with petri net.

component shall be connected to the system. The connection of the corresponding component is indicated by the number of the circuit breaker related to it. The concerned circuit breaker should be closed as in action activated by its Event-out.

B. APPLICATIONS TO MICROGRIDS: FORMAL VERIFICATION FOR THE RELIABILITY OF THE PETROLEUM PLATFORM

In the next stage, we verify the model properties and check the correctness of the three models by PRISM. It can be checked manually by creating a new property formula named [E [F "deadlock "]]. [E [F "deadlock "]] is a CTL [22], [23] formula applied to check if there is any deadlock in the models. The simulation of the code by PRISM shows that the models are deadlock free as indicated by the Red Cross in Fig. 11. This formula is proved to be not false because we do not have a blocking situation during this running and we verify that the model meets our requirements as a result. In the sequel, we evaluate the proposed control strategy based on real data using MATLAB Simulink.

VI. EXPERIMENTAL EVALUATIONS: CASE OF THE TUNISIAN PETROLEUM PLATFORM

In this paper, we evaluate the performance of energy production and consumption at several intervals of time through three control strategies according to climatic history

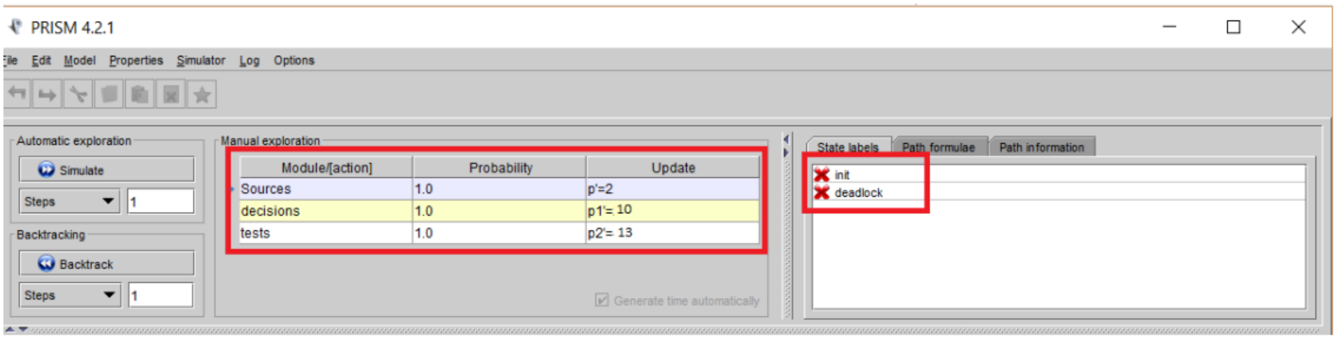


FIGURE 11. Verification of the code functionality.

(insolation, wind speed). The first manages the energy consumption without load shedding. The second applies the policy of energy management with load shedding only. The third considers both the energy production prediction and the load shedding which is the contribution of this paper. We note that this experimental evaluation has to be in the same period of time of the blackout that causes the stops of the platform to prove the performance of the developed theory of energy management. CIPEM Company[3] provides us the necessary information concerning dates and durations of the breakdowns.

In this experimental evaluation, we compare the different strategies of control and their effects on the energy consumption by the different categories of the existing loads (shown in the case study). We use three power supply availability rates (Av(%)) for non-critical loads (NCL), for critical loads with low priority (CLLP), and for critical loads with high priority (CLHP). The instantaneous availability (A) may have only two values: 1 in the case of availability and 0 in the case of unavailability. The average availability Av(t) is the mean value of the instantaneous availability between time = 0 and time = t.

$$A_v(t) = 1/t \int_0^t A(t)dt \tag{29}$$

The energy production by the sources is evaluated according their availability (Eqs. (1) to Eq. (15)).

As shown in Fig. 12, an evaluation is based on a comparison between three strategies of control:

i) The first strategy (Fig. 12-(1)) shows the energy consumption without load shedding. In this case, all the loads are power supplied if one of the deployed sources (renewable energy or backup sources) is available. In the case of absence of all the renewable energy for a long time, the loads can be unpowered if the backup storage autonomy time is less than the absence time of the renewable one, ii) The second strategy (Fig. 12-(2)) is based on load shedding of non-critical loads when the diesel generators are the only available sources. This strategy is used to increase only the time of power supply for the critical loads. iii) The third strategy (Fig. 12-(3)) is the

[3]www.cipem.com.tn

TABLE 1. Experimental results of three control strategies during the month of June.

Control strategy	Load type	Availability rate %
Strategy 1	NCL	75
	CLLP	75
	CLHP	75
Strategy 2	NCL	75
	CLLP	85
	CLHP	85
Strategy 3	NCL	75
	CLLP	85
	CLHP	99.68

load shedding and forecasting strategy that presents the contribution of this paper. Within this strategy, we aim to control the energy consumption according to the predicted resources availability. If only the diesel generators are available and the probability of integration of the renewable energy is less than its limits, then several load shedding methods will be considered as described in the previous subsection.

With the load shedding only, we are able to reduce the time of blackout to 4 pu (from t = 26pu to t = 30pu). The availability of critical loads rises from 75% to 85%. This reduction is not enough to ensure the continuity of the platform power production. The use of the load shedding and prediction strategy of control provides a better reduction of this time blackout to 0.1 pu. This strategy boosts the autonomy of the diesel generator. The load prediction and shedding strategy have allowed the system to survive without renewable energy or refueling for a considerable period of time (from t = 13 to t = 29.90). The availability of energy for critical loads rises from 75% (without load shedding Fig. 12-(1)) to 99.68% (with load shedding and prediction Fig. 12-(3)). For summary, see table 1.

As shown in Fig. 13 the load prediction and shedding strategy have allowed the system to survive without renewable energy or refueling for a considerable period of time (from t = 12 to t = 29.85 in January (Fig. 13-(1)) and from t = 13 to t = 29.94 in August (Fig. 13-(3))). The availability of energy for critical loads is increased to 99.64% in January and to 99.71% in August.

The availability of energy using the proposed strategy for the period between January and October 2018 is given

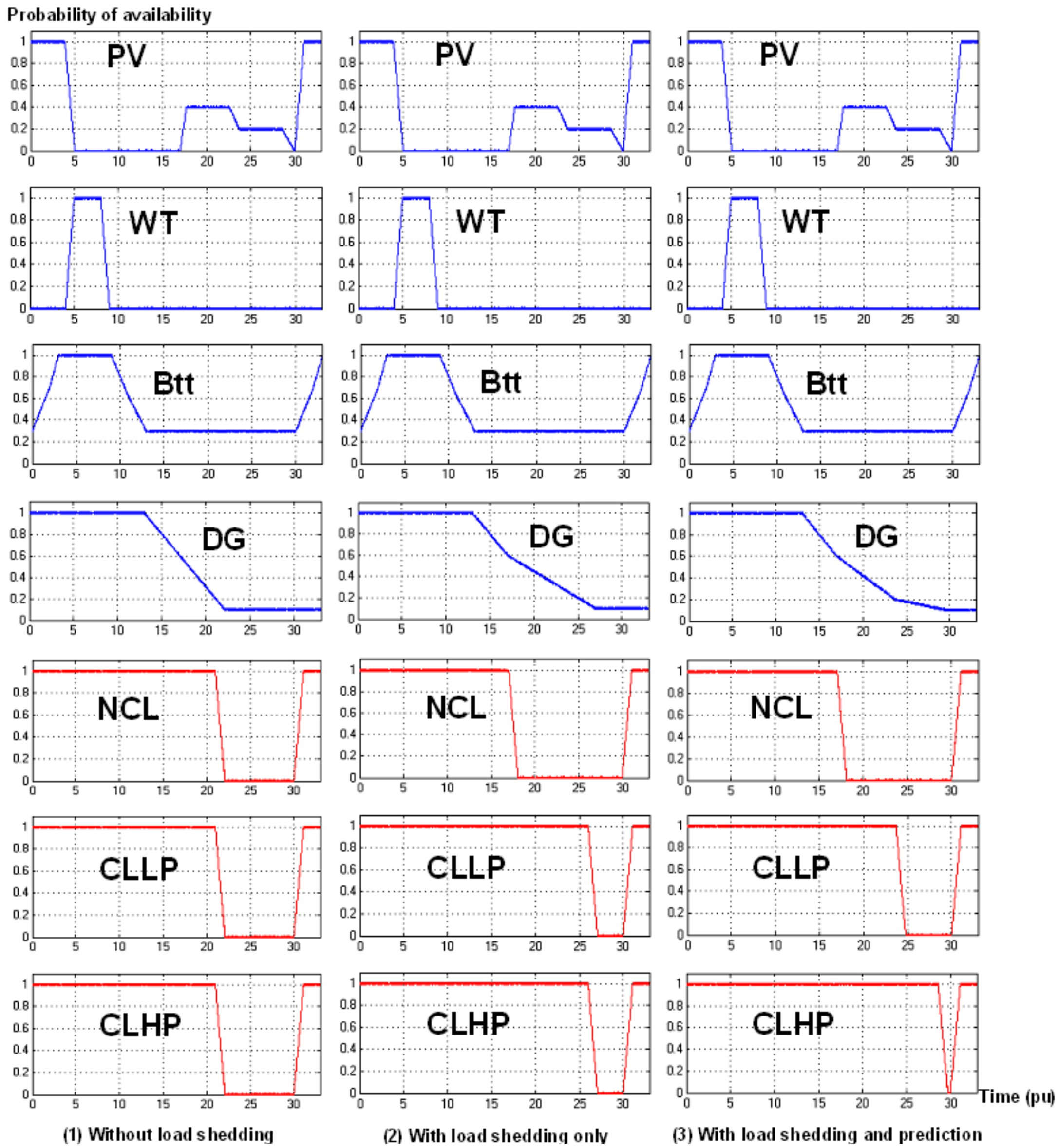


FIGURE 12. Experimental results of the control strategy. (1) Without load shedding. (2) With load shedding only. (3) With load shedding and prediction.

TABLE 2. Experimental results using proposed strategy for the period between January and October 2018.

Months	Jan	Fab	Mar	Apr	May
Availability rate %	99.64	99.69	99.70	99.65	99.71
Months	Jun	Jul	Aug	Sep	Oct
Availability rate %	99.68	99.65	99.71	99.65	99.70

by Table 2. For this period the availability varies between 99.64% and 99.71%. As shown in Fig. 14 the mean value of availability is 99.68%.

A. EVALUATIONS AND DISCUSSIONS

The proposed control strategy increases the availability A of the critical loads, especially those with high priorities. When the renewable energy is not available and batteries are exhausted, the energy consumption has to be smarter to avoid the emergence of dangerous situations. In the experimental results for June, we start with availability of the microgrid equal to 75% then corrected to 99.68%. The improvement of availability varies from one month to another. The extreme values reached during the first ten months of 2018 are 99.64% for January and 99.71% for August. The mean value of availability is 99.68%. Although this control strategy deactivates some loads, it allows the platform to make some imperative decisions in case of a predicted long absence of renewable sources. It reduces on the other hand the stress on backup sources and protects the platform from dangerous situations.

According to these experimental results, we conclude that: i) It is necessary to increase the utilization of renewable

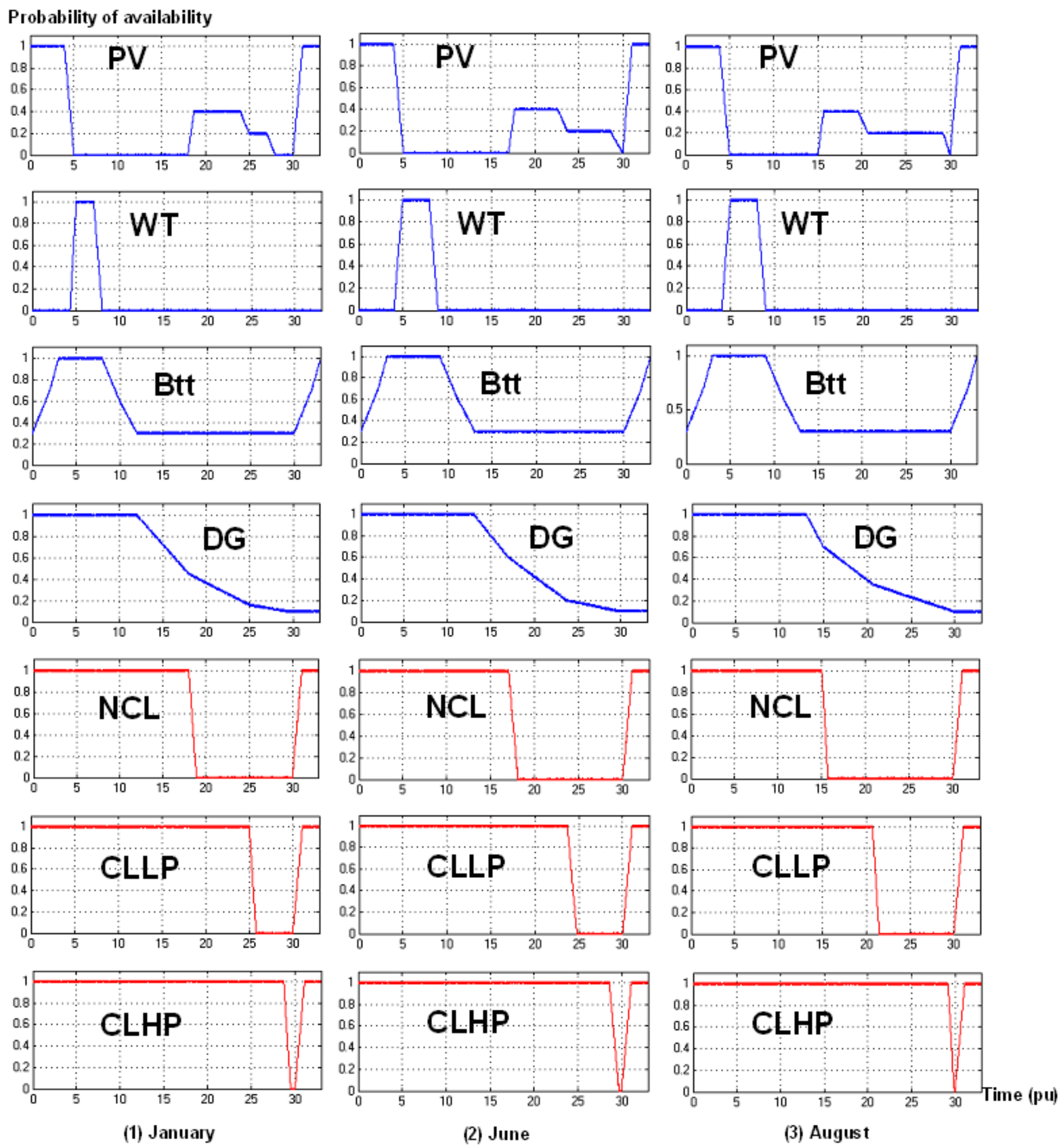


FIGURE 13. Experimental results using proposed strategy for January, June and August 2018.

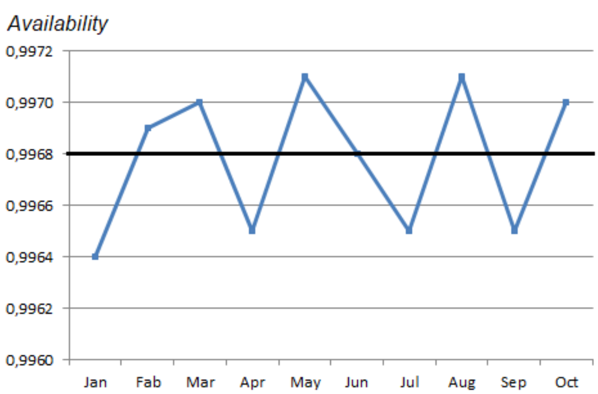


FIGURE 14. Experimental availability between January and October 2018.

energy for global environmental advantages and offer more reliability, ii) Energy production prediction for load shedding methods shall be based on real-time information and it provides an increased availability of energy for critical loads that can reach 100%, iii) The multi-agent strategy of control allows the different deployed components to communicate and switch information between them, which facilitates interaction of the system and the management of energy, and iv) The component sizing and resizing may, in certain circumstance, increase the availability of energy but they are always an exhausting method, costly and unavailable in some areas.

VII. CONCLUSION

In this paper, we present feasible solutions to solve a real problem in a Tunisian offshore petroleum platform "Maamoura" in the Gulf of Hammamet (50km far from Tunis in Tunisia) supplied by its own renewable and backup sources. Taking into consideration that the deployed back up storage cannot handle the energy management for a long period of time, we intend to manage the energy consumption in a more intelligent and effective way.

We implement a new multiagent architecture based on mathematical formulae and modeled using Markov Chain as well as stochastic Petri nets for formal verification. The main idea of this multi-agent solution is to predict the availability of resources to know their duration of absence and to optimize the consumption level when using backup sources. This perspective is based on the load shedding strategy as a primary condition to maximize energy supply. The experimental results reveal that the platform could avoid losses estimated at least up to 200,000 US dollars per year. The microgrid availability is raised to a mean value of 99.68%.

Energy efficiency can be further improved by applying machine learning algorithms and using a learning agent. In a future work, we are going to improve the proposed multiagent structure using an algorithm that calculates a system performance and autonomy to reach an availability of 99.9999% for all loads. Future work will consider discrete event system models with faults or other safety properties [88]–[92].

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests for this paper.

REFERENCES

[1] J. Ye, Z. Li, and A. Giua, "Decentralized supervision of petri nets with a coordinator," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 45, no. 6, pp. 955–966, Jun. 2015.

[2] W. K. Hastings, "Monte Carlo sampling methods using Markov chains and their applications," *Biometrika*, vol. 57, no. 1, pp. 97–109, Apr. 1970.

[3] K. Jensen, "Coloured petri nets and the invariant-method," *Theor. Comput. Sci.*, vol. 14, no. 3, pp. 317–336, 1981.

[4] H. Hansson and B. Jonsson, "A logic for reasoning about time and reliability," *Formal Aspects Comput.*, vol. 6, no. 5, pp. 512–535, Sep. 2004.

[5] K. Ballman, "Coloured petri nets: Basic concepts, analysis methods and practical use," *Amer. Math.*, vol. 105, no. 5, p. 493, 1998.

[6] R. German, C. Kelling, A. Zimmermann, and G. Hommel, "TimeNET-a toolkit for evaluating non-Markovian stochastic Petri nets," *Trans. Per. Eval.*, vol. 24, no. 1, pp. 69–87, Aug. 1995.

[7] S. P. Meyn and R. L. Tweedie, *Markov Chains and Stochastic Stability*. Berlin, Germany: Springer, 2002.

[8] K. Czajkowski, S. Fitzgerald, I. Foster, and C. Kesselman, "Grid information services for distributed resource sharing," in *Proc 10th IEEE Int., Sym., High Per., Dis., Comp.*, Aug. 2001, pp. 181–194.

[9] X. Wang, I. Khemaissia, M. Khalgui, Z. Li, O. Mosbahi, and M. Zhou, "Dynamic low-power reconfiguration of real-time systems with periodic and probabilistic tasks," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 1, pp. 258–271, Jan. 2015.

[10] F. Dabek, R. Cox, F. Kaashoek, and R. Morris, "Vivaldi: A decentralized network coordinate system," *ACM SIGCOMM Comp. Commun. Rev.*, vol. 34, no. 4, pp. 15–26, Aug. 2004.

[11] C. Größer, M. Leucker, B. Bollig , and F. Ciesinski, "Controller synthesis for probabilistic systems," *Exploring New Frontiers of Theoretical Informatics*, New York, NY, USA: Springer, 2004, pp. 493–506.

[12] J. Xiang, K. Ogata, and K. Futatsugi, "Formal fault tree analysis of state transition systems," in *Proc. 5th IEEE Quality Softw.*, Sep. 2005, pp. 124–131.

[13] T. Markvart, "Microgrids: Power systems for the 21st century," *Refocus*, vol. 7, no. 4, pp. 44–48, Jul./Aug. 2006.

[14] L. Yu, "Fault tree analysis and reliability assessment of auxiliary power supply system for an HVDC plant," M.S. thesis, School Elect. Eng., KTH Roy. Inst. Technol., Stockholm, Sweden, 2007.

[15] N. Q. Wu, M. C. Zhou, and Z. W. Li, "Short-term scheduling of crude-oil operations: Enhancement of crude-oil operations scheduling using a Petri net-based control-theoretic approach," *IEEE Robot., Autom., Mag.*, vol. 22, no. 2, pp. 64–76, Jun. 2015.

[16] H. Kress-Gazit, G. E. Fainekos, and G. J. Pappas, "Where's Waldo? sensor-based temporal logic motion planning," in *Proc IEEE Int., Conf., Robot., Autom.*, Apr. 2007, pp. 3116–3121.

[17] S. Wagner, G. Guaglio, I. Eusgeld, and W. Kroger, "Balancing safety and availability for an electronic protection system," in *Proc Eur., Saf. Relia., Conf.*, Sep. 2008, pp. 35–63.

[18] M. Kloetzer and C. Belta, "A fully automated framework for control of linear systems from temporal logic specifications," *IEEE Trans. Autom. Control*, vol. 53, no. 1, pp. 287–297, Feb. 2008.

[19] C. Baier, J. P. Katoen, and K. G. Larsen, *Principles of Model Checking*. Cambridge, MA, USA: MIT Press, 2008, p. 965.

[20] N. Wu, M. Zhou, L. Bai, and Z. Li, "Short-term scheduling of crude oil operations in refinery with high-fusion-point oil and two transportation pipelines," *Enterprise Inf. Syst.*, vol. 10, no. 6, pp. 581–610, 2016.

[21] Z. Li and M. Zhou, "Elementary siphons of Petri nets and their application to deadlock prevention in flexible manufacturing systems," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 34, no. 1, pp. 38–51, Jan. 2004.

[22] S. Karaman and E. Frazzoli, "Sampling-based motion planning with deterministic μ-calculus specifications," in *Proc IEEE Conf. Decision Control*, Shanghai, China, Dec. 2009, pp. 2222–2229.

[23] T. Wongpiromsarn, U. Topcu, and R. M. Murray, "Receding horizon temporal logic planning for dynamical systems," in *Proc IEEE Conf. Decision Control*, Shanghai, China, Dec. 2009, pp. 5997–6004.

[24] T. Chen, T. Han, J. P. Katoen, and A. Mereacre, "Quantitative model checking of continuous-time Markov chains against timed automata specifications," in *Proc 24th Annu. IEEE Sympo. Logic Comp. Sci.*, Aug. 2009, pp. 309–318.

[25] Z. Li and M. Zhao, "On controllability of dependent siphons for deadlock prevention in generalized Petri nets," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 38, no. 2, pp. 369–384, Mar. 2008.

[26] Y. Tong, Z. W. Li, and A. Giua, "On the equivalence of observation structures for petri net generators," *IEEE Trans. Autom. Control*, vol. 61, no. 9, pp. 2448–2462, Sep. 2016.

[27] M. Lahijanian, J. Wasniewski, S. B. Andersson, and C. Belta, "Motion planning and control from temporal logic specifications with probabilistic satisfaction guarantees," in *Proc IEEE Inter. Conf. Robot. Autom.*, Sep. 2011, pp. 3227–3232.

[28] B. Ninness and S. Henriksen, "Bayesian system identification via Markov chain monte carlo techniques," *Automatica*, vol. 46, no. 1, pp. 40–51, Jan. 2016.

[29] M. N. Q. Wu and M. C. Zhou, "Intelligent token Petri nets for modelling and control of reconfigurable automated manufacturing systems with dynamical changes," *Trans. Inst. Measur. Control*, vol. 33, no. 1, pp. 9–29, May 2011.

[30] J. Rifkin, "The third industrial revolution: How lateral power is transforming energy, the Economy, and the world," *Survival*, vol. 55, no. 2, pp. 173–178, 2013.

[31] S. Sarkar and V. Ajjarapu, "MW resource assessment model for a hybrid energy conversion system with wind and solar resources," *IEEE Trans. Sust. Energy*, vol. 2, no. 4, pp. 383–391, Oct. 2011.

[32] X. Wang, Z. Li, and W. Wonham, "Dynamic multiple-period reconfiguration of real-time scheduling based on timed DES supervisory control," *IEEE Trans. Ind. Informat.*, vol. 12, no. 1, pp. 101–111, Feb. 2016.

[33] S. Paoletti, M. Casini, A. Giannitrapani, A. Facchini, A. Garulli, and A. Vicino, "Load forecasting for active distribution networks. In Innovative Smart Grid Technologies," in *Proc 2nd IEEE PES Int. Conf. Exh. (ISGT)*, Sep. 2011, pp. 1–6.

[34] V. Pantelic and M. Lawford, "Optimal supervisory control of probabilistic discrete event systems," in *IEEE Trans. Autom. Control*, vol. 57, no. 5, pp. 1110–1124, May 2012.

[35] Y. Hong and R. C. Lian, "Optimal sizing of hybrid wind/PV/diesel generation in a stand-alone power system using Markov-based genetic algorithm," *IEEE Trans. Power Del.*, vol. 27, no. 2, pp. 640–647, Apr. 2012.

[36] H. Tazvinga, X. Xia, and J. Zhang, "Minimum cost solution of photovoltaic-diesel-battery hybrid power systems for remote consumers," *Solar Energy*, vol. 96, no. 1, pp. 292–299, 2013.

[37] A. V. Anayochukwu, "Optimal control of PV/wind/hydro-diesel hybrid power generation system for off-grid macro base transmitter station site," *Electron. J. Energy Environ.*, vol. 1, no. 2, pp. 37–55, 2013.

[38] L. Bai, N. Wu, Z. Li, and M. Zhou, "Optimal one-wafer cyclic scheduling and buffer space configuration for single-arm multicluster tools with linear topology," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 10, pp. 1456–1467, Oct. 2016.

[39] N. Hatziargyriou, *Microgrids Architectures Control*. Hoboken, NJ, USA: Wiley, 2014, 341 p.

[40] Y. Chen, Z. Li, and M. Zhou, "Optimal supervisory control of flexible manufacturing systems by Petri nets: A set classification approach," *IEEE Trans. Autom. Sci. Eng.*, vol. 11, no. 2, pp. 549–563, Apr. 2014.

[41] J. Zhang, M. Khalgui, Z. Li, G. Frey, O. Mosbahi, and H. Ben Salah, "Reconfigurable coordination of distributed discrete event control systems," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 1, pp. 323–330, Jan. 2015.

[42] PRISM 4.3 (2015). *PRISM Model checker*. [Online]. Available: http://www.prismmodelchecker.org/

[43] C. Giotitsas, A. Pazaitis, and V. Kostakis, "A peer-to-peer approach to energy production," *Techno. Soc.*, vol. 42, pp. 28–38, Sep. 2015.

[44] E. Kuznetsova, C. Ruiz, Y. F. Li, and E. Zio, "Analysis of robust optimization for decentralized microgrid energy management under uncertainty," *Int. J. Elec. Power Energy Sys.*, vol. 64, pp. 815–832, Jul. 2015.

[45] M. O. Ben Salem, O. Mosbahi, M. Khalgui, Z. Jlalia, G. Frey, and M. Ben Smida, "ZiZo: Modeling, simulation and verification of reconfigurable real-time control tasks sharing adaptive resources- application to the medical project BROS," in *Proc 8th Int. Conf. Health Inf.*, Jun. 2015, pp. 20–31.

[46] R. E. Barlow, L. C. Hunter, and F. Proschan, "Optimum redundancy when components are subject to two kinds of failure," *J. Soc. Indus. App. Math.*, vol. 11, no. 1, pp. 64–73, Mar. 1963.

[47] K. R. Voorspools and W. D. Dhaeseleer, "The evaluation of small cogeneration for residential heating," *Int. J. Energy Res.*, vol. 26, no. 13, pp. 1175–1190, Jul. 2009.

[48] T. Han and J. P. Katoen, "Counterexamples in probabilistic model checking," in *Proc Int. Conf. Tools Algo. Const. Anal. Sys.*, , 2010, pp. 72–86.

[49] Y. Chen, Z. Li, K. Barkaoui, and A. Giua, "On the enforcement of a class of nonlinear constraints on Petri nets," *Automatica*, vol. 55, pp. 116–124, May 2015.

[50] R. Su, J. H. Schuppen, and J. E. Rooda, "Model abstraction of nondeterministic finite-state automata in supervisor synthesis," *IEEE Trans. Autom. Control*, vol. 55, no. 1, pp. 2527–2541, Sep. 2010.

[51] J. Widen, "Correlations between large-scale solar and wind power in a future scenario for Sweden," *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 177–184, Apr. 2011.

[52] X. Zhuan and X. Xia, "Development of efficient model predictive control strategy for cost-optimal operation of a water pumping station," *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 4, pp. 1449–1454, Jul. 2013.

[53] M. A. Schilling and M. Esmundo, "Technology S-curves in renewable energy alternatives: Analysis and implications for industry and government," *Energy Policy*, vol. 37, no. 5, pp. 1767–1781, Nov. 2009.

[54] Y. F. Chen, Z. W. Li, and K. Barkaoui, "New Petri net structure and its application to optimal supervisory control: Interval inhibitor arcs," *IEEE Trans. Syst., Man, Cybern., Syst*, vol. 44, no. 10, pp. 1384–1400, Oct. 2014.

[55] A. Tariq and N. Ketjoy, "PV penetration limits in low voltage networks and voltage variations," *IEEE Access*, vol. 5, pp. 16784–16792, 2017.

[56] S. Conti, G. Faraci, R. Nicolosi, S. A. Rizzo, and G. Schembra, "Battery management in a green fog-computing node: A reinforcement-learning approach," *IEEE Access*, vol. 5, pp. 21126–21138, 2017.

[57] J. Zhu *et al.*, "Learning automata-based methodology for optimal allocation of renewable distributed generation considering network reconfiguration," *IEEE Access*, vol. 5, pp. 14275–14288, 2017.

[58] J. Feng, B. Zeng, D. Zhao, G. Wu, Z. Liu, and J. Zhang, "Evaluating demand response impacts on capacity credit of renewable distributed generation in smart distribution systems," *IEEE Access*, vol. 6, pp. 14307–14317, 2018.

[59] P. Penkey, N. Gaul, B. K. Johnson, and H. L. Hess, "Sizing and location identification for an electrical energy storage system in a renewable microgrid," in *Proc. IEEE Conf. Technol. Sustainability*, vol. 2016, pp. 83–88.

[60] T. Logenthiran, D. Srinivasan, and T. Z. Shun, "Demand side management in smart grid using heuristic optimization," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1244–1252, Sep. 2012.

[61] G. Ebner, D. Döring, F. Schettler, K. Wüerflinger, and M. Zeller, "Fault handling at hybrid high-voltage AC/DC transmission lines with VSC converters," *IEEE Trans. Power Del.*, vol. 33, no. 2, pp. 901–908, Apr. 2018. doi: 10.1109/TPWRD.2017.2748163, 2017.

[62] K. Yedidi, S. Tatapudi, J. Mallineni, B. Knisely, J. Kutiche, and G. TamizhMani, "Failure and degradation modes and rates of PV modules in a hot-dry climate: Results after 16 years of field exposure," in *Proc. PVSC*, Jun. 2014, pp. 3245–3247.

[63] F. Huerta, R. L. Tello, and M. Prodanovic, "Real-time power hardware in the loop implementation of variable-speed wind turbines," *IEEE Trans. Indus. Elec.*, vol. 64, no. 3, pp. 1893–1904, Mar. 2017.

[64] U. Shipurkar, H. Polinder, and J. A. Ferreira, "Modularity in wind türbine generator systems-Opportunities and challenges," in *Proc. 18th Eur. IEEE Conf. Power Elec. App.*, Sep. 2016, pp. 1–10.

[65] Y. Tong, Z. Li, C. Seatzu, and A. Giua, "Verification of state-based opacity using Petri nets," *IEEE Trans. Autom. Control*, vol. 62, no. 6, pp. 2823–2837, Jun. 2017.

[66] Z. Ma, Z. Li, and A. Giua, "Characterization of admissible marking sets in Petri nets with conflicts and synchronizations," *IEEE Trans. Autom. Control*, vol. 62, no. 3, pp. 1329–1341, Mar. 2017.

[67] Z. Ma, Y. Tong, Z. Li, and A. Giua, "Basis marking representation of Petri net reachability spaces and its application to the reachability problem," *IEEE Trans. Autom. Control*, vol. 62, no. 3, pp. 1078–1093, Mar. 2017.

[68] S. Shakti, S. Mukesh, and K. S. Chandra, "Optimal power scheduling of renewable energy systems in microgrids using distributed energy storage system," *IET Trans. Renew. Power Gener.*, vol. 10, no. 9, pp. 1328–1339, Oct. 2016.

[69] P. K. Shetty, L. Lewlyn, and R. Rodrigues, "Total productive maintenance of a diesel power generating unit of a institution campus," in *Proc. Int. Conf. Mech. Elect. Technol.*, Sep. 2010, pp. 68–71.

[70] M. R. Amini, M. Mahdavi, and M. J. Omidi, "Discrete-time Markov chain analysis of energy efficiency in a CR network regarding primary and secondary traffic with primary user returns," *IEEE Access*, vol. 6, pp. 22305–22323, 2018.

[71] R. Chan *et al.*, "Adaptive duty cycling in sensor networks via Continuous Time Markov Chain modeling," in *Proc. IEEE Inter. Conf. Commun.(ICC)*, Jun. 2015, pp. 6669–6674.

[72] M. Gao, K. Wang, and L. He, "Probabilistic model checking for green energy router system in energy Internet," in *Proc. GLOBECOM*, Jun. 2017, pp. 1–6.

[73] O. Karoui, Z. Li, N. Wu, M. Khalgui, E. A. Nasr, and A. M. E. Tamimi, "One-step control-ahead approach for the design of an optimal petri-net based deadlock prevention policy," *IEEE Access*, vol. 06, pp. 34307–34323, 2018.

[74] I. Khemaissia, O. Mosbahi, M. Khalgui, Z. Li, and T. Qu, "Coherence and feasibility of real-time software tasks in networked adaptive system," *IEEE Access*, vol. 6, pp. 35824–35843, 2018. doi: 10.1109/ACCESS.2018.2845942.2018.

[75] H. Chniter, Y. Li, M. Khalgui, A. Koubaa, Z. Li, and F. Jarray, "Multi-agent adaptive architecture for flexible distributed real-time systems," *IEEE Access*, vol. 6, pp. 23152–23171, 2018.

[76] O. Gasmi, O. Mosbahi, M. Khalgui, L. Gomes, and Z. Li, "Performance optimization of reconfigurable real-time wireless sensor networks," *IEEE Trans. Syst., Man, Cybern. Syst.*, to be published.

[77] S. Ben Meskina, N. Doggaz, M. Khalgui, and Z. Li, "Reconfiguration-based methodology for improving recovery performance of faults in smart grids," *Inf. Sci.*, vols. 454–455, pp. 73–95, Jul. 2018.

[78] O. Khlifi, O. Mosbahi, M. Khalgui, G. Frey, and Z. Li, "Modeling, simulation and verification of probabilistic reconfigurable discrete-event systems under energy and memory constraints," *Iranian J. Sci. Technol., Trans. Electr. Eng.*, vol. 23, no. 1, pp. 323–330, Jul. 2018.

[79] A. B. Ahmed, O. Mosbahi, M. Khalgui, and Z. Li, "Toward a new methodology for an efficient test of reconfigurable hardware systems," *IEEE Trans. Autom. Sci. Eng.*, vol. 15, no. 4, pp. 1864–1882, Oct. 2018.

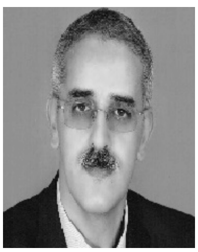
[80] I. Ghribi, R. B. Abdallah, M. Khalgui, Z. Li, K. Alnowibet, and M. Platzner, "R-codesign: Codesign methodology for real-time reconfigurable embedded systems under energy constraints," *IEEE Access*, vol. 6, pp. 14078–14092, 2018.

[81] H. Kanchev, D. Lu, F. Colas, V. Lazarov, and B. Francois, "Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4583–4592, Oct. 2011.

[82] D. Rwegasira *et al.*, "A framework for load shedding and demand response in DC microgrid using multi agent system," in *Proc. 21st Conf. Open Innov. Assoc. (FRUCT)*, Nov. 2017, pp. 284–289.

[83] H. Grichi, O. Mosbahi, M. Khalgui, and Z. Li, "RWiN: New methodology for the development of reconfigurable WSN," *IEEE Trans. Autom. Sci. Eng.*, vol. 14, no. 1, pp. 109–125, Jan. 2017.

[84] S. B. Meskina, N. Doggaz, M. Khalgui, and Z. Li, "Multi-agent framework for smart grids recovery," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 7, pp. 1284–1300, Jul. 2017.
[85] H. Grichi, O. Mosbahi, M. Khalgui, and Z. W. Li, "New power-oriented methodology for dynamic resizing and mobility of reconfigurable wireless sensor networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 7, pp. 1120–1130, 2018.
[86] M. Gasmi, O. Mosbahi, M. Khalgui, L. Gomes, and Z. W. Li, "R-node: New pipelined approach for an effective reconfigurable wireless sensor node," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 6, pp. 892–905, Jun. 2018.
[87] C. Gu, Z. W. Li, N. Q. Wu, M. Khalgui, T. Qu, and A. Al-Ahmarimm, "Improved multi-step lookahead control policies for automated manufacturing systems," *IEEE Access*, vol. 6, pp. 68824–68838, 2018.
[88] C. Gu, X. Wang, and Z. W. Li, "Synthesis of supervisory control with partial observation on normal state tree structures," *IEEE Trans. Autom. Sci. Eng.*, 2018. doi: 10.1109/TASE.2018.2880178.
[89] G. H. Zhu, Z. W. Li, N. Q. Wu, and A. M. Al-Ahmari, "Fault identification of discrete event systems modeled by Petri nets with unobservable transitions," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 2, pp. 333–345, Feb. 2019.
[90] G. H. Zhu, Z. W. Li, and N. Q. Wu, "Model-based fault identification of discrete event systems using partially observed Petri nets," *Automatica*, vol. 96, pp. 201–212, Oct. 2018.
[91] X. Y. Cong, M. P. Fanti, A. M. Mangini, and Z. W. Li, "Decentralized diagnosis by Petri nets and integer linear programming," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 10, pp. 1689–1700, Oct. 2018.
[92] X. Y. Cong, M. P. Fanti, A. M. Mangini, and Z. W. Li, "On-line verification of current-state opacity by Petri nets and integer linear programming," *Automatica*, vol. 94, pp. 205–213, 2018.



MONCEF BEN SMIDA received the Ph.D. Diploma degree from University Tunis-El Manar, Tunisia. He is currently an Assistant Professor with the National Institute of Applied Science and Technology (INSAT), University of Carthage, Tunisia. He is also a member of the LSA Lab, Polytechnic School, University of Carthage, Tunisia. He is involved in several research and development projects for the development of new reconfigurable microgrids under several functional, real-time, and power constraints. His research interests include smart and microgrids.

KHAOULA MILED received the engineering diploma degree in industrial informatics and automation from the National Institute of Applied Science and Technology (INSAT). Her Ph.D. thesis was with functional safety of microgrids with the LISI Laboratory, INSAT, University of Carthage. She is currently pursuing the Ph.D. degree with the National Institute of Applied Science and Technology (INSAT), University of Carthage, Tunisia.

MOHAMED KHALGUI received the B.S. degree in computer science from Tunis El Manar University, Tunis, Tunisia, in 2001, the M.S. degree in telecommunication and services from Henri Poincaré University, Nancy, France, in 2003, the Ph.D. degree in computer science from National Polytechnic Institute of Lorraine, Nancy, in 2007, and the Habilitation Diploma degree in information technology (computer science) from Martin Luther University of Halle-Wittenberg, Halle, Germany, in 2012.

He was a researcher in computer science with the Institut National de Recherche en Informatique et Automatique INRIA, Rocquencourt, France, with ITIA-CNR institute, Vigevano, Italy, and with Systems Control Laboratory, Xidian University, Xi'an, China. He was a collaborator with KACST Institute, Riyadh, Saudi Arabia, with the SEG Research Group, Patras University, Patras, Greece, the Director of the RECS Project with O3NEIDA, Ottawa, ON, Canada. He was also the manager of the RES Project with Synesis Consortium, Lomazzo, Italy, of the Cyna-RCS Project with Cynapsys Consortium, Paris, France, and of the BROS and RWiN Projects with ARDIA Corporation, Tunis, Tunisia. He was a Professor at National Institute of Applied Sciences and Technology, University of Carthage, Tunisia, and he is currently a Professor with Jinan University, Zhuhai, China. He has been involved in various international projects and collaborations. He received the Humboldt grant in Germany for preparing the Habilitation diploma at Martin Luther University of Halle-Wittenberg.

Dr. Khalgui is a member of different conferences and boards of journals.

GEORG FREY received the Diplom-Ingenieur (M.Sci.) degree in electrical engineering/control engineering from the Karlsruhe Institute of Technology, Karlsruhe, Germany, in 1996, and the Doktor-Ingenieur (Ph.D.) degree in electrical engineering/automation from the University of Kaiserslautern, Germany, in 2002. He was an Associate Professor with the University of Kaiserslautern and was also with the German Research Center for Artificial Intelligence (DFKI). Since 2009, he has been a Full Professor with Saarland University, Saarbrücken, Germany, and holds the Chair of Automation, renamed to the Chair of Automation and Energy Systems, in 2014. Since 2014, he has been the Dean of the Faculty of Physics and Mechatronics.

ZHWIU LI (M'06–SM'07–F'16) received the B.S. degree in mechanical engineering, the M.S. degree in automatic control, and the Ph.D. degree in manufacturing engineering from Xidian University, Xi'an, China, in 1989, 1992, and 1995, respectively, where he joined in 1992. From 2002 to 2003, he was a Visiting Professor with the Systems Control Group, Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. From 2007 to 2008, he was a Visiting Scientist with the Laboratory for Computer-Aided Design and Lifecycle Engineering, Department of Mechanical Engineering, Technion–Israel Institute of Technology, Haifa, Israel. From 2008 to 2010, he was a Visiting Professor with the Automation Technology Laboratory, Institute of Computer Science, Martin-Luther-University of Halle-Wittenburg, Halle, Germany. He is currently with the Institute of Systems Engineering, Macau University of Science and Technology, Taipa, China. His current research interests include Petri net theory and application, supervisory control of discrete event systems, workflow modeling and analysis, system reconfiguration, game theory, and data and process mining.