Journal of Engineering and Computer Sciences
Qassim University, Vol. 9, No. 2, pp. 121-137 (July 2016/Ramadan 1437H)

Optimal Dispatch of Smart Electrical–Power Micro–grids Based on Renewable Energy Resources Part II

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(Received 21/5/2016, accepted for publication 1/9/2016)

Abstract. This paper is the second part of two and presents the optimal operation scheduling of a real case of renewable energy resources connected as a micro–grid. It consists of a wind turbine, a solar unit, a fuel cell and two storage battery banks implemented at the Laboratory. The algorithm proposed in the first part has been used as SCADA software to operate the generation units, assuring a global functioning of all equipment's efficiently, taking into account the maintenance, operation and the generation measurement and control considering all involved costs. The optimal dispatch software acts similar to a simple personal computer network to link together seldom–used equipment (standby)and all loads allowing its optimal control by a mini Supervisory Control and Data Acquisition (SCADA) system and Programmable Logic Controllers (PLC) devices.

The application of the methodology to a real case represented by a small power system connected as a micro–grid for one week period optimal scheduling, one week power dispatch, demonstrates the effectiveness, and the robustness of the proposed model. The low execution time for solving 672 MIQP problems simultaneously is also verified in this research work. The proposed model helps operation engineers to minimize the operation cost of generating units and storage systems by an intelligent optimal method, taking into account the reliability expressed in the undelivered energy cost.

Keywords: Micro–grids, Smart–grid, SCADA, Scheduling, Optimization.

1. Introduction

A huge reorganization of the traditional distribution networks toward active networks characterized by a high penetration of Distributed Generation (DG) units, based on technologies such as internal combustion engines, small and micro gas turbines, fuel cells, and photovoltaic and wind power plants is seen in the last few decades. Distributed Energy Resources (DER) has been receiving increasing attention as alternatives option to centralized energy resources. Thus, developing more DERs can cut down on cost for construction projects of large power generating plants and transmission lines. Use on–site generation may be an attractive option, since it alleviates the need for building the costly transmission grid. Moreover, a micro–grid can play significant role to enhance local reliability, reduce feeder losses, support local voltages, voltage sag correction, or provide uninterruptible power supply functions [1].

In [2]it is shown that DERs can be connected to load points within the distribution and/or transmission networks.

A set of energy resources working co–operatively to create a cost effective, reliable and environmentally friendly energy provision system has also been presented. The particular emphasis of this research work is on why a micro–grid is different from centralized generation or other grid–connected decentralized distributed energy resources. Specifically, the method explicitly defines the time period that the micro–grid is expected to operate in islanded mode and autonomous (off power grid). This method were applied in United Kingdom to a set of commercial load profiles, under better current estimates of the energy prices and technology capital cost to determine the investment attractiveness of micro–grid implementation.

In [3], a control strategy for inverters based on DGs and a protection scheme are carried out and the coordination between them is proposed to control both voltage and frequency during islanded operation.

In [4] the issue of the autonomous control of micro–grids is addressed. However, in [5], several schemes for sharing power between generators in micro–grids are compared and the minimization of fuel use in a micro–grid with a variety of power sources is then discussed.

In a power system, not only the daily load curve can be well estimated or measured, but also the weekly and yearly one. The estimation could be based on statistical, analytical or technological models. Power system contains several elements that can be characterized as follows:

- Load–The power system contains controlled and uncontrolled loads. The load curve can be well forecasted. In this case, the loads have been forecasted for one week–672 periods 15 minutes each.

- Generator–The generators have a set of technical constraints that are minimal/maximal power capacity limit, fuel amount consumption (total generated energy) and speedup ratio.

- Storage–The electric energy cannot be stored economically. Only small energy systems use super capacitors and batteries, the greater systems contain pumped water storage, pressurized air, hydrogen generator, etc. The storage units have double characteristics: these are loads with limited capabilities, and later they may turn into generators. Due to the power losses in the transformation procedure, the storage would never reach to 100% of efficiency. In this paper, two battery banks have been used as storage systems.

Nowadays there is an upward trend for using small isolated power systems, against centralized power producer systems when regarding rural and distant places.

In this type of system the most important producers are the renewable energy sources (e.g., photovoltaic panels (PV), fuel cells, wind turbine etc.) in combination with diesel generators. These small power producing networks need a distributed and autonomous generation control.

In [6], a review and analysis of the main characteristics of electrical micro–grids and the systems based on fuel cells for poly–generation and hybridization processes is presented. In this reference, the context of DER includes some emergent technologies for electrical generation, cogeneration and tri–generation, such as: fuel cells, gas micro–turbines, Stirling motors, costs of photovoltaic systems and wind generators. These technologies participate as active devices in electrical micro–grids, which can operate in a low voltage distribution network or an islanded network. The configuration is used to supply electricity, hot water, cold water for air conditioning in buildings. In this practical application the Solid Oxide Fuel Cell (SOFC) technology has been used in order to maximize the benefits of technologies working together rather than separately.

In [7] a control strategy for micro–grid is developed. The micro–grid consists of a fuel cell power module and two synchronous generators in a stand–alone environment. The load–sharing in micro–grids involves a fixed frequency inverter–interfaced dominant energy source. It is shown that traditional load–frequency control scheme is no longer applicable. To alleviate such a problem, a new load–sharing control strategy based on load–voltage characteristics has been proposed.

This paper deals with an optimal management of renewable energy resources connected as a micro–grid working not only under isolated operation but it may also work while connected to a LV power distribution grid. This micro–grid is controlled by a SCADA Software, which has been tested in the Laboratory. This control can be handled via Internet (IP) or IP–Phone, where the micro–grid becomes an intelligent grid. The optimization problem has been described on part I of this research work, which is managed each 15 minutes time interval (one week and 672 periods) by the micro–grid central controller located at one of the generation buses. The problem is formulated as a MIQP model and is solved by a deterministic optimization technique based on CPLEX [8], implemented in General Algebraic Modeling Systems (GAMS). This algorithm is used as SCADA software in this paper that is part II of this research work. A SCADA Software can operate the distributed generation units, assuring a global functioning of all equipment's efficiently, considering the maintenance, operation and the generation measurement and control with all involved costs considered. The Virtual Power Dispatch (VPD)software acts similarly to a simple personal computers network to link together seldom–used equipment's(standby)and all loads allowing its optimal control by a mini Supervisory Control and Data Acquisition (SCADA) system and Programmable Logic Controller (PLC) devices.

This paper is organized as follows: Section 2 deals with the Optimal Dispatch of the Renewable Energy Resources. Section 3 presents the details of the Laboratory equipment. Section 4 presents the Test Case and the discussion of the obtained results. Finally, Section 5highlights the main conclusions.

2. Renewable Energy Resources Optimal Dispatch

The main idea is to achieve the optimal operation of the micro–grid power system by a virtual way. This virtual is based on Internet using of the available communication protocols. The Laboratory consists of the mini Supervisory Control and Data Acquisition (SCADA) equipped with an Industrial computer acting as the communication gateway for local and remote operators, and MOVICON™II [9] software that can be integrated with MATLAB programming language[10]. MATLAB can also be integrated with the General Algebraic Modeling System (GAMS). The GAMS is specifically designed for modeling linear, non–linear and mixed–integer optimization problems.

The system is especially useful with large, complex problems. GAMS system is available for use on personal computers, workstations, mainframes and supercomputers. In this paper, the model exposed in section 3 of Part I of this research work has firstly been coded in GAMS system.

The data base is performed in MS Excel, and finally this data is sent to the GAMS coded model for running the adequate solvers. The obtained results from GAMS systems are sent as a file which would be read by MOVICON™ II system. This system is used as a programming language to communicate the decision to interruption devices equipped by PLC devices. This system is also used for limiting all equipment and loads to optimal obtained values. The mini SCADA has a connection to Internet provider via Modem. Future development may reveal that a web–site or a wiki can be built for optimally managing all this installation via internet using the available communication protocols. Authors of this paper think that future development of this work should be done, to gradually emigrate to the application of IP–Phones to allow users to widely control the equipment while taking the Electricity Market dynamic prices into account.

SCADA algorithm (the developed optimization model, section 3 of this research work) takes advantage of the emerging trend towards micro–grids made up of DG assets, linked together using secure, cost–effective communication network technology and controlled by a remote Dispatch Workstation. The SCADA Software does not only dispatch existent technologies in the laboratory, but it can also dispatch the neutral assets of others equipment such as diesel and natural gas generators, micro–turbines, steam and combustion turbines, wind–diesel hybrid systems, fuel cells, and other renewable and energy storage systems technologies if existed.

For this purpose, the authors propose a Web portal for future which will give consumers insight into their energy use and information for better home energy management. Some customers can also choose to install in–home automation tools, giving them increased control over home energy usage.

The associated costs of these interconnections are proportional to distance between grids, being an important restrain to this application type. These interactions have to be done at LV level to maintain a good voltage level and to reduce the distribution active power losses.

At the heart of the micro–grid, the VPD acts like a Distributed Energy Management System (DEMS). The system provides information and displays the present status of systems, generates prognoses and quotations of all connected equipment, and controls electric power generation of each unit according to its type as scheduled obeying the optimization model of the Part I of this research work. The system overview is subdivided into producers and loads, contracts in the future, and power storage systems. Conveniently positioned at the center of the display is the “balance or equilibrium node” (the sum of the incoming and outgoing power must equal zero). Additional information is provided on "forecasting and usage planning" and "monitoring and control." As a result, a portfolio manager may be able to display by color bar graphs showing the power generated by specific equipment.

Before a quotation is placed on the energy market through an energy trader, it is checked and approved by the portfolio manager. Once it has been approved and accepted by the market, DEMS generates an operating optimal schedule for the individual power unit in the virtual producer. The schedule specifies exactly when and how much power must be available from which producer. All this aspects can be included on the presented algorithms.

In the near future, the communication systems that ensure reliable connections between the control center and individual power generation unit will be via wireless communication modems. The advantage of this approach is that, it requires no costly cables or rented landlines at the level of real–world power system.

3. Renewable Energy Resources Equipment for Testing the Methodology

The Micro–grid power system connected in the Laboratory consists of a small renewable energy system that integrates a wind turbine, photovoltaic panels, a fuel cell unit and other equipment. The test system is implemented at the roof of a building (see Fig.1) and other equipment are installed on its interior.

(a)

(b)

(c)

(d)

Fig. (1). Elements of the Intelligent Renewable Micro–grid power system; (*a*) Solar panels and wind turbines installed, *(b)* Batteries implemented, *(c)* Inverters, *(d)* converter and regulator.

The equipment of power generation is with the following characteristics:

3.1 Photovoltaic Modules

Two photovoltaic modules–Kyocera, composed by 54 multi-crystal cells each one.

Electrical Performance

PV Module Type KC200GH–2P

At 1000 W/m^2 (STC)

Maximum Power (WP)	200 W	Maximum Power Voltage	1000 V
Maximum Power Current	7.61 A	Open circuit voltage (VOC)	32.9 V
Short–circuit current (ISC) [A]	8.21 A		

At 800 W/m2 (NOCT)

Maximum Power (WP)	142 W	Maximum Power Voltage	23.2 V
Maximum Power Current	6.13 A	Open circuit voltage (VOC)	29.9 V
Short–circuit current (ISC)	6.62 A		

- Tracking systems – DEGERtraker 300EL;

The "DEGERenergie" tracking system not only helps to exploit every minute of sunshine irradiation, but also to make the best use of diffuse light–all year round. This leads to an added solar energy yield of 35–45% for dual–axis tracking systems. The result is increased efficiency and thus, shorter amortization times or higher profits.

3.2 Photovoltaic Inverter–Sma;

Inverter type Sunny boy SB1100

Input (DC)

Max. DC input power	1210 W	Max. DC voltage	400 V
PV voltage range, MPPT	139–320 V	Max. input current	10 A
Number of MPP trackers	1	Max. number of strings (parallel)	2

Output (AC)

Nominal AC output power	1000 W	Max. AC output power	1100 W
Max. output current	5.6 A	Rated AC voltage	180–260 V
Power factorcos φ =	1	AC connection	Single–phase
Max. efficiency 93 %	Euro ETA	91.6 %	

3.3 Wind Turbine–Type: Whisper 200;

The Whisper 220 nominal power generation is 1000 W at 11.6 m/s and 24 V. Monthly production (day and night) approximately, 200 kWh/month. The versatile Whisper 200 powers applications from remote homes to water pumping. The blade is of 9–foot (2.7 m). A high voltage model is available for transmission over long distances.

3.4 Turbine Inverter– Called "Steca";

Inverter Type Steca Compact 2600–24

Characterization of the operating performance

System voltage	24 V	Continuous power	2300 VA
Power 30 min.	2600 VA	Max. efficiency	95 %

AC input side

Input voltage AC 150–230 V Charging current adjustable 0–55 A

Max. current / power on transfer relay … 16/ 3.7 A/ kVA

Switching time transfer relay < 20 ms

DC output side

Battery voltage 19–32 V

AC output side

Output voltage AC 230 +0/-10% V Output frequency 50 ±0.05% Hz

Load detection (standby) 1–25 W

3.5 Storage Battery–Exide Technologies (12 Modules–24v);

Exide type designation OPzS SOLAR 190

Nominal Voltage per Unit (12 x 2 V)2 V/ 24 V

Nom. Capacity C120 1.8 VPC 25ºC190 Ah Short circuit current 1400 A

Constant–current discharge in A @ 25ºC

V_{PC}	1.85	120 h	190	
24		145	48 h	165

3.6 Fuel Cell–Type: Stack Np20;

The system FCBA/EV represents an application of a stack of fuel cells with Proton Exchange Membrane (PEM) for the combined production of electric energy and heat.

Output data:

Output electric power 20 W Maximum output power 24 W

No–load voltage 3.6 V Current during the operation ≈10 A

Voltage during the operation ≈2.0 A Maximum current 15 A

Hydrogen consumed during the operation ≈290 Nml/min

Gas supply:

Maximum voltage of fan 12 V Maximum absolute operating pressure of H_2 2.0 bar

Diameter of H_2 pipe/duct 3.18 mm =1/8” outer diameter

3.7 Fuel Cell Inverter–Sma;

Inverter Type Sunny Island 2224

Output Values

Nominal AC voltage 230 (202–253) V Nominal frequency (fnom) 50 (45–65) HZ

AC output power at 25ºC 2200 W AC output power for 30 min at 25ºC 2900 W

Nominal AC current (IAC, nom) 9.6 A Harmonic distortion of output voltage (kV_{AC})…< 4 %

Power factor cos φ = -1 to +1

Input Values

Input voltage 230 (172.5–264.5) V Input frequency (fext) 50 (40 to 70) Hz

Max. AC input current 25 A Max. input power 5.75 kW

3.8 Battery Data

Battery voltage 24 (16.8–31.5) V Max. battery charging current 90 A

Continuous charging current 80 A Battery capacity 100–10000 Ah

Max. efficiency 93.6 % Internal consumption 6 W

3.9 Load Data

Practically lighting bulbs, rated power: 20–100 W (controllable) plus 2700 W of resistive load and 1350 VA of inductive and capacitive load (Elettronica Veneta: RL–2/EV, IL–2/EV, CL–2/EV) which can be connected in single phase of three phase star connection at 220–380 V and 50 Hz.

3.10 SCADA System:

Software HMI–MOVICON™11

The software MOVICON™11 (Monitoring, Vision and Control) is used to interface the SCADA system with the Operator. MOVICON™11system provides a several tools for creating powerful visualization and control projects within few clicks. These tools can also be applied in transmission and distribution network projects.

The MOVICON™11 incorporates the technologies to control and to distribute information for better–management of the project. You could realize any type of supervision application, be it simple or complex without compromising the functioning and the performance of the system.

PLC devices Automation–XGB Series;

The PLC devices are used to switch the logic state of some equipment. The company Ls Industrial System provides the XGB module. The compact dimension, high performance and functionality are three important characteristics for the selection of this series.

Measurement System–CPM–51; The CPM series Multifunction Power Metering provide high accuracy measurement, display and communication (Mod–bus RTU) of all electrical and power quality parameters, including harmonic measurement total (THD) or Individual harmonic distortion.

They also have digital inputs and outputs and interface with versatile functions such as remote control, alarm, statistic and records.

• Storage – Storage maximum charging capacity: 4560 W x 2; Storage maximal power discharging capacity: 50 W

Many of them generate power in the form of direct current (e.g. PV, fuel cells) or in the form of alternate current at a different frequency from the required 50 Hz (e.g. wind generators, micro–turbine). Therefore, the system containing these sources requires a power electronic interface. The system is represented on Figs. 1 and 2.

The system can operate in connection with the grid or in an isolated system. In both situations, the control of all equipment is done with a centralized system of measurement and control. With this control system, it is possible to measure the generated energy by the wind turbine, photovoltaic panels, fuel cells, storage discharging and the energy consumed by the load. When implementing the central control, it is possible to regulate the fuel cell, the storage and the load for balancing the system according to the defined strategy [11].

It is also possible to compare the forecast values of wind turbine and photovoltaic panels' generation with the real values. This possibility improves the management of renewable energy resources.

The generation capability of the different units will be on–line monitored, and remotely switched by the scheduler.

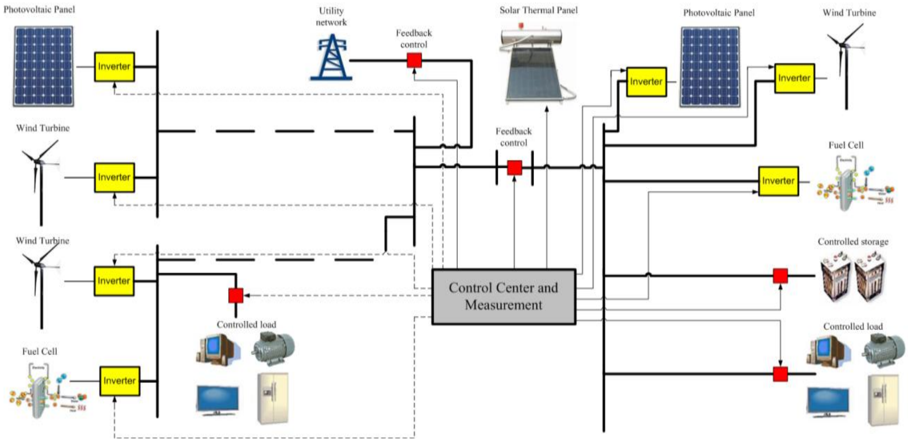

Fig. (2). Intelligent micro–grid control

When there is an imbalance between active power generation and active power load demand, the frequency deviates from its nominal value. Therefore, the isolated system should be able to maintain the frequency in an acceptable operating range to achieve power quality standards [12].

In a further extension of this research work, the remote switches will be realized on IP–Phone base, so the physical micro–grid will be extended to a fully virtual managed intelligent micro–grid.

4. Test Case

A real test system has been performed to illustrate the generality and the effectiveness of the proposed optimization methodology. This case study corresponds to micro–grid Laboratory of Renewable and storage Equipment (see Figs.1 and 2). The forecasted wind power generation, photovoltaic power generation and load used to perform the optimization model are shown in Fig. 3.

The time horizons can be fifteen minutes, an hour, a day, a week, a month or every fifteen minutes in a year (8760 h, 35040 time intervals which means 35040 MIQP optimization problems to solve simultaneously). The expected results of the optimization problems are the optimal operating scheduling of how the equipment's should be used by an optimal and intelligent way, and summary results for the considered scenario, such as the total cost, power generation in each time interval of fifteen minutes during one week scheduling, consequently, these above mentioned 672 non–linear optimization problems should simultaneously be solved.

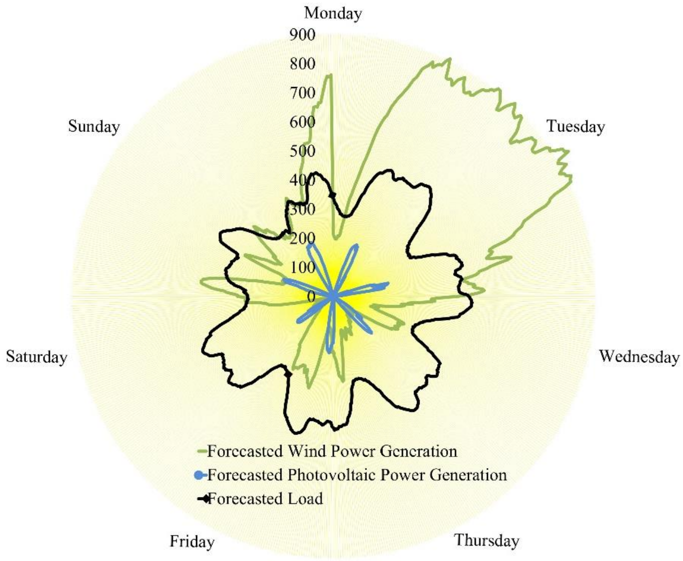

Fig. (3). Forecasted Wind Power, Photovoltaic and Load for one week–672 periods–15 minutes each

The optimization problem of Laboratory's equipment's has been analyzed for one week period, 672time intervals for each fifteen minutes sequential time. Generation scheduling needs the costs of each specific generation technology to be considered. In the context of intelligent grid towards smart–grid, it is expected that online dynamic prices provided by the electricity market to SCADA of the smart–grid via smart–metering. In this case, the considered prices are: Wind energy cost is 0.4 Eur/kWh; photovoltaic energy cost is 0.4 Eur/kWh; fuel cell energy cost is 0.9 Eur/kWh; storage energy discharging cost is 0.6 Eur/kWh; storage energy charging cost is 0.4 Eur/kWh; un–delivered energy cost is 1.5 Eur/kWh and the excess energy cost is 0 Eur/kWh. These values are determined to carry out the optimal scheduling of the equipment, but these costs are not limited to the mentioned values. This fact should not affect the proposed methodology, but of course the results, since these values are used on the optimization problem.

Some important results as well as the optimal renewable energy dispatch have been obtained taking into account the marginal cost of each generation technology and the forecasted wind power, photovoltaic power and loads.

For the application of the methodology a digital program in GAMS platform has been developed. The optimization problem has been tested on a PC compatible with Processor Core Duo CPU,U9400@1.40–GHz, 3 GB of random-access-memory (RAM), the Windows 7 Professional, 32–bit Operating System and GAMS compiler have been used. The average CPU time is 0.14s with 1787 iterations, solving at the same time the 672 Mixed–Integer Quadratic optimization problems.

Fig.4 depicts all resulted values of the Energy excess and the un–served energy obtained from optimal dispatch problem for one week from 00:00 of Monday January 10, 2011 to 23:45 of Sunday 16 January, 2011 respectively. In this figure, it is very clear that from 4:00 in Monday to16:15 in Tuesday the wind speed was very high (see Fig. 3). Consequently, the wind power generation is high accordingly; the load is less than the wind power generation and therefore, it may only be covered by this power generation type.

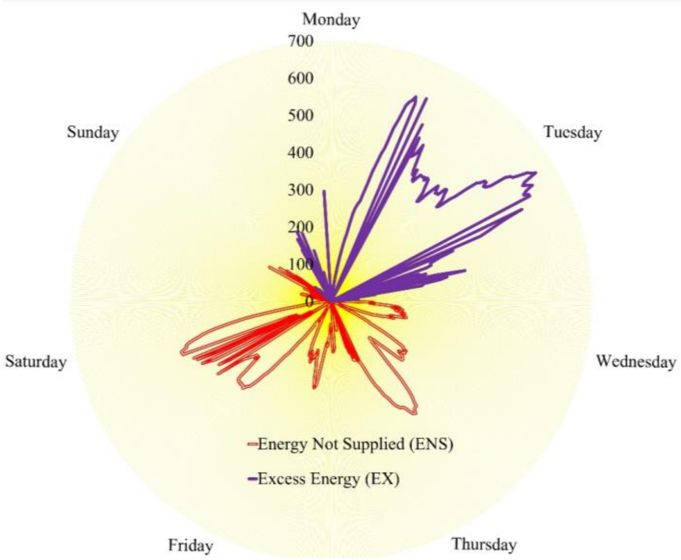

Fig. (4). Obtained results of energy excess and no–supplied for one week dispatch

Thus, in this case there are an exceeding power generations of different type. This exceeding power is not only used for battery bank 1 and bank 2 charging (see Fig. 5) but also the additional power could be injected to the main distribution grid. This scenario may also occur on some time intervals on Saturday and Sunday respectively, but with minor impact values (see Figs. 3, 4 and 5). On the same Fig.4, it can be noted the un–served energy occurs with different variation from the 00:30 of Wednesday to 3:15 inclusively. This un–served energy may be translated on loads shedding, which is intensified from Friday to Saturday inclusively. Other scenario of energy curtailment with certain intermittence takes place on Sunday, January 16 of 2011. These loads shedding may occur because the loads are more than the power generation. The storage systems (Battery Bank 1 and 2) try to alleviate the situation of this no–supplied energy, and therefore they have been discharged accordingly (see Fig. 5), but they cannot supply all loads due to its power capacities limit.

Fig.5 illustrates the batteries (bank 1 and 2) charging and discharging respectively. It can be noted that the time intervals of batteries (bank 1 and 2) charging corresponds to the time intervals when there is power generation in excess. It can also be observed that the time interval of battery (Bank 1 and 2) discharging correspond to the time interval of un–served energy.

Fig. 6 shows that the power generated by the Fuel cell is dispatched from 17:45 of Tuesday to 23:45 of Saturday when the loads are more than the overall power generated by other units.

Fig. 6 depicts the results of optimal dispatch of DERs connected into micro–grid. On this figure, it can be observed that the photovoltaic power is the main power source from Monday to Sunday and more exactly every day from about 8:00 to 17:00.

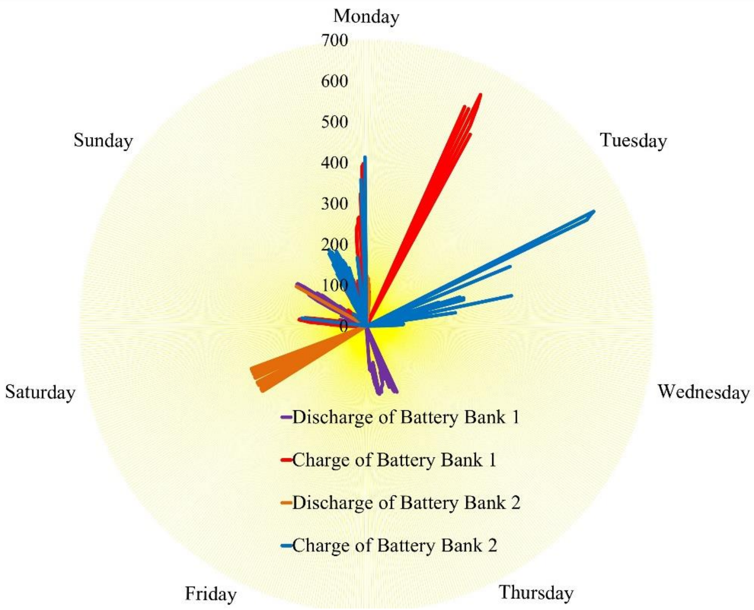

Fig. (5). Obtained results of charge and discharge of the storage systems for one week dispatch

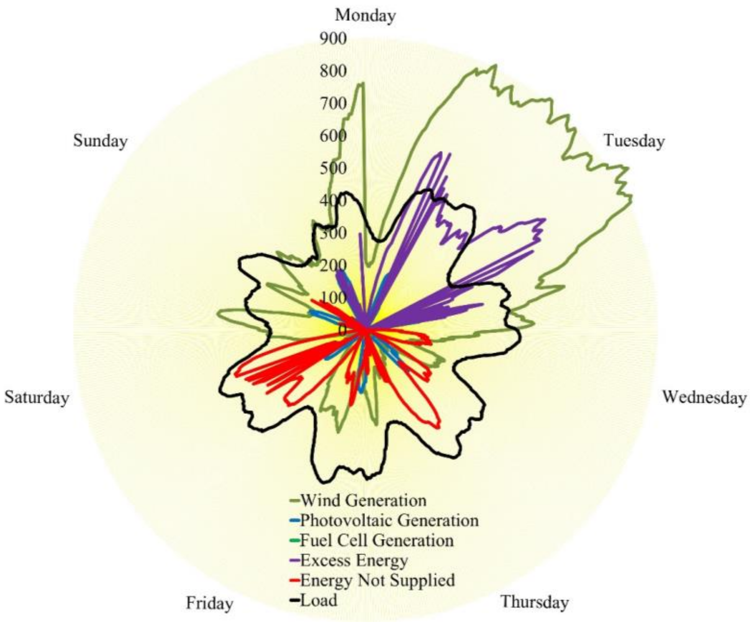

Fig. (6). Obtained results of optimal dispatch of micro–grid for one week dispatch

5. Conclusions

The proposed methodology of management strategy software has been implemented to a real micro–grid Laboratory through mini–SCADA and PLC devices. The application of the methodology for one week period, 672 time intervals, demonstrates the effectiveness, and the robustness of the proposed model. The low execution time for solving 672 MIQP optimization problems simultaneously is also verified in this research work to have a low execution time. The proposed model helps operation engineers to minimize the operation cost of generating units and storage systems by an intelligent optimal method, taking into account the reliability expressed in the un–delivered energy cost. Finally, the results show the applicability of this methodology for larger power system.

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التوزيع الأمثل لمصادر الطاقة المتجددة في شبكات القوى الصغيرة الذكية

الجزء الثاني

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(قدم للنشر في ٢١/٥/٢٠١٦؛ وقبل للنشر في ١/٩/٢٠١٦)

ملخص البحث. هذا البحث هو الجزء الثاني من بحثين ويقدم توقيتات تشغيل حالة حقيقية لمصادر طاقة متجددة متصلة بشبكة متناهية الصغر. الشبكة التي تم تنفيذها في المعمل تتكون من توربينة رياح ووحدة طاقة شمسية وخلية وقود وبطاريتي تخزين. ولقد تم استخدام الخوارزمي المقترح في الجزء الأول كنظام اشراف وتحكم وجلب بيانات لتشغيل وحدات التوليد مع ضمان الكفاءة العالية للمعدات آخذين في الاعتبار تكلفة الصيانة والتشغيل والقياسات والتحكم، وتتصرفت حزمة برمجة الإرسال الأمثل بطريقة مشابهة لشبكة حاسب شخصي بسيطة تربط المعدات الاحتياطية مع الأحمال محققا التحكم الأمثل بواسطة نظام مصغر للسيطرة والتحكم وجلب البيانات مع أجهزة تحكم منطقي مبرجمة.

ويظهر تطبيق الطريقة على حالة حقيقية عبارة عن نظام قوى صغير متصل بشبكة متناهية الصغر لمدة أسبوع كفاءة وفاعلية النموذج المقترح، ويساعد النموذج المقترح مهندسي التشغيل على تقليل تكلفة تشغيل وحدات التوليد ونظم التخزين بطريقة ذكية تأخذ في الاعتبار الاعتمادية لتكلفة الطاقة غير المزودة.