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Design and Implementation of Multi-Source and Multi-Consumer Energy Sharing System in Collaborative Smart Microgrid Installation

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Abstract- *Many published studies debated electrical energy management. They mainly investigate the multi-source installation to develop energy efficiency during its different phases: production, distribution, and consumption. Although it is rarely discussed, energy sharing is a critical part of the energy management system. In this contribution, a demand-side management algorithm is developed, that incorporates energy consumption scheduler capacity. It provides optimal energy sharing, counting on suitable energy cost parameters and adequate multi-source installation. Using this proposal, the electrical bill decreases thanks to the optimal daily attribution of schedules to households formed by a multi-consumer microgrid. This application guarantees a maximal reduction of electrical cost for the set of energy partners as one prosumer used to consume and produce power. In addition, it maintains energy efficiency as it aids in avoiding breakdowns, and depressing the peak-to-average ratio. It admits that the utility company is, as usual, always reachable non-renewable source. At the same time, renewable energy was engendered by photovoltaic panels concomitant with wind turbines stations. The application is based on the JNET protocol stack. The proposed energy sharing algorithm is implemented by using Arduino board and JN5148 nodes as a star Wireless Sensors Network topology. It is installed as a prototype in the Digital Research Center of Sfax in Tunisia. This proposed incentive-based algorithm managed to reduce the smart microgrid annual cost by almost 55% without harming the public utility. It can even ensure a more significant diminution by selling the surplus of renewable power at the end of each day*.

Keyword: Consumption optimization, Electricity cost reduction, Energy consumption scheduler, Energy sharing, Renewable energy, Smart microgrid.

1. INTRODUCTION

The optimization of electrical energy consumption presents a necessity nowadays and sometimes even an obligation, particularly in the financial field. Therefore, it is crucial to rationalize, plan and enhance energy efficiency while avoiding losses and wastes of electricity at different levels and phases. The process includes stages starting with the production, moving to the distribution, and up to the consumption. It creates a rigid electrical system that always maintains reliable, harmonized and balanced distribution and moderate consumption. The management of energy intervenes in all domains; for that reason, many published studies explore this framework. Some of these researches include algorithms based on smart electricity pricing, while others are built on agreements and deals with conventional energy producers. These agreements are usually conducive to loading electricity in the case of insufficient renewable production to cover the requirement of consumers. Among the popular example, the real time pricing (RTP) [1]: According to these programs, the hourly electrical energy price varies according to weather variation. This permanent change presents a major disadvantage since it inconveniences customers by following the tariff fluctuation. It is also accompanied by another issue which is the creation of new different peak hours by condensing loads at the lower tariff hours. This synchronization issue can be responsible for maintaining the Peak to Average Ratio (PAR) [2] or even increasing it. Almost all algorithms that include the real-time pricing capacity, as the critical peak pricing (CPP) [3] and the time of use pricing (ToUP) [4] can not solve this PARs problem along with other deficiencies and disadvantages. In the context of algorithms related to agreements with the utility

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company, such as the direct load control (DLC) [5] programs, the company holds all power to control certain appliances. Furthermore, it can remotely switch the status of these type of equipment (ON and OFF) depending on the possible energy load and its hourly corresponding energy price. Economic management presents an important issue in the smart grid field. At this level, optimizing is part of energy management goals. For this purpose, various efforts have been made to optimize the energy cost in the last few years. A recent research paper applied linear programming to optimize the economic management of the production units and the storage devices [6]. However, the cost decrease is inconsiderable and insignificant. Moreover, from the generation point of view, a suggested solution optimized the microgrid energy consumption cost by considering both intra-day and day-ahead markets studies [7]. But, its objective functions are unrealistic, especially the day-ahead market approach. In addition, to reduce pollutant emissions and power resources operation cost, a day-ahead two-stage stochastic multi-objective framework has been suggested by adopting the ε-constraint approach [8]. But, the framework did not rely on real recorded historical data, which presents a major limitation. Also, these objectives were achieved by utilizing a fuzzy-based model [9]. Furthermore, to realize an optimal microgrid scheduling, recent studies implemented the method of scenario-based stochastic programming [10], [11]. Yet, this method failed to offer trusty and realistic solutions.

Despite being a new concept, energy sharing presents a crucial and substantial energy management part that is unfortunately neglected. The scarcity of work concerned with this important part is one of the many motivations that lead to work on it. Therefore, a system that focuses on electrical energy sharing within a multi-source and multi-consumer smart microgrid installation is proposed. To manage the "energy sharing system" in an optimal way, it has suggested in previous works [12], [13], and [14] a new protocol stack model which comprises a protocol and physical layer essentially. In addition, the appropriate renewable installation and the suitable energy cost function form for the application example are adjusted. As for this paper, the works continue to optimize renewable production, the load from the utility company, and the cost of electricity. In this paper, to decrease as much as possible the electricity cost, it is taking into account various orientations to investigate and test the proposal. First, the supreme renewable production optimization is achieved by changing the tilt angle of the solar module while following the maximum solar radiation. So, the concept of movable panels comes into play. Second, consumption optimization is proposed by considering the dynamic pricing and organizing the energy load thanks to the energy consumption scheduler (ECS) capacity. Then, the practical architecture design is presented while introducing the types of nodes and the used hardware. Finally, the efficiency of the proposed sharing algorithm is evaluated by analyzing the simulation results and the hardware implementation studies the feasibility of the proposed work. Despite the dynamic electricity pricing integration, the proposed algorithm does not cause any annoyance to users' private lives, contrary to the real-time pricing (RTP). This pricing methodology solves the PARs problem because it limits the creation and manifestation of the peak hours, unlike almost all the real-time pricing algorithms. Another advantage of the proposal is that it does not inconvenience users because it allows the utility company to control only a limited number of devices with flexible operational time. In opposition to algorithms such as the direct load control (DLC) programs where the utility company holds all power to control several devices that hinder smart microgrid users. Overall, this proposed incentive-based algorithm decreases as much as is achievable the electrical energy cost. It can achieve this reduction without causing economic losses to the utility company. On the contrary, it provides profit for the utility company and the users. In addition, it can even guarantee a financial income by selling the surplus of renewable power. For the optimization process, the MATLAB simulator is used to evaluate the optimality and convergence of the proposed algorithm. The simulation is made by running the M files codes of the MATLAB simulator. Therefore, the hardware implementation is based on Wireless Sensors Nodes deployed at six users, three sources, and one central station. The rest of this paper is organized as follows. In section 2, the energy sharing system will be described. Then, the hypothesis will be introduced in section 3. After that, the consumption optimization algorithm is proposed by defining in detail the steps of electrical energy sharing within the application, in section 4. Next, the movable photovoltaic panels will be intervened and the hardware implementation will be exposed respectively in sections 5 and 6. Section 7 will exhibit and explain the results and discussion. Section 8 concludes the suggested contribution.

2. THE PROPOSED SHARING SYSTEM

Usually, a lot of studies debating the hardware installation of common renewable energy resources

[12], [13], [14]. This paper examines the multi-source solution within this framework and demonstrates that even with a reduced renewable energies installation, an excellent energy sharing system can provide superb results. Therefore, the proposed system can be beneficial for all smart microgrid users who share them. To efficiently share energies, the fundamental hypothesis is the common interests of all users: sharing the same space (common garden or building roof …), energy demand, participating in the installation costs, etc. The collaborative installation has various advantages, such as the encouragement of users to install renewable energy sources. Even when they are considered relatively expensive or insufficient for covering the total demand of the load. For this purpose, integrating an optimal sharing system is considered the main condition. Fig. 1 exhibits the topology of collaborative energy sharing installation. This topology generally includes:

- The users in the common area.
- The sources: in the context of this application, a multi-source solution is considered. The utility company (the public company of electricity (PC)) presents the non-renewable source to cover, if necessary, the renewable energy insufficiency. Whilst the renewable energy is harvested via wind turbines coupled with photovoltaic panels (PV).
- The sharing station: is a primordial part; it acquires the data from users and sources. It also makes the decision that defines the appropriate source to use, so the user will keep or switch the source or use both sources.
- Data channel: In the proposed architecture, as illustrated in Fig.1, the data communication is designed to use Wireless Sensors Network by utilizing JN5148 nodes.

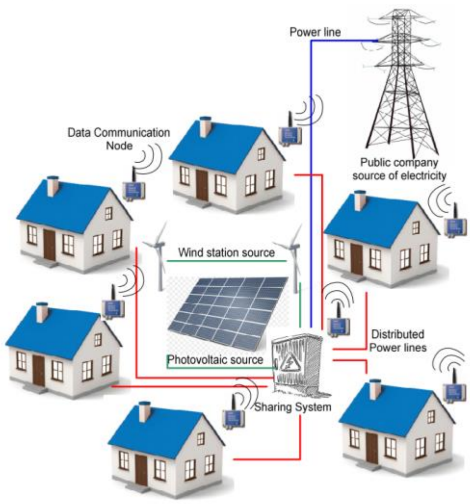

Fig. 1. Energy Sharing topology and strategy for smart microgrid

In this application, an energy consumption scheduler (ECS) capacity is incorporated. Thus according to each user's energy profile and necessity, we assign, eventually, to each one the optimal planning. Appropriate planning guarantees reducing the total annual energy cost as low as possible and ensures the decrease of PARs number and values during the whole year. To each user, a set of different plannings is proposed. Those schedules respect their habitual need for energy and consumption profile which adjust the predefined energy. To optimally share the microgrid energy, it is primary to take into consideration a set of conditions. First, all users should share common renewable and conventional sources. Second, users and PC must agree to be entirely respected, which encompasses regulations and rules. Third, a smart meter must equip each household with a microgrid. Its role is mainly to optimally manage the energy requests by adjusting consumption and also remotely commanding some devices by connecting and disconnecting them. The outline of our sharing process is as follows: the proposed algorithm haphazardly attributes to every user one of his schedules (schedule A, B, or C). Then, it selects a random user and continues varying his planning until engendering the minimum annual total cost of the smart microgrid and immediately assigns this planning to him. After that, it passes to the next user and repeats the same previous procedures up to assign the optimal schedules.

3. HYPOTHESIS

It is assumed, in this application, that there are two renewable sources: PV and wind turbines, a single non-renewable source: the public company of electricity (PC) and N consumers (N = 6, in this case). In this paper, a demand-side management algorithm with energy consumption scheduling (ECS) capacity is offered. It intends, mainly, to reduce the annual microgrid cost of energy, but it minimizes the PARs simultaneously. To reach both objectives, as long as there is renewable production, users should load it at first according to their assigned schedules. If there is a production excess, it is stocked for the next hour and redo until the excessive production is entirely exhausted. In this case, the users head towards the non-renewable source, which is a paying one.

Consequently, the cost function gets involved. Generally, the cost is inferior when renewable energy production is allegedly higher. For example: for the PV, the afternoon and hot days, mainly, in summer and as for wind station, days when wind power is significant.

Table 1.The different plannings of each user

Scenario	Plannings of users					
	User 1	User 2	User 3	User 4	User 5	User 6
1	A1	A2	A3	A4	A5	A6
2	B1	B2	B3	B4	B5	B6
3	C1	C2	C3	C4	C5	C6

3.1. Users

The application users are principally the participants in smart microgrids who share common areas and sources. They can be industries, households, or any other type of user who requests to diminish their electricity bills and eliminate breakdowns as much as possible. So, they need to efficiently manage their electrical consumption by scheduling them and avoiding energy loss/waste and breakdowns generated by load peaks. Therefore, this algorithm that effectively plans the operation of soft energy consumption constraints devices is developed.

3.2. Shiftable and non-shiftable devices

In general, there are two types of devices according to the method of controlling them depending on the ability to change the periods and durations of their operations. This change can be either by an advance, a delay or a partition. The shiftable appliances are devices that can easily undergo this processing. Whereas severe energy consumption constraints characterize the non-shiftable devices, it is impossible to adjust their uses. The scheduling strategy is more focused on shiftable devices in this application thanks to their flexible operational time. Therefore, the proposed algorithm can optimally shift their usage from the peak hours to lower-load ones. According to the associated plannings, it modifies their operating times and switches their states, from ON to OFF and inversely by using the smart meters that include ECS capacity. It is assumed that a household of this smart microgrid contains 5 electrical devices of each type, i.e. 10 devices in total. Lighting (quotidian use for 10 standard bulbs: 1.00 kWh), heating (quotidian use: 7.1 kWh), refrigerator-freezer (quotidian use: 1.32 kWh) and electric stoves (quotidian use: 2.01 kWh for regular and 1.89 kWh for self-cleaning) [15] are the non-shiftable operation appliances. Stern consumption scheduling constraints characterize them. Regarding the shiftable devices, the households are equipped with: washing machines (quotidian use: 1.49 kWh for energy-star, 1.94 kWh for regular), dishwashers (quotidian use: 1.44 kWh), clothes dryers (quotidian use: 2.50 kWh) and plug-in hybrid electric vehicles (PHEV) (quotidian use: 9.9 kWh) [15]. Furthermore, it is admitted that the microgrid consumption demand is greater in the evening and inferior over the night. It is supposed also that electric cars will be charged mainly between the afternoon hours each day and the early morning hours on the next day. The average of one user daily consumption is 28.36 kWh, accordingly it is equal to 170.18 kWh for the whole smart microgrid (for all the 6 users in this application).

3.3. Renewable and non-renewable sources

The production of photovoltaic panels (PV) and wind turbines are practically complementary. This is why they are integrated into this application as renewable sources. Generally, the cost of installing this type of source is negligible due to its relatively rapid profitability. Its production compensates the installation costs in a shorter period compared to its productive duration, particularly for wind stations. But renewable production is not reliable since it is directly dependent on several factors such as location, weather, environment, etc. Also, as it is considered an infinite source because it is always available, the public company of electricity (PC) is indispensable for the microgrid to meet the necessary loads. For these reasons, it is decided to consider the PV, wind turbines and PC as energy sources.

3.4. Schedules

According to his consumption profile, it is attributed, until now, three particular schedules (plannings) to each user, as shown in Table 1. These plannings depend on their regular daily consumption and respect their quotidian electricity needs. They set the daily load partition by specifying for each device the ON and OFF hours and its load available when it is in the ON state. Hence, the dissimilarities between schedules are essentially located in the difference in operating hours of the electrical shiftable devices and the hourly amounts of predetermined energy to be consumed. The partitions of non-shiftable appliances are very similar, which results in the difference between schedules being principally defined in the shiftable appliances partitions. Fig. 2 presents the model of the schedules. It is a matrix where the columns correspond to the 24 hours of a day and the lines present the devices consumptions. It declares the possible consumption of each device at each hour.

Dishwasher=[$dish_1$ $dish_2$ $dish_3$ … $dish_{23}$ $dish_{24}$]

Washing_machine_ES=[$washES_1$ $washES_2$ $washES_3$ … $washES_{23}$ $washES_{24}$]

Washing_machine_REG=[$washRE_1$ $washRE_2$ $washRE_3$ … $washRE_{23}$ $washRE_{24}$]

Clothes_dryer=[$cloth_1$ $cloth_2$ $cloth_3$ … $cloth_{23}$ $cloth_{24}$]

PHEV=[$PHEV_1$ $PHEV_2$ $PHEV_3$ … $PHEV_{23}$ $PHEV_{24}$]

Ref_freez=[ref_1 ref_2 ref_3 … ref_{23} ref_{24}]

Heating=[$heat_1$ $heat_2$ $heat_3$ … $heat_{23}$ $heat_{24}$]

Lighting=[$light_1$ $light_2$ $light_3$ … $light_{23}$ $light_{24}$]

Self_cleaning=[$self\_clean_1$ $self\_clean_2$ $self\_clean_3$ … $self\_clean_{23}$ $self\_clean_{24}$]

Regular=[reg_1 reg_2 reg_3 … reg_{23} reg_{24}]

Fig. 2. The model of schedules

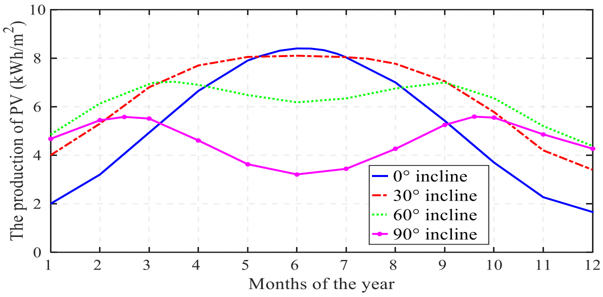

Fig. 3. The production of PV for different inclinations

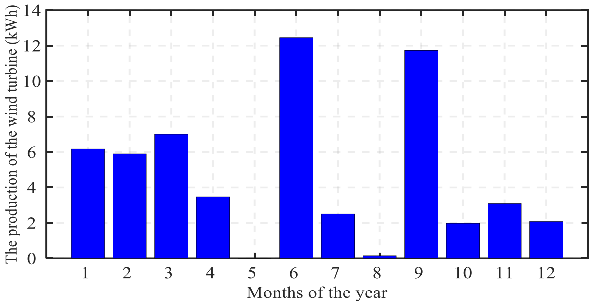

Fig. 4. The model of a wind turbine production

3.5. Multi-source modelling

This microgrid is a multi-source, multi-consumer installation so the households share joint conventional (PC) and renewable (PV, wind) sources. The production of the second type has always the distribution priority. This implies that as long as renewable energy is available, users can take advantage of real-time or previously-stored energy loading while respecting schedules. Every hour storage is accessible for the following hour.

3.5.1. Public company source and energy cost function modelling

The public company of electricity supplies the smart microgrid with non-renewable electric power. It is presented as an infinite source considering that it is always reachable. But the load from it must be reduced as much as possible for the reason that users will, conclusively, pay for it. Since the objective is to decrease the annual total energy cost, it is necessary to minimize this load volume, mainly at high tariffs. Those periods are generated by the peaks of load that can ensue breakdowns. The energy cost function is a significant and crucial equation that encloses parameters that influence and determine energy costs. The cost function is directly dependent on the PC. Hence its characteristics (form, types and values of coefficients, etc ...) are linked to this company.

A second-degree polynomial function is adopted [15], it is formulated as:

$$C_h(L_h) = a_h \times L_h^2 + b_h \times L_h + c_h \quad (1)$$

where a_h , $c_h \geq 0$ and $b_h > 0$ present the coefficients of the cost function and L_h denotes the total load (across all users) corresponding to an hour $h \in H=\{1,...,24\}$ of a day. It is calculated as follows:

$$L_h = \sum_{n \in N} l^h_n \quad (2)$$

N indicates the set of users and l^h_n defines the corresponding load of the user $n \in N$ at the hour $h \in H$.

3.5.2. The model of photovoltaic panels production

It is known that the production of photovoltaic panels is not one hundred percent predictable. In the context of this application, a model of a whole one-year PV production is adopted. It is a realistic example that specifies the production according to the surface covered by PV. The values of the produced amounts in kWh/m^2, are taken from a PV installation located near Lyon in France. This model, exhibited in Fig. 3 [16], offers the results of several inclinations of solar module (0°, 30°, 60° and 90°). Then, to obtain the PV production, the algorithm multiplies the daily extracted value by the photovoltaic module surface.

3.5.3. The model of wind turbines station production

The wind station is a set of "*m*" wind turbines. The scalar *m* presents the number of turbines with the following basic nominal characteristics: output power 400W, rotation speed 900 rpm and wind speed-ref 12.5 m/s (45 Km/H) [17]. Fig. 4 explains the model of wind turbine production. It depicts the monthly average production, in kWh, that varies in the interval [0 12.45] during a year [17].

3.6. The optimal combination of renewable sources

In the context of a previous work [14], multiple and various combinations of renewable sources are evaluated to obtain an optimal solution. As a result, the optimal combination is a solar module with a surface of 10.5 m^2 of PV and 25 wind turbines (in the case of 0° incline). This renewable combination guarantees the minimum possible cost in a whole year while avoiding any kind of loss or waste of electrical energy.

3.7. Pricing assumptions

The assumptions involve the set of parameters related to the energy cost function. This function ensures the benefits of consumers and producers while determining the suitable type and values of their coefficients. The study of the coefficients is crucial considering that their values are the principal criteria that guide to find the optimal daily costs. Consequently, it produces the optimal annual total cost of the whole microgrid. The coefficients can be constant or variable. The last term c_h of the cost function presents daily fixed charges for electricity. The first term a_h is a penalty imposed on users when they exceed the consumption threshold at the hour $h \in H$. As for b_h, a dynamic value that varies hourly is attributed. It depends on the renewable energy production and the requisite electricity consumption at this hour according to the organizational chart [12] presented in Fig. 5. It is assumed that *R(h)* is the quotient of the total renewable production (*RP(h)*) at the hour $h \in H$ and the total consumption at the same $h \in H$ for all users (L_h):

$$R(h) = RP(h) / L_h \quad (3)$$

When *R(h)* is equal to or greater than 1, there is sufficient renewable energy then b_h is assigned by the maximum value 0.4 to encourage users to consume only renewable energy. In the case where *R(h)* is equal to 0, there is no renewable energy, so users are obliged to load from the PC, then b_h set to the minimum value 0.1. In the case where *R(h)* is in]0 1[, b_h varies linearly according to the following equation:

$$b_h(h) = a_{eq} \times R(h) + b_{eq} \quad (4)$$

where a_{eq} and b_{eq} are equal to 0.3 and 0.1, respectively. Fig. 5 depicts the organizational chart applied to calculate b_h.

The optimal combination of renewable sources is adopted and a_h and c_h are fixed at 0.003 and 0.00625 respectively. To show the importance of considering a variable coefficient b_h, a simulation with a constant b_h equal to 0.25 is also done. As illustrated in Fig. 6, b_h with dynamic value ($b_h \in$ [0.1 0.4]) engenders a cost considerably lower (3087 < 4782.27). It is decreased by roughly 35% (in comparison of the cost resulting from constant b_h) which presents a critical result that exhibits how influential the dynamic pricing is.

All the costs presented in this paper are normalized (they are provided before the multiplication by the price unit that can be either 1Tunisian dinar (TD) ,1 Euro or 1 US Dollar (USD) for example). Also, the orders of the magnitude of the cost function coefficients are inspired by the PC pricing in Tunisia.

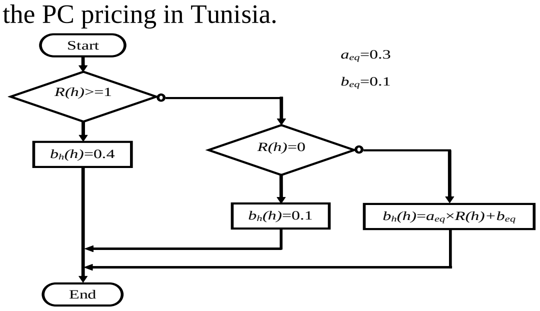

Fig. 5. The organizational chart of b_h coefficient value

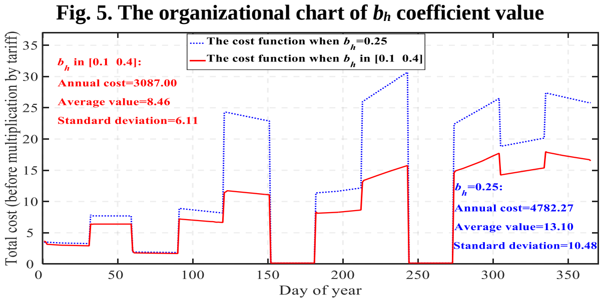

Fig. 6. The illustration of the total cost with different values of b_h

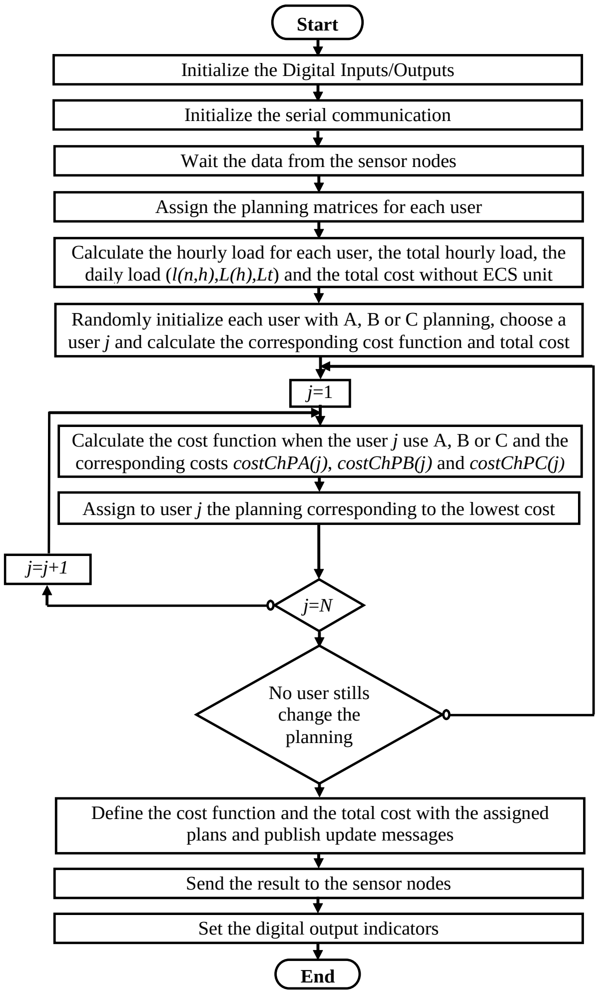

Fig. 7. The organizational chart of the energy sharing algorithm

4. THE ORGANIZATIONAL CHART OF THE CONSUMPTION OPTIMIZATION ALGORITHM

The algorithm decreases maximally the electrical energy cost without causing financial losses to the PC, but rather it provides profit for both: PC and the smart microgrid users. In addition, it simultaneously diminishes the consumption peaks through the fact that it shifts the load from peak hours to others with lower loads. Indeed, this alteration shifts the load from the highest tariff intervals. Subsequently, it avoids the high electricity bills by attributing optimal schedules to users. The proposed consumption optimization algorithm follows the organizational chart steps depicted in Fig. 7. The first step is to initialize the Digital Inputs/Outputs and the serial communication. Then, the system waits the data from the sensor nodes. The next step is to assign to each user his own three schedules: A, B and C. Next, the sharing algorithm computes the hourly load for each user $n \in N$, the total hourly load of the whole smart microgrid (*l(n,h)*, *L(h)*). And it computes the daily total load without ECS unit integration (*Lt*) also. After that, it adjusts the cost function and calculates the total energy cost before the utilization of ECS capacity. In the next step, it randomly initializes schedules to the set of users (A, B or C), establishes the energy cost function, and computes the equivalent microgrid cost. Later, it haphazardly selects a user $j \in N$ and adapts the cost function. In addition, it calculates its costs values with A, B and C plannings of this random user while keeping the previously assigned plannings to the rest of users. It calculates the corresponding whole costs too (*costChPA(j)*, *costChPB(j)* and *costChPC(j)*). At that moment, it considers the planning corresponding to the lowest daily cost as the optimal schedule for the user *j*. Immediately, the algorithm passes to the following user and repeats identical demarche until the set of users is attributed by their most optimal schedules (no user still changes his planning). After that, it adjusts the cost function and the total cost. Ultimately, it broadcasts the update messages, sends the result to the sensor node and sets the digital output indicators. The steps starting with the random attribution of plannings are repeated daily for an entire year.

5. MOVABLE PHOTOVOLTAIC PANELS

As previously illustrated in Fig. 3, the photovoltaic panels can be positioned in several inclinations (0 °, 30 °, 60 ° and 90 °). In the case when the photovoltaic panels become movable, they daily follow the inclination corresponding to the greatest photovoltaic production. The tracking is ensured by a tool called a tracker which is used to automatically position the solar module at its optimal inclination. Thus, with the same quantity of PV (surface covered by PV), the production becomes higher. The red curve, in Fig. 8, shows the photovoltaic production of a movable PV.

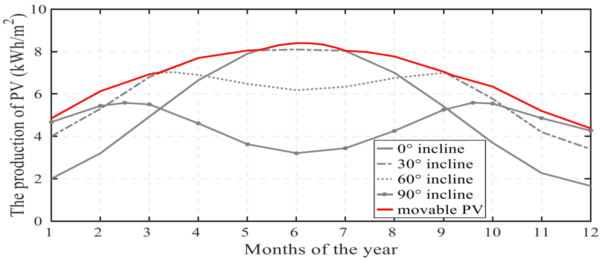

Fig. 8. The production of a movable PV

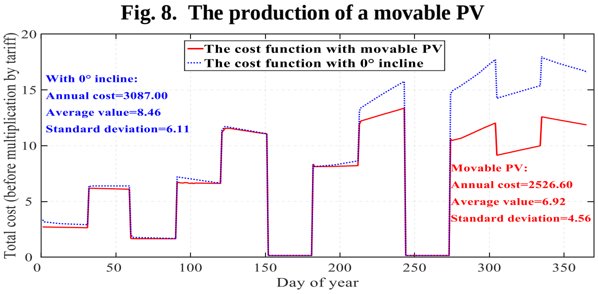

Fig. 9. The illustration of the total annual cost of horizontal and movable PV

The cost variations during a year in the two cases when PV module inclination is equal to 0° and when its inclination is variable (movable) are illustrated in Fig. 9. The curve in blue shows the cost of the first case which is already used for all previous simulations and the curve in red corresponds to the movable PV. The latter is constantly inferior to the other except at day intervals [70 90], [120 190] and [245 270] in which the two curves coincide. The total annual cost of the movable panels is equal to 2526.60 which is lower than the cost 3087 generated by panels located at 0° incline. It corresponds to a reduction of 18% in comparison to the cost resulting from horizontal PV. In conclusion, it is essential to adopt mobile photovoltaic panels to improve the performance of the smart microgrid.

6. HARDWARE IMPLEMENTATION

6.1. Architecture design

The practical energy consumption scheduler solution consists of distributing, at the start of each day (time 00:00), the optimal planning to the entire intelligent microgrid to guarantee the lowest cost. This optimal planning is automatically indicated by light indicator. The general architecture of this intelligent electrical network essentially includes three parts: acquisition board, central board and user node board. It is a star topology based on the JNET protocol stack with JN5148 nodes. The "acquisition board" part is only used to control the production arising out of renewable sources, while the energy estimation is established by the models already described in this paper. Fig. 10 describes the architecture design of the smart microgrid application.

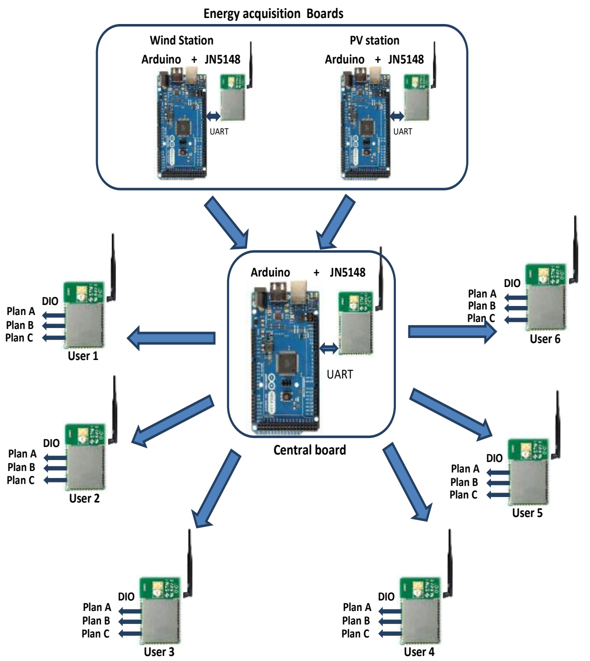

Fig. 10. The illustration of the architecture design

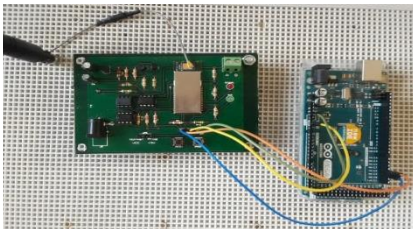

Fig. 11. The illustration of the central control board

Fig. 12. The illustration of the user control board

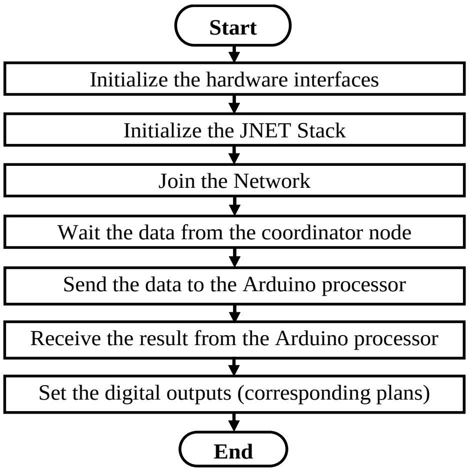

Fig. 13. The organizational chart of the node operation

6.2. Central control board

The central board consists of an Arduino Mega board. It implements the proposed algorithm associated to a JN5148 coordinator node to improve the temporal performance. Accordingly, the JN5148 is concerned with the protocol stack execution. Fig. 11 depicts the central control board illustration and implementation and also an example of execution.

6.3. User control board

The user node only includes a JN5148 router. It receives the frame from the coordinator node (central board) in the form of a text message (example A1). The card incorporates a connector allowing to retrieve the digital output signals (DIO). In the case of this smart microgrid application, there is the possibility to either use three LEDs corresponding to the schedules associated with each user (A, B and C), or connect an LCD. Fig. 12 presents an illustration of one user control board.

Fig. 13 illustrates the organizational chart of the node operation. It starts by the initialization of the hardware interfaces and the JNET Stack. Then, the node joins the network and waits the data from the coordinator node. After that, it sends the data to the Arduino processor. Later, it receives the result from the Arduino processor. Finally, it sets the digital outputs (the corresponding plans).

7. RESULTS AND DISCUSSION

This section reveals the optimal parameters of a smart microgrid application example including the pricing and the solar module types (constant or dynamic and fixed or movable). The proposed energy sharing algorithm optimization is also discussed while proving its efficiency in reducing electricity bills. It ensures energy reliability as well as the lowest possible cost.

7.1. The prototype of the smart microgrid installation

The smart microgrid prototype is installed in the Digital Research Center of Sfax in Tunisia. It is made by the central transformer station (which presents the public company distribution and the central part of the proposed sharing system), six derivation blocks (which present the six users in the study) and two renewable sources. Fig. 14 shows the prototype of the central node used to test the efficiency of the proposed sharing algorithm. It is installed in the transformer station, computes the acquired data from all the energy analyzers, and executes the proposed algorithm. This central node includes:

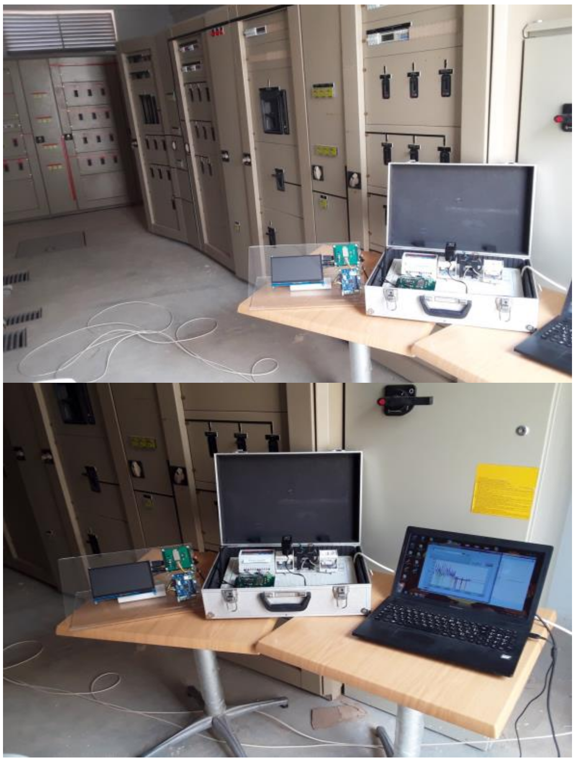

Fig.14. The prototype of the central node installed in the smart microgrid

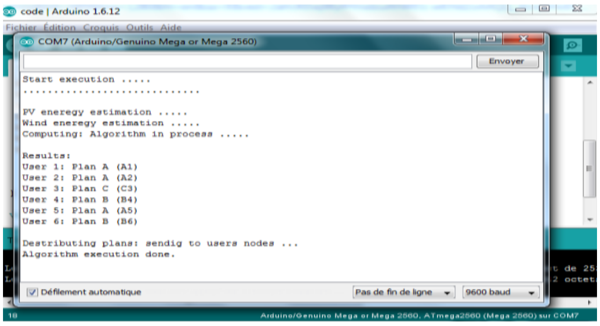

Fig. 15. An execution case illustration of the sharing algorithm

- Interface board to acquire data from the energy analyzer.
- Microcontroller board to read all the acquired data of the installation and executes the sharing algorithm.
- RF microcontrollers to ensure the communication between the different parts of the smart microgrid (sources and users).

The implementation is made for the level of the plannings sharing (as shown in Fig. 15). Whereas the simulations are performed to extensive studies.

7.2. Cost reduction performances

It is already mentioned (in section 3) that a_h and c_h are constants (a_h = 0.003 and c_h = 0.00625). As demonstrated in Fig. 6, the dynamic coefficient generates an improved result, i.e. the annual total cost engendered by the variable b_h is considerably reduced compared to the case when b_h is equal to 0.25 (3087 < 4782.27). The cost is lowered by more than 35% which presents a significant improvement and optimization that manifests the influence of the dynamic pricing on cost reduction. Therefore, this application applies dynamic pricing by assigning a variable value to the coefficient b_h of the energy cost function.

After applying the dynamic pricing and movable solar module, it is essential to examine the contribution of the proposed energy consumption scheduling algorithm in electricity bill reduction. Thus, Fig. 16 indicates the obtained annual total costs before and after applying the proposed algorithm. This sharing algorithm always leads to lower costs over a year. It guarantees almost 55% of the annual total cost diminution (2526.60 from 5607.60). It presents a crucial result that confirms the efficiency of this consumption optimization algorithm and indeed ensures its optimality.

In the case when the microgrid does not only consume renewable energy, but it sells the surplus that exceeds its need as well. At the end of the day, the set of users sell the extra to the public company of electricity. For the sale the same formula (1) of the energy cost function is adopted while keeping the dynamic value of the coefficient b_h. Here, there is no need for penalty or fixed charges, for this reason, the other coefficients are equal to zeros (a_h = c_h=0).

Fig. 17 illustrates the different annual total costs corresponding to the two cases: the microgrid sells or not the renewable energy excess. According to this figure, the electricity cost is negative (- 4986.18) when the surplus is sold. This negative value signifies that renewable consumption is lower than renewable source production during most days of the year. In this case, the average value of the daily cost is -13.66, so the microgrid users' income is higher than the money to pay to the PC, i.e. they earn money by selling the extra. Finally the overall result presents an optimum smart microgrid architecture that satisfies the energy required by users without paying an extra cost to the utility company.

Table 2 summarizes the different cases while showing the influence of the different parameters or assumptions used. It highlights the influence of the consumption optimization on reducing the annual total electrical cost of the smart microgrid. This optimization is mainly insured by the ECS units with a dynamic pricing and movable PV. Table 2 allows to compare the resulting costs. The analysis of this table proves the importance of implementing the ECS units which serves to reduce the cost by more than 14%. Also it indicates the improvement given by the dynamic pricing by contribution to the constant coefficient b_h. In addition, the movable PV has a significant role in cost minimization. Furthermore, the sale of surpluses, at the end of each day, makes users earn money instead of paying for electricity. So, counting on the contribution, even without selling energy excess, the annual electricity cost decreases from 5607.60 to 2526.60 (almost 55%).

Table 2.The annual costs resulting from the different parameters used in different cases

Cases							The annual cost (before multipli-cation by tariff)
ECS units	The coefficient b_h= 0.25	The coefficient b_h in [0.1 0.4] (dynamic pricing)	Photovo-ltaic panels with 0° incline	Movable PV(0°, 30°, 60° or 90°)	Without selling excesses	With selling exces-ses	
not used	used	not used	used	not used	used	not used	5607.60
used	used	not used	used	not used	used	not used	4782.27
used	not used	used	used	not used	used	not used	3087
used	not used	used	not used	used	used	not used	2526.60
used	not used	used	not used	used	not used	used	-4986.18

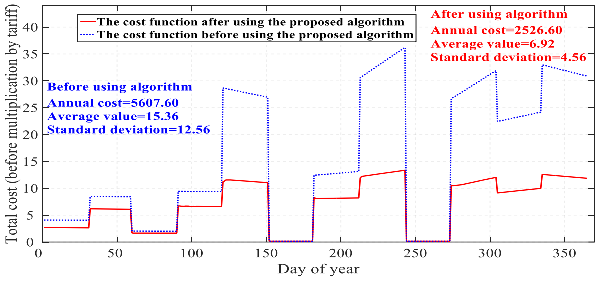

Fig. 16. The illustration of the total annual cost reduction

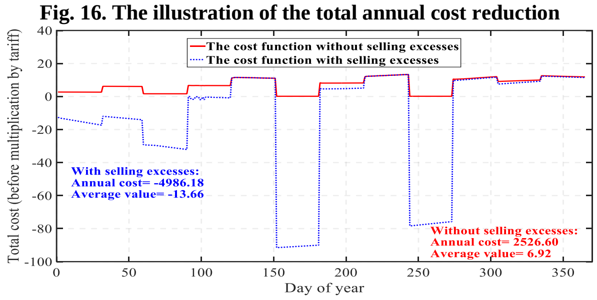

Fig. 17. The total annual costs when users sell renewable energy or not

7.3. The contribution of the proposal

The proposed energy sharing algorithm improves the efficiency of the microgrid on all levels. It starts at the level of energy production by ensuring optimal renewable production. The improvement is presented by optimizing the quantity of renewable production with a minimum of sources installation. The movable PV panels achieve it. For the distribution level, thanks to the ECS capacity, this proposed demand-side management program guarantees reliable scheduling that respects the consumption profile of each user. It leads to rationalizing the energy. As for the consumption phase, this proposed incentive-based algorithm matches the needs of users with the optimal electricity consumption. Adding those optimizations to the dynamic pricing leads to decrease as much as possible the electricity bills. The total annual cost reduction of the whole smart microgrid reaches almost 55%. The proposed algorithm also limits the creation and the manifestation of the peak hours. So, unlike almost all the real time pricing algorithms (RTP), it succeeds to achieve this immense percentage of the cost decrease while skipping the PARs problem. If necessary, it shift the usage of a limited number of shiftable appliances from the peak hours to lower-load ones. So, it does not annoy the users contrary to the direct load control (DLC) programs where the utility company holds all power to remotely control many devices. Despite the dynamic pricing integration, the proposed algorithm did not bother or annoy users' private lives contrary to the real-time pricing algorithms. In fact, it calculates the hourly energy price and sends it directly to the conventional energy producer without the intervention of the users. Then, in case of users load, the utility invoices the consumption. As mentioned in section 3, the renewable production assumption counts on data taken from real renewable installations. Subsequently, the simulations are realistic unlike impractical results of some other studies that are characterized by reliability lack. Those works include several programs that implement stochastic frameworks such as the day-ahead two-stage stochastic multi-objective framework and the scenario-based stochastic programming approach. They also involve the market studies that use unrealistic objective functions as both intra-day and day-ahead markets studies. In addition, the main contribution of this proposal is the cost reduction which is considerable in comparison with the results of other suggested methods like the linear programming. The proposed algorithm decreases as much as is achievable the electrical energy cost. It succeeded in diminishing the smart microgrid annual cost by almost 55% without causing economic losses to the utility company. But better than that, it provides profit for both: conventional energy producer and the smart microgrid users. Furthermore, it can even insure a financial income by selling the surplus of renewable power.

The simulation is executed by assuming that the smart microgrid covers 6 households (users) and three different schedules that organize the operation of a set of devices are associated with each user. To achieve better results, these assumptions can be developed, especially by the augmentation of schedules number.

8. CONCLUSION AND FUTURE WORK

In this paper, an incentive-based sharing algorithm with energy consumption scheduling capacity is proposed. It mainly decreases the annual electrical bill of smart microgrids by almost 55 %. It also diminishes the peak-to-average ratios that serve to avoid breakdowns and balance the whole residential load by reaching a mutual equilibrium point between consumers, sources, and sources-consumers. It improves the efficiency of the microgrid energy, starting with the production passing to the distribution and going up to the consumption phase. This application is a multi-source, multi-consumer installation when several participants or users share the same sources. The utility company is considered as the common conventional source, whereas the shared renewable energy was generated by photovoltaic panels concomitant with wind turbines. This demand-side management program daily assigns to the participants the optimal energy schedules that their totality provides the lowest total daily cost and so on for a year. Each user keeps the same daily consumption, but the optimization algorithm adopts a different energy distribution that guarantees the minimum cost for the whole microgrid. The system shares the energy by integrating the optimal renewable installation (number of wind turbines and PV surface and tilt) and the most suitable parameters of the energy cost function. In practice, the architecture presents a star network based on the JNET protocol stack, which essentially involves three parts: central board, acquisition board, and user node board. Thanks to the Arduino board and JN5148 nodes, the algorithm is implemented. Eventually, the results validate the algorithm's effectiveness and high performance, yet there is always room for further improvement.

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