New Forecasting-based Solutions for Optimal Energy Consumption in Microgrids with Load Shedding
Case Study: Petroleum Platform

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Abstract: This paper presents a new control strategy for optimal energy consumption in microgrids based on forecasting and load shedding method. In islanded mode, only local generation resources are usable. In this mode, the availability of resources is very influenced by meteorological factors. In order to achieve a high availability of energy, microgrid has to satisfy high requirements on intelligent power management. The main objective of this study is to develop a control based on the forecast of production and the priority of loads to ensure high availability of electrical power for critical loads. A mathematical model for the proposed strategy is developed. The simulation of this model on Matlab Simulink for different cases of microgrid topology (sources and loads) shows clearly a high improvement of degree of availability of electrical power supply distribution in microgrid.

1 INTRODUCTION

Microgrid system is a new concept that aims to integrate decentralized energy sources efficiently and reliably. A microgrid consists mainly of distributed energy resources, energy storage devices, flexible loads and energy controllers. A microgrid can operate in a connected mode if is interconnected to the main grid, or in an island mode if is disconnected from. In island mode, the main constraints to ensure a high availability are the intermittent behaviour of distributed generation sources and their possible unavailability when they are required to product. To improve the availability, several studies are interested in the use of hybrid sources and power management strategies based on balancing between loads demand and production sources. In order to achieve a high availability of energy and minimize the influence of intermittent behaviour of sources, an intelligent power management based on forecasting production and loads shedding methods should be used. The proposed control strategy in this paper is based on the using of the forecast weather information to predict the availability of renewable sources and the ability of refuelling of programmable sources in an island microgrid. This method gives to the microgrid management system the ability to make the right decision about the achievement refuelling and to choose between using the energy produced to supply total loads or using the load shedding method to store the energy in storage devices for use thereafter in order to supply main loads. In this paper, a mathematical approach is presented to show the different relationships between the different components of microgrid and the influence of their yields by the meteorological factor (insolation and wind). This mathematical approach is used to show the advantage of the new forecasting based control strategy in the improvement of availability. Several simulations on matlab Simulink of the mathematical model of the proposed strategy are developed for different cases of microgrid topology (sources and loads). The simulation results show a high improvement of availability of electrical power supply distribution in microgrid. Comparing to the control strategy without forecasting and load shedding, this new control strategy allows to increase the availability value from 85% to 100%. This paper is organized as follows: Section 1 presents the state of the art of microgrid power availability. The second Section explains the case study and the problem. Section 3 proposes the new control solution for optimal availability. In Section 4, we evaluate the proposed solution. Finally, Section 5 summarizes this paper.

2 STATE OF THE ART

Nowadays, many human activities depend critically

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on a secure supply of energy. With Growing concern about the availability of primary energy, rising electricity demand, use of renewable energy sources such as wind and solar become an obligation (Bhoyar and Bharatkar, 2013). The new generation of electric networks should integrate renewable energy into the electrical grid (Hatziargyriou, 2014). Thus, system security, environmental protection, quality of electricity, cost of supply and energy efficiency should be considered in new ways to meet the changing needs in a liberalized market environment. Microgrid is a contained network of distributed generation sources and energy storage devices that are connected to the loads. The generation can be from renewable sources, that reduce (or cancel) the need to conventional energy sources. The potential for improving the availability of Microgrid power supply is one of the main motivations behind the development and deployment of microgrids. Because of the importance of the availability of electrical energy for various applications and the fluctuating availability of renewable energy sources, a lot of research are interested in different kinds of power sources hybridisation and their availability. The adequate choice of sources is the most important step to improve availability. The hybridisation can be on the type of sources (renewable or programmable source, energy storage devices) or on kind of the same type of source energy storage devices (wind turbine and PV, fast-dynamic storage devices and long-term storage devices, fuel cell, diesel generator) or on both of them. After an adequate choice, the sizing of these sources plays a mattering role in the guarantee of the continuity of service (Logenthiran and Raj, 2010). Many optimizing methodologies are proposed to calculate the optimum size of energy source and storage system considering availability criterion (Y. Nian and Liu, 2013). Some papers explores how microgrids availability is impacted by the different topology design choices for the power electronic interfaces between the distributed generation (DG) sources and the rest of the microgrid. This work focuses on the effect of DC or AC architecture choice, converter design on system availability. Power management strategy (Wang Haiyan and BiYing, 2011) also have a significant impact on the availability of electrical energy, especially in the case of insufficient production of energy or hardware problem. Several research works have been interested in the impact of the strategy of control on the different criteria of microgrid power supply (WANG, 2013), especially the power-quality and the availability of electrical produced energy (Thang, 2012). Whatever the approaches of control (centralized/decentralized approaches) and especially in island mode, they require

Figure 1: Petroleum platform in Gulf of Hammamet in Tunisia.

forecasting of the generation from renewable power sources, electricity demand (and heat demand in some cases). Prediction of the evolution of this quantity allows us to face unsafe situations and optimize production costs and power supply availability (H.X. Yang and Burnett, 2003) (V. and K.U, 2014) . Therefore, forecasting options may have a direct impact on the economic viability and supply availability of microgrids, since they allow them to enhance their competitiveness compared to centralized generation. To have a wider degree of freedom on control strategy of electrical power supply distribution in microgrid comparing to the control based on forecasting (V. and K.U, 2014) and the control based on load shedding (Lee and Huang, 2013), we propose a new optimized control strategy combining these two aspects by taking in consideration the priority of the load supply. The basic idea of our proposed strategy is to use the forecasted weather information to predict the availability of renewable sources of refuelling of programmable sources in an island microgrid. We aim in this paper to make the right decision about the achievement refuelling and load shedding.

3 CASE STUDY AND PROBLEM

We will describe in this section the Microgrid architecture and the climate values and we will introduce the problem.

3.1 Microgrid Architecture

The Microgrid investigated in this paper is an abstraction of a petroleum platform (Figure 1) islanded located on the Tunisian Coast. This Microgrid conception adopted for this case study is composed of PV arrays, a wind turbine, a diesel generator with its fuel tank, a storage device (batteries) and two loads (Figure 2). The Microgrid is designed as follows:

- Each renewable energy source (PV, Wind turbine) is sized to be able to generate the electrical power supply required by both loads and batteries in favourable weather conditions,

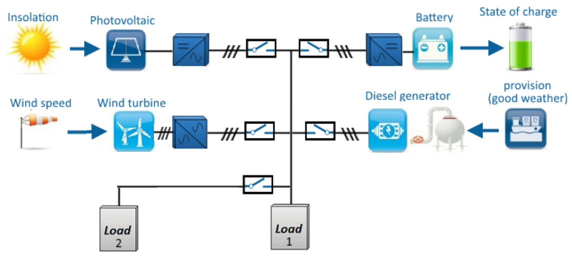

Figure 2: Microgrid.

- Diesel generator is dimensioned to be able to produce electrical energy required by the load. The autonomy of this source is proportional to the level of fuel in its tank and its produced energy,
- Battery is sized to be able to provide the electrical power supply required by both loads with an autonomy proportional to its charge level and the electrical power request by loads. The battery becomes another load in her charging phase,
- load 1 is a critical load, it must be always connected to the grid. Load 2 is a secondary load, it can be disconnected in some cases.

The problem in this case is the intermittent nature of all the sources of energy in this islanded microgrid. The availability of sources is relative to the meteorological terms (Gooding, 2013). Based on sizing solutions, the system - especially the elements of storage - must be oversized; price and weight are the weak points of this solution. We can increase the availability by hybridisation of sources with other sources that can operate in the bad times, such as the waves energy sources. This solution decreases the weight supported by the platform, but it is very expensive and this type of energy is still in the process of study and development. In this case, an adequate management of energy can ensure or at least improve the availability of electrical energy for the critical loads without needs of new sources and new weight on the platform. This strategy can minimize the aspect of intermittent sources of energy by the use of the forecast of the meteorological factors and can act accordingly.

3.2 Climate values

The proposed Microgrid management systems must be enhanced with forecasting technical functionalities able to predict the power production of distributed production sources in the next hours or days. To that purpose, historical measurements database are needed to generate the forecasting models. In Tunisia, you can get this data from the National Institute of Meteorology[1].

3.3 Problem and Discussion

In the island function mode of a microgrid, the availability of power supply is very influenced by the intermittent behaviour of its distributed sources. With a view to improve this availability, the hybridisation and the oversizing of sources represents a good technical solution, but this solution is very expensive. In economical point of view, the solutions based on control strategy are always the cheapest. This kind of solution is characterized by its flexibility and ability to be adapted to the climate change. For this reason, a microgrid must have an intelligent control strategy based on forecasting methods that can minimize the impact of weather conditions on the renewable and programmable sources availability. The strategy of control should minimize the impact of the unavailability of renewable sources by increasing the availability of backup sources (programmable sources and storage devices).

4 CONTRIBUTION

Our contribution consists in the development of the new forecasting-based solution for optimal energy consumption in microgrids with Load Shedding. This contribution is based on mathematical formulation of the electrical network structure of Tunisian offshore petroleum platform existing in the Gulf of Hammamet with taking into account the weather condition.

4.1 Architecture

A microgrid is composed of Photovoltaic Cells, Wind turbine, Battery, Diesel Generator and loads. All the sources are sized so that each of them - when is available- is able to meet the energy demand loads. The availability of renewable sources depends on climatic factors (insolation and wind). The availability of the battery depends on the charge level. The battery can be charged and discharged through the microgrid. The diesel generator is available when the tank is not empty. The tank can be filled with refuelling in case of good weather. There are two types of loads in the microgrid: (i) critical load that should be supplied all the time, (ii) and uncritical load that can be disconnected from network in the case of load shedding.

[1]http://www.meteo.tn

4.2 Optimal Energy Consumption

In this subsection, we will describe the notation and the problem formulation.

4.2.1 Notation

We denote in the following by:

PV	Photovoltaic Generator
WT	Wind Turbine
B	Battery
GE	Diesel Generator
$P_{Source}(t)$	Electrical power exchanged between the source and the rest of network
$P_{Load1}(t)$	Electrical power consumed by critical load
$P_{Load2}(t)$	Electrical power consumed by uncritical load
En	Insolation
V_V	Wind speed
E_{charge}	Battery charge level
E_{clim}	Sea State
N_{Charge}	Level of the fuel in the tank of the diesel generator
E_{clim_0}	Nominal sea State
$\psi(t)$	Electrical power produced by this source

4.2.2 Problem Formulation

In term of availability A(t) (Equation 1), all electrical energy sources can have two states:

- 1: available energy producer.
- 0: unavailable energy producer.

In its charging phase, the battery acts as a load that may consume excess production. The battery can have a third state:

- -1: load state of battery.

$$\left\{\begin{array}{c} A_{PV}(t) = 1;0 \\ A_{WT}(t) = 1;0 \\ A_B(t) = 1;0;-1 \\ A_{GE}(t) = 1;0 \end{array}\right. \quad (1)$$

Only available sources can be connected to the grid. The state of penetration of sources C(t) to the network is defined by equation(2):

$$\left\{\begin{array}{c} C_{PV}(t) = \lceil \frac{En}{En_0} \rceil - 1 \\ C_{WT}(t) = (\lceil \frac{V_V}{V_{V_0}} \rceil - 1).\overline{A_{PV}(t)} \\ C_B(t) = (\lceil \frac{E_{Charge}}{E_{Charge_0}} \rceil - 1).\overline{A_{WT}(t)}.\overline{A_{PV}(t)} \\ C_{GE}(t) = (\lceil \frac{N_{Charge}}{N_{Charge_0}} \rceil - 1).\overline{A_B(t)}.\overline{A_{WT}(t)}.\overline{A_{PV}(t)} \end{array}\right. \quad (2)$$

Where:
$En_0(t)$, V_{V_0}(t), N_{charge_0}(t) and E_{clim_0}(t) are the nominal values from which the sources are capable of producing energy.

The electrical power supplied by different sources to the microgrid is equal to:

$$\left\{\begin{array}{c} P_{PV}(t) = C_{PV}(t).\psi_{PV}(t) \\ P_{WT}(t) = C_{WT}(t).\psi_{WT}(t) \\ P_B(t) = C_B(t).\psi_B(t) \\ P_{GE}(t) = C_{GE}(t).\psi_{GE}(t) \end{array}\right. \quad (3)$$

The power produced in the microgrid may not be sufficient to satisfy the totality of power demand for all the time. For this reason, we should be allocated a specified priority for each load. In this study, we have two levels of priority:

- Load 1: critical load, it must be supplied most of the time,
- Load 2: uncritical load. It can be disconnected in the load shedding phase ($C_{Load2} = 0$).

To ensure the availability of power supply, the produced power must check the following inequation:

$$\begin{array}{c} P_{PV}(t) + P_{WT}(t)) + P_B(t) \\ +P_{GE}(t) \geq P_{Load1}(t) + P_{Load2}(t).C_{Load2} \end{array} \quad (4)$$

In case of basic load shedding (without forecasting), the load shedding method takes into consideration only the real-time information about production and consumption.

$$\begin{array}{c} C_{Load2}(t) = f(P_{PV}(t), P_{WT}(t), \\ E_{charge}, N_{charge}, P_{Load1}, P_{Load2}) \end{array} \quad (5)$$

In the case of a load shedding based on the forecasting, the uncritical load can be disconnected. C_{Load2} can be re-written as:

$$C_{Load2}(t) = \beta_{GE}(t).\beta_B(t) \quad (6)$$

With

$$\left\{\begin{array}{c} \beta_{GE}(t) = (\lceil \frac{\sum_{i=1}^{n} .E_{Clim}(i)}{n.E_{Clim_0}} \rceil - 1).(\lceil \frac{\sum_{i=1}^{n} .N_R(i)}{n.N_{R_0}} \rceil - 1) \\ \beta_B(t) = (\lceil \frac{\sum_{i=1}^{n} .E_n(i)}{n.E_{n_0}} \rceil - 1).(\lceil \frac{\sum_{i=1}^{n} .V_V(i)}{n.V_{V_0}} \rceil - 1) \\ .(\lceil \frac{\sum_{i=1}^{n} .N_{Charge}(i)}{n.N_{Charge_0}} \rceil - 1) \end{array}\right. \quad (7)$$

$\beta_{GE}(t)$ and $\beta_B(t)$ are predictive probabilistic index about the state of the diesel generator and battery availability in the future. These two indexes will be used in order to optimize the load shedding and the refuelling system decision.

5 EVALUATION

In this section, we will deal with the power system model as well as the simulation result of the petroleum platform.

5.1 Power System Modelling

We present in this subsection the photovoltaic generator, the wind turbine, the diesel generator and the battery.

5.1.1 Photovoltaic Generator

The behaviour of photovoltaic generator (PVG) can be presented by the following equation:

$$\psi_{PV}(t) = \eta_{PVG}.A_{PVG}.G_{ir} \tag{8}$$

With:

- $A_{PVG}(m^2)$ is the PVG surface,
- η_{PVG} is the PVG conversion efficiency given by: η_{PVG}= η_r[1-β.(Tc-Tcref)]

5.1.2 Wind Turbine

As seen in equation(9), the energy of wind turbine .ψ_{WT} and mechanical output power of wind turbine P_m.

$$\psi_{WT}(V) = \begin{cases} P_n.\frac{V-V_{dem}}{V_n-V_{dem}}, V_{dem} \leq V \leq V_n \\ P_n, V_n \leq V \leq V_{max} \\ 0, Otherwise \end{cases} \tag{9}$$

$$P_m(t) = \tfrac{1}{2}.C_p(\lambda,\beta).\rho.AV^3 \tag{10}$$

With:

- ρ: Air density (Kg/m^3),
- A: Turbine swept area (m^3),
- V: Wind speed (m/s), V_n: Nominal wind speed, V_{Max}: Maximal wind speed, V_{dem}: Startup Wind speed,
- $C_p(\lambda,\beta)$: Performance coefficient of the turbine,
- λ: Tip speed ratio of the rotor blade tip speed to wind speed,
- β: Blade pitch angle (deg).

5.1.3 Diesel Generator

The used model is a very simple. If its tank is not empty, the diesel generator is a generator able to provide an electrical power P_{gen}. After each unit of time T of operation of generator, the fuel level decreases by a quantity proportional to T and P_{gen}.

5.1.4 Battery

There are many models to charge and discharge the batteries. For the problems of sizing, it is enough to use models that feel the State Of Charge (SOC) of the battery in a simple manner.

5.2 Simulation Result

In this subsection, a number of simulation results that highlight the influence of: (i) the strategy of command and (ii) the oversizing of backup sources on the availability of electrical energy are presented and discussed. We will focus mainly on calculating the availability of energy: (i) at the level of critical loads, (ii) at the level of the entire system. We will focus also on the evolution of the charge level of the battery and the fuel level in the tank of diesel generator. The instantaneous availability may have only two values, 1 in the case of availability and 0 in the opposite case. The average Availability $A_A(t)$ is the mean value of the instantaneous availability between time=0 and time=t (Taylor and Ranganathan, 2013).

$$A_A(t) = \frac{1}{t}\int_0^t A(x)dx \tag{11}$$

The rate of load shedding is also an important index. It gives us the idea about the availability of electrical energy at the level of uncritical load and also at the entire system.

5.2.1 Case 1: Without Forecasting and Load Shedding

This case does not address the paper's contribution. It deals with a simulation without forecasting and load shedding. Two types of load are considered: both powered or both unpowered. Note that the refuelling occurs only in the good weather if the tank is empty. Table 1 shows the power supply availability index for: (i) critical loads, (ii) entire system and (iii) the load shedding rate for uncritical loads. Since there is no load shedding, so the power supply availability for the main loads and the power supply availability for all the system are equal. The calculation of availability at the level of charges has given an availability rate equals to 85.17 %. That it may be considered as a mediocre value. Figure 3 presents the evaluation of the instantaneous and average power availability at

Table 1: Availability values.

Power supply availability for the main loads	0.8517
Power supply availability for all the system	0.8517
Load shedding rate	0%

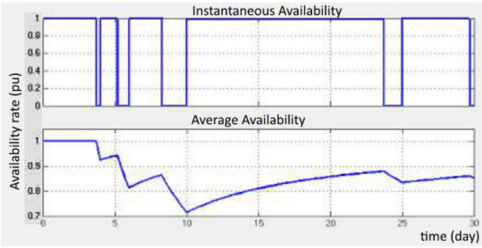

Figure 3: Instantaneous and average availability.

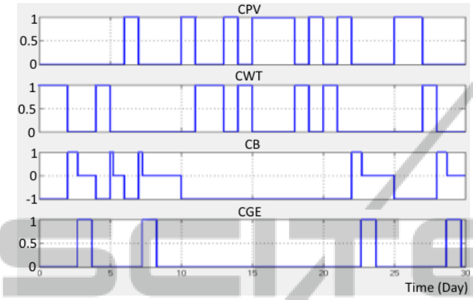

Figure 4: State of penetration of sources.

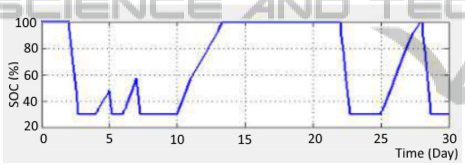

Figure 5: State of charge of the battery.

the level of critical load. Figure 4 shows the state of penetration of sources (to the microgrid) which provide energy for consumers (Equation 2).

Note that: at each moment, only one source can be penetrated to the network. We can also see the evolution of the state of charge in the battery on Figure 5.

Figure 6 gives us information about the possibility of refuelling, the act of refuelling and the evolution of level of fuel in the tank of the diesel generator. According to this figure, we have three times of refuelling.

5.2.2 Case 2: Without Forecasting and with Load Shedding

This case is interested in a simulation that we did without forecasting but with load shedding, if the system is powered by the non-renewable energy sources, there is automatically a load shedding. Comparing with the previous value of simulation without load shedding, we note that the power supply availability rate for critical loads increases more than 9% but the power supply availability rate for the entire system is decreased by 7% (Table 2). Using the strategy of load

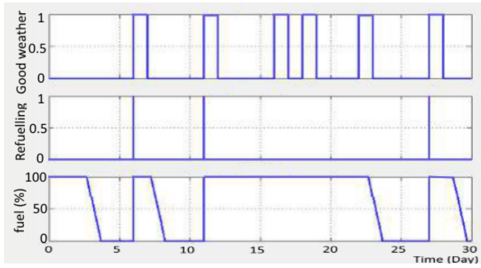

Figure 6: Good weather, refuelling and fuel level.

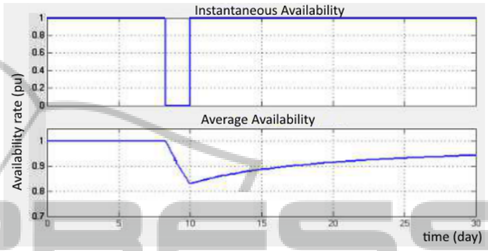

Figure 7: Instantaneous and average availability.

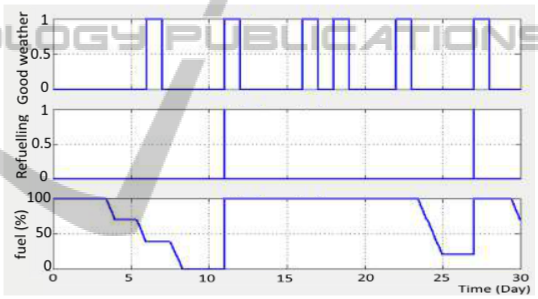

Figure 8: Good weather, refuelling and fuel level.

Table 2: Availability values.

Power supply availability for the main loads	0.9433
Power supply availability for all the system	0.7883
Load shedding rate	36.67%

shedding, we note that the supply system becomes totally unavailable only once (Figure 7). The gain that we obtain in Case 2 comparing to Case 1 is the improvement of power availability at the level of critical loads. The reader can observe this improvement by comparing Figure 7 to Figure 3. Table 2 shows that the application of load shedding without forecasting desceases the power supply availability of the system from 0.85 to 0.78.

Despite that the availability rate of the power supply for critical loads increases, we note that the number of refuelling act decreases. This presents an economic gain in term of fuel and its transport (Figure 8).

Figure 9 shows the influence of load shedding on the rate of the connected loads.

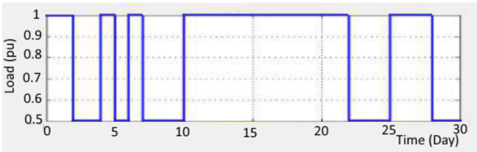

Figure 9: Load(pu).

Figure 10: Instantaneous and average availability.

5.2.3 Case 3: With Load Shedding and Forecasting Only for Refuelling

Case 3 is interesting in the paper's contribution that deals with the prediction of the future weather conditions to manage the current energy consumption to optimize the refuelling process. Using the same previous strategy of load shedding, we can optimize the values of availability (Figure 10), if we improve the refuelling decision system taking into consideration the present state of tank and the provisional statements of all the sources of microgrid. This forecast helps the system to take the right decision of refuelling: Figure 11 shows three times of refuelling which improve the availability of the diesel generator. Thanks to this new solution of Case 3, the power supply availability is increased from 0.94 to 0.98 (compared to Case 2) thanks to the proposed Equation 7.

Table 3: Availability values.

Power supply availability for the main loads	0.9847
Power supply availability for all the system	0.809
Load shedding rate	36.67%

5.2.4 Case 4: With Forecasting and Load Shedding

In this case, we present the paper's contribution that deals with the forecasting and load shedding. Table 4 and Figure 12 show a full availability of power supply thanks to the proposed forecasting solution with load shedding. Figure 13 shows the state of penetration of sources and Figure 14 shows the state of charge of the battery. Figure 15 shows the influence of the load shedding on the rate of the connected loads. The reader can observe the gain that we get by applying the forecasting with load shedding. Figure 16 gives us information on the possibility of refuelling, the act of refuelling and the evolution of the level of the fuel in the tank of the diesel generator. In Case 4 compared to Case 3, the power supply availability is increased from 0.98 to 1 thanks to the proposed Equation 6 and 7.

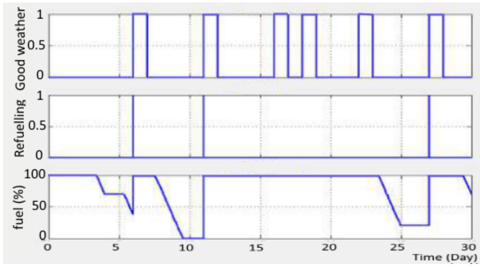

Figure 11: Good weather, refuelling and fuel level.

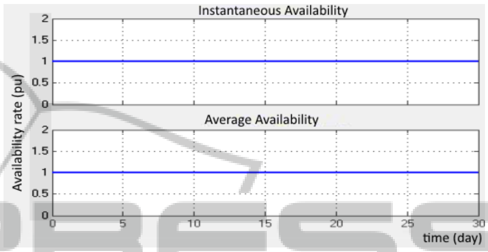

Figure 12: Instantaneous and average availability.

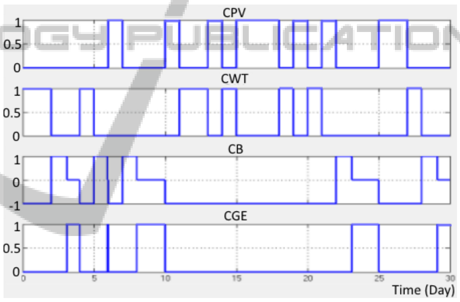

Figure 13: State of penetration of sources.

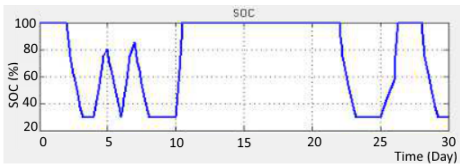

Figure 14: State of charge of the battery.

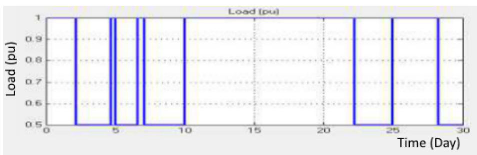

Figure 15: Load(pu).

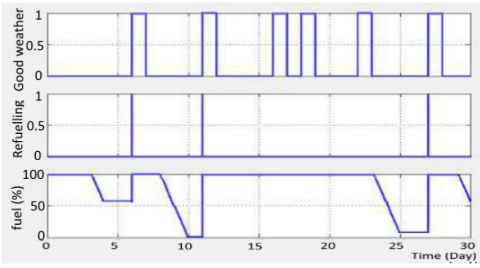

Figure 16: Good weather, refuelling and fuel level.

Table 4: Availability values.

Power supply availability for the main loads	1
Power supply availability for all the system	0.809
Load shedding rate	38.12%

5.2.5 Result

According to the results obtained, it can be seen that:

- The type of hybridisation affects the availability. But when we choose the sources, the reconfiguration is costly and takes time,
- Note that the load shedding is a very important strategy to increase the availability of electric power in the priority loads, but it decreases the rate at secondary loads and the system as a whole,
- Load shedding may be based on real-time information or forecasts or of course both. The right choice of this command and forecasting methods provide a very high availability level of critical devices, which can reach 100%.

6 CONCLUSION

In order to ensure a high availability in the islanded and autonomous microgrid, we propose a new forecasting-based solution for optimal energy management. The major problem of this solution is the probabilistic aspect of the forecasting data on which the strategy is based on to make its decision. The load shedding increase the availability in the level of critical loads; but in return, this method decreases the availability in the level of uncritical loads. Despite their problems, this strategy provides good results in a case study. Predictive control strategy can help the microgrid to improve the power supply availability for its user by proactive control. Comparing with existing solutions, our new solution presents several economical and technical benefits and it can be implemented easily. The implementation of this proposed solution and its experimental result will be published nearly.

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