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

Part I

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Abstract. The scheduling of the Renewable Energy Resources generation units which feed the small loads in the context of micro–grid while considering all the technical constraints can essentially be stated as a Mixed–Integer optimization problem. This paper is the first of two and presents the mathematical formulation of the optimal operation scheduling of a micro–grid with the corresponding small loads considered as a deterministic optimization problem. This problem is formulated as a Mixed–Integer Quadratic Programming model (MIQP) due two types of variables, integer and continuous corresponding to the decision that must be taken into account and the output power respectively, while satisfying all technical constraints minimizing the total marginal power generation cost. This model is solved by a deterministic optimization technique CPLEX–based, and is implemented in General Algebraic Modeling System (GAMS).

In the second part, the implementation of the micro–grid power system based on renewable energy resources, which consists of a wind turbine, a solar unit, a fuel cell and two storage battery banks is described. The proposed algorithm presented in this first part is then used as Supervisory Control and Data Acquisition (SCADA) software to control the micro–grid. The SCADA software with Programming Logic Control (PLC)can control the generation units, assuring an optimal global functioning of all equipment, including the loads shedding when necessary, taking into account the maintenance, operation, measurement and control considering all involved costs.

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

Nomenclature

C_{w_i}	Energy cost coefficient (Eur/kWh) for energy generated by Wind turbine connected at node *i*
C_{Pv_i}	Energy cost coefficient (Eur/kWh) for energy generated by Photovoltaic panels connected at node *i*
C_{Fc_i}	Energy cost coefficient (Eur/kWh) for energy generated by Fuel Cell connected at node *i*
$C_{Sc_i}, C_{Sc_{2i}}$	Energy cost coefficient (Eur/kWh) for energy used for charging the battery bank 1 and

	battery bank 2 respectively connected at node *i*
C_{Sd_i} , $C_{Sd_{2_i}}$	Energy cost coefficient (Eur/kWh) for the energy discharge of battery bank 1 and battery bank 2 respectively
C_{ENS_i}	Energy cost coefficient (Eur/kWh) for the Energy not served to loads connected at node *i*
C_{EX_i}	Energy cost coefficient (Eur/kWh) for Excess generated energy at node *i*
P_{w_i}	Generated power by Wind turbine connected at node *i*(kW)
Nd	Nodes number of distribution network
P_{Pv_i}	Generated power by Photovoltaic panels connected at node *i*(kW)
P_{Fc_i}	Generated power by Fuel cells connected at node *i* (kW)
P_{Sc_i}, $P_{Sc_{2_i}}$	Storage charging power of battery bank 1 and bank 2 respectively connected at node *i* (kW)
P_{Sd_i},$P_{Sd_{2_i}}$	Storage discharging power of battery bank 1 and bank 2 respectively connected at node *i* (kW)
P_{ENS_i}	Un–delivered power (kW) at node *i*
P_{Ex_i}	Excess generated power (kW)
$Load_i$	Load power (kW) connected at node *i*
ΔP_i	Active power losses of distribution network due to power flowing through the line *I* (kW)
Z_{ij}	Conductor impedance(Ω)
t	Time interval (hour)
X_i, X_{2_i}	Binary variable corresponding to battery bank 1 and bank 2 charging respectively connected at node *i*
Y_i, Y_{2_i}	Binary variable corresponding to battery bank 1 and bank 2 discharging respectively connected at node *i*
P_{s_i}	Storage battery power state (kW)
P_{Wmax_i}, P_{Wmin_i}	Wind power generation capacity minimum and maximum limit respectively(kW)
P_{Vmax_i}	Photovoltaic power generation capacity limit connected at node *i* (kW)
P_{FCmax_i}	Fuel cell power generation capacity limit connected at node *i* (kW)
P_{Smax_i}, $P_{Smax_{2_i}}$	Storage battery bank 1 and bank 2 maximum capacity power limit respectively connected at node *i*(kW)
$P_{Sdinitial_i}$, $P_{Sdinitial2_i}$	Storage battery bank1 and bank 2 initial discharging power limit respectively connected at node *i* (kW)
P_{Scmax_i}, $P_{Scmax_{2_i}}$	Storage battery bank1 and bank 2 charging power limit respectively connected at node *i* (kW)
P_{s0_i}, P_{s02_i}	Storage battery bank 1 and bank 2 initial charging power respectively connected at node *i* (kW)
V_i	Voltage of bus *i* of the distribution network (V)
I_{ijmax}	Maximum current of the conductor *ij*, as extracted from conductor manufacturer catalog
ER	Engineering Recommendations
ER G59/1	Recommendations for the connection of embedded generating plant to the Regional Electricity Companies' distribution systems
ER G75/1	Recommendations for the connection of embedded generating plant to public distribution networks above 20kV or with outputs over 5MW
ER G83/1	Recommendations for the connection of small scale embedded generators (up to 16A per phase) in parallel with public low voltage distribution networks
ETR	Engineering Technical Reports
ETR –113	Notes of guidance for the protection of embedded generating plant up to 5MW for operation in parallel with Public Electricity Suppliers' distribution systems
IEEE Std.1547	IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems
IEC 11–20	Systems for the generation of electric energy and uninterruptable power systems connected to grids of category I and II and version V1

1. Introduction

Distributed Energy Resources (DER) have been receiving a great attention as alternatives to centralized energy resources. It has been accepted as a good option for future energy systems with respect to sustainable development and low–carbon society construction [1]. An attractive choice for conventional dispersed generating units, which also reduces the greenhouse gas emission and increases the energy efficiency usage is a small scale distributed generation resource independent of their types. Using on–site generation closer to the loads may be an efficient technical option, since it alleviates the need for building or reinforcement of the costly transmission and distribution grids. Moreover, a micro–grid can play significant role to enhance generation, transmission and distribution local reliability, reduce feeder active power losses, support voltages of the local buses by providing local reactive power, voltage sag correction, or provide uninterruptible power supply functions to their loads[2], [3].

As the DER systems penetration increases into distribution and transmission networks, their interconnection is developed to be grid–like which may adapt to the concept of micro–grid. The micro–grid concept is a cluster of distributed generation units and loads with all equipment's, serviced by a distribution system, and can operate (*i*) the grid–connected mode, (*ii*) the autonomous (islanded) and (*iii*) ride–through between the two modes[4] taking into account all necessary equipment of each above mentioned mode.

The European Community indeed is promoting and encouraging different projects initiatives from universities to European industries to support the research not only in this field, but also in the field of electric vehicles with a specific platform [5] and different calls within the FP7 framework program. The European directive 20/20/20 aligns with the interest in these systems which is increased by the possibility of implementing them on large scale renewable energy sources to limit greenhouse gas emissions by year 2020, and also reducing the transmission and distribution active power losses also by the same year 2020. The coordination of all these distributed generating units and their loads is a challenging issue that demands distributed intelligence infrastructure which is referred to Smart–Grids. In literature, few articles proposed operational solutions for micro–grids controlled by SCADA software making the grid intelligent, self–adaptive, self–balanced, self–monitored and therefore, operating as a Smart–Grid.

In [6]a linear programming model for cost minimization corresponding to unit commitment of generating units and storage system within a micro–grid has been developed. The results of this work indicate that a micro–grid can offer an economic option as a decentralized power generation. In this reference, the game theory technique has been used as a suitable tool to analyze the fundamental aspects of this scheduling problem.

In [7],it has been proposed an optimization model that is able to individuate the subdivision of a given distribution network into an optimized number of sustainable micro–grids, which is individually easy to solve. The algorithm provides the optimal configuration of micro–grids in an existing distribution system. Likewise, [8]presents a Mixed-Integer Linear programming (MILP) optimization model for the integrated plan and optimal evaluation of DER. In this model, given the loads sites, the local climate data, the utility local tariff structure, and the technical and financial feature on candidate to be chosen of DER technologies, the model minimizes the overall marginal energy cost for a test period by selecting the optimal units to install and determine their better operating schedules.

Interest in small isolated power systems could also be an attractive technical and economical option for power utility companies; since they can help improving the power quality, namely the voltage level and power supply flexibility, since they are acting as a small local power system. Also, they can provide spinning reserve and reduce the transmission and distribution networks costs by serving local loads, and can be used to feed the customers in the event of an outage in the primary substation [9].

In [10], a new formulation of unit commitment scheduling problem is presented. In this methodology, due to increasing execution time expressed by the binary variables, the benders decomposition optimization technique has been used splitting the problem in two parts, for solving the unit commitment problem efficiently. The scheduling problem is decomposed into two constrained optimization problems: a master and a slave. The master problem is formulated as Mixed Integer Programming and determines the optimal states ON/OFF of generating units, and then the step handles effectively the binary decision variables. The sub–problem or slave is formulated as a non–linear programming problem and assures the solution obtained by the master problem to verify all the technical constraints. This method appears to be suitable for solving a complex scheduling of a large micro–grid that is not the case under study.

In[11]an optimization model is proposed which determines the amount of power that micro–grid should exchange with wholesale local energy market so that the total benefit, that is the (Revenues–Costs) is maximized. The technical operation constraints of DER are included both the inter–temporal and non–inter–temporal constraint types.

In [12] a comprehensive survey of various islanding protection schemes is presented and developed. In this reference, a new idea that is keeping the DER connected during system disturbances and islanding operation and protection of DG is discussed. This idea is continuously debated upon by researchers across the globe. Actions are taken in this direction like efficient digital islanding protection scheme, which are being developed and also implemented. This idea is the contrary of the available technical recommendations G83/1, G59/1, G75/1, ETR–113, IEEE

Std.1547, IEC 11–20, where DG should automatically be disconnected from Medium Voltage (MV) and Low Voltage (LV) utility distribution network in case of tripping of the circuit breaker supplying the feeder connected to the DG.

In [13]an optimal scheduling of a renewable micro–grid in an isolated load area has been formulated as a MILP. The optimization problem is running for a period of one day (24 Hours) and 1 Hour time interval each. In [14] a scheduling of DER in an isolated grid has been proposed. In this reference, the optimization problem is stated as a MILP problem, which has been solved firstly by Branch and Bound optimization technique. The obtained solution is used by an artificial neural network (ANN) for training purpose aiming to finally use the ANN to better manage the DER. In [15] an optimal methodology for renewable energy dispatching in islanded operation has been proposed. The optimization problem is solved by MILP and also with Evolutionary Particle Swarm Optimization (EPSO). In this reference, the MILP has been demonstrated to be the more adequate optimization technique used to solve the stated problem by handling efficiently the binary variables. In all these references, the optimal scheduling is stated as MILP without minimization of the active power losses, without distribution network constraints and without considering the bus voltages.

This paper deals with detailed formulation of a micro–grid working not only under isolated operation but also when it is connected to a LV power distribution grid. This micro–grid is controlled by a SCADA Software and PLC technology. This control can be handled via Internet (IP) or IP–Phone, where the micro–grid becomes an intelligent grid. The problem is described next, 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, where the active power losses, the distribution network constraints and the buses distribution network voltages have been taken into account. This problem is solved by a deterministic optimization technique based on CPLEX [16], implemented in General Algebraic Modeling Systems (GAMS) [17].

This algorithm has been implemented into the SCADA. A SCADA Software can operate the generation units, assuring a global optimal functioning of all equipment serving all loads efficiently, taking into account all involved costs. This algorithm is an open software, which means all operators can configure the objective function and also the constraints according to his most adequate option. The SCADA software acts to link together seldom–used standby equipment and all loads allowing its optimal control by a mini Supervisory Control and Data Acquisition (SCADA) system and Programmable Logic Controllers (PLC) devices.

This paper is organized as follows: Section 2 deals with the Operation of Renewable Energy Resources. Section 3 presents the detailed MIQP mathematical formulation of the problem. Section 4 explains the optimization method used to solve the problem. Finally, Section 5 highlights the main conclusions.

2. Renewable Energy Resources Operation

The major challenge of this paper is to achieve the optimal operation of the micro–grid power system equipment by a virtual way. To deal with this challenge, it is necessary to formulate detailed optimization model, where all involved marginal costs are minimized subject to all technical constraints. This model may act as a SCADA software algorithm (the developed MIQP optimization model) that 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 SCADA Dispatch Workstation. The Software does not only dispatch existent generating technologies and loads in the Micro–grid power system, but it can also dispatch other equipment such as: micro–turbines, steam and combustion turbines, wind–diesel hybrid systems, fuel cells, and other renewable and energy storage technologies if existed.

The SCADA Software is able to create any number of virtual energy programs and provide the best solutions from the total dispatched energy resources available by controlling all generation equipment's and loads at certain optimal operation points. This allows power producers to select the kind of optimal operation generating units and the exact amount of dispatched power necessary to feed all loads. The software makes it possible to combine environmentally friendly micro generators such as fuel cells, solar cells, and micro–turbines that are becoming economically feasible through optimal dispatching and scheduling for widespread deployment. Another useful feature of the SCADA algorithm is its ability to transmit schedules results via internet to remote sites enabling generator sets to be deployed or tested at any time without the need for time–consuming site visits of operators and engineers.

On the context of this paper, the scheduling of DER controlled by the above mentioned SCADA system may lead to a new concept: the Virtual Power Dispatch (VPD).VPDs is the software controlling the multi–technology and multi–site heterogeneous entities. In the scope of a VPD, producers can assure that their generators are optimally operated and follow the optimization results of the scheduling problem. At the same time, VPDs will be able to achieve a more robust generation profile taking into account all involved cost and satisfying all technical constraints, raising the value of non–dispatched generation technologies [18].

The VPD can also operate in isolated networks when is necessary. In this type of installation the VPD can handle the system management and equipment functioning optimally. VPD can reduce maintenance and operation costs of the isolated system and increase its efficiency. The system management is made remotely, providing the possibility of controlling the aggregated producer's generation that may be connected to the network and at the same time all the isolated local power systems (generation and consumption). It is possible to manage several isolated grids at the same time. This type of management has many particular specifications, involving some adjustments to the VPD software. One of the differences is the combinatory goal.

The “normal” VPD has as primary goal of combining the generation of aggregated producers to sell the biggest quantity of programmed energy in the market, to remunerate the producers and to get not only its own profits, but also the costumers’ satisfaction. When VPD software is managing isolated grids the most important goal is to deliver the necessary energy to assure the optimal function of loads connected into isolated system. Therefore, it is necessary to manage the reserves and operation of controllable generation units (fuel cells and micro turbines).

The other important aspect that VPD has to consider in the isolated micro–grid operation is the necessity of controlling the generation and the end–users energy consumption and storage systems. Since, the system is isolated, the VPD usually has to shed some loads to maintain the system equilibrium or balance when the generation is not sufficiently enough, in this case, the storage system may be used if there is power enough. The VPD can develop Demand Response (DR) strategies, helped by smart–metering devices, to advise the users about a wrong electric energy usage or simply an overload or expensive cost during the load peak or other considered expensive period. It is expected that developing an auto–balancing, self–monitoring power grid will give utility customers real–time information about their energy usage, and thus allow them to manage their energy consumption more efficiently and with rational cost when appropriate. Large power systems of the future which will certainly seek considerable savings in their costs should take the following actions into account in their VPD management: changes in customer energy management, better grid reliability, greater energy efficiency, increased use of distributed renewable energy sources and support for plug–in hybrid electric vehicles and intelligent–home appliances.

In isolated micro–grid operation mode, the VPD has control of all the system; therefore, it has voltage and frequency control methods and mechanisms that permit to adjust technical constraints to obtain an adequate quality service to the consumers´ demands.

VPD is a Distributed Energy Management System (DEMS). The system may be sophisticatedly elaborated to display the present status of systems on each operation point, generates prognoses and quotations, and controls electric power generation of each unit according to its type as scheduled by the optimization model. The system overview is subdivided into power producers and loads consumptions, contracts in the future, and power storage system. Using installation status information, such as electric power output, and combining it with electricity market price forecasts, DEMS generates, a forecast that also takes into account the next day’s (day ahead) or online dynamic prices and the total power available for sale. Even weather data is factored into the energy management system to provide a forecast of the power available from distributed generation sources with fluctuating availability, such as wind and sunshine.

Optimal DEMS algorithm shows the generation–loads status of all systems included in a virtual power producer and generates an operating schedule for its power generation. This schedule is controlled in the demand side mode.

3. Problem Formulation

In this research paper, in order to reach an overall optimum of the operation of the micro–grid system, the optimal generation–loads scheduling problem is formulated as a MIQP model. It has been developed aiming to find the optimal scheduling of the distributed renewable energy units, storage systems and its corresponding operation strategies during a specified time period. This model is very flexible due to the inclusion of all costs: investment cost, operating cost, maintenance and running cost among others. The Economic dispatch problem is one of the fundamental issues in power systems operation and scheduling. Essentially, it can be stated as an optimization problem aiming to minimize the total generation cost, while satisfying all technical constraints formulated for micro–grid system.

The optimization model has integer and continuous variables. The integer variables express the decision of equipment, the on–off status operation of distributed generation units, as well as the existence of energy storage devices. The continuous variables express the input and output power flow of the systems components.

The problem formulation of the small power system is developed as a VPD operation in an isolated grid. However, it may be connected to the distribution network. Fig.1 presents the scheme that can be used in the power balance formulation which is the basic rule of any power system.

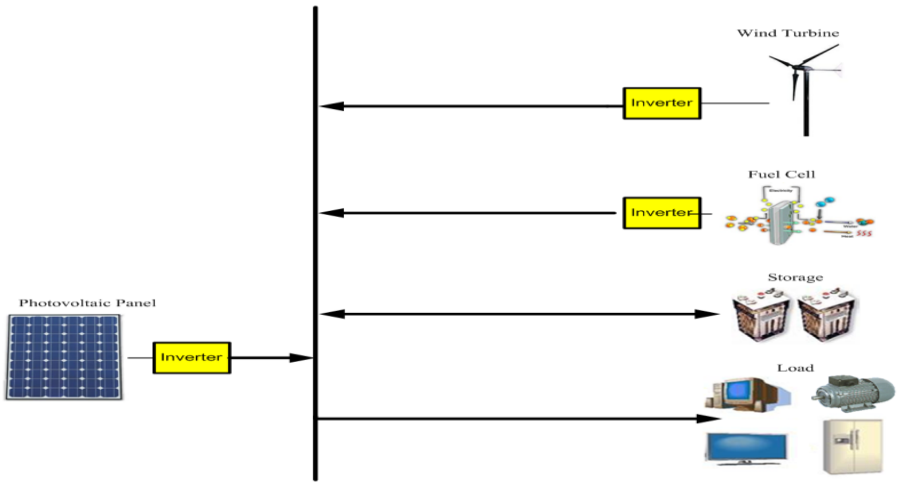

Fig. (1). Micro–grid power system equipment operated as an isolated system

To determine the optimal generated power by wind, photovoltaic, fuel cell units and the storage batteries banks charging and discharging, the optimal operation is formulated taking into account the following considerations:

• The wind power generation strongly depends on the weather conditions. The generation capability limits can be estimated or calculated in advance for the considered time period. In this case is for a period of one week each 15 minutes time interval (672 time periods). Wind energy is dispatched during the mentioned time period due to the low generation cost in Eur/kWh;

• The photovoltaic generation can also be well forecasted, too; in this case, is for one week each 15minutes time interval.

• The fuel cell has limited power output for a long time, but the total generated energy is determined by the amount of the hydrogen fuel;

• The storage discharging is limited for maximal power discharging capacity and existing storage energy; in this case, two battery banks have been considered independently.

• The loads are forecasted considering several aspects, however most of the loads can be controlled between upper and lower limits (this is the DSM–Demand Side Management); in this case, is for one week each 15minutes time interval.

• To system balance, the VPD can settle terms of reserve. For example, the VPD can limit the minimum reserve to the specific percentage (%) of Forecasted load. This reserve can be assured by storage system and fuel cell units.

The main objective is to carry out an optimal dispatch taking into account all the aforementioned considerations. The expected result will be the following priorities and according to the generation price types: in this paper the First considered generation due to its price is the wind; the second considered is photovoltaics' and the third is the Fuel cell (if it is necessary). The surplus of energy is used for charging the storage battery banks systems. The different units have different costs, as well. The wind and solar energy are cheaper, or with low cost. The storage energy has been limited; the hydrogen based fuel cells have expensive cost and limited capacity. It is only used as an emergency power reserve.

This continuous constrained portfolio MIQP problem is solved by CPLEX in GAMS platforms will be seen next.

The optimal schedule of the demand and generation units can be made for fifteen minutes, one hour, and one day or for one week. Thus, it depends on the load forecasting, for wind and photovoltaic energy generation forecast and other available data.

The problem constraints have been elaborated considering the five different operation modes here presented:

1.There is a surplus of energy to store (for more details see Fig. 2).

2.The primary power generation is not enough; therefore, the battery or batteries banks are discharged. In this case a specified percentage (%)could be considered.

3.In case of the lack of primary power generation (no wind blooming and/or sunshine irradiation) the battery or batteries banks and Fuel Cell come into operation (see Fig. 3).

4.In case of the lack of energy on the storage systems, only Fuel Cell comes into operation due to its availability as distributed power generation unit.

5.In insufficient energy generation case the load must be shed to maintain the load and generation balance. In this case, there are specified values of un–served energy which is determined by optimization problem solution.

6.In case of all loads and storage systems have been satisfied, then an excess of power generation may exist. In this case, this excess of power may be injected to the main grid (the distribution network) with a predetermined accorded cost per kWh, of course, if it is permitted. In this paper, due to the actual legislation, power injection from a small user to the main grid is not allowed. Therefore, in this case the cost is considered zero. This does not present any limitation of the proposed methodology, it may be considered, but in this case, the obtained results could be different.

The main propose is to find the minimal marginal cost for a 672 periods, each 15 minutes during a week schedule. However, it can be extended to a month or a year. In this case, the proposed methodology is still valid.

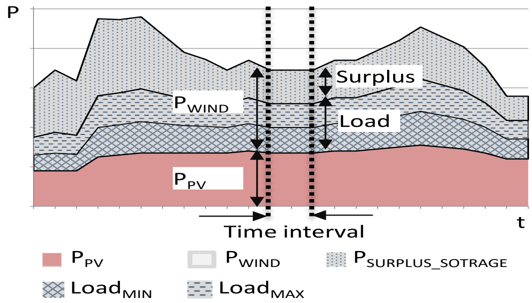

Fig. (2). Problem constraints considering operations modes: surplus of primary energy

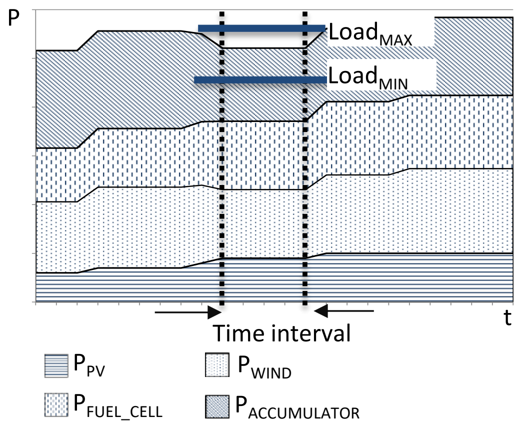

Fig. (3). Problem constraints considering operations modes: storage and fuel cell are in operation

The objective function is similar to [13], but the principal difference is the cost of the active power losses occurring into distribution network lines. This function is stated as follows:

$$Min\, f = \sum_{i=1}^{Nd}\sum_{t=1}^{n} C_{w_i}(t)\cdot P_{w_i}(t) + C_{Pv_i}(t)\cdot P_{Pv_i}(t) + C_{Fc_i}(t)\cdot P_{Fc_i}(t) + C_{Sd_i}(t)\cdot P_{Sd_i}(t) + C_{Sd_{2_i}}(t)\cdot P_{Sd_{2_i}}(t) - C_{Sc_i}(t)\cdot P_{Sc_i}(t) - C_{Sc_{2_i}}(t)\cdot P_{Sc_{2_i}}(t) + C_{ENS_i}(t)\cdot P_{ENS_i}(t) - C_{EX_i}(t)\cdot P_{Ex_i}(t) - \sum_{i=1}^{Nd}\sum_{t=1}^{n} C_i(t)\cdot \left|Z_{ij}\right| {I^2}_{ij}(t) \quad (1)$$

$t = 1,\dots,n;\; i = 1,\dots,nd-1; \quad i \neq j; \quad j = 1,\dots,nd$

Subjected to the following technical constraints:

While minimizing the total marginal cost involved, the total power generation value should be equal to the total system power demand plus the distribution network active power losses.

First Kirchhoff Law or Power Balance on the nodes of the network which is the basic rule of any power distribution system:

$$\sum_{i=1}^{Nd}\sum_{t=1}^{n} P_{w_i}(t) + P_{v_i}(t) + P_{Fc_i}(t) + P_{Sd_i}(t) + P_{Sd_{2_i}}(t) + P_{ENS_i}(t) - P_{EX_i}(t) - P_{Sc_i}(t) - P_{Sc_{2_i}}(t) - Load_i(t) - \sum_{i=1}^{Nd}\sum_{t=1}^{n} \Delta P_{ij}(t) = 0 \quad (2)$$

$\Delta P_{ij}(t) = \left|Z_{ij}\right| {I^2}_{ij}(t); t = 1,\dots,n; i = 1,\dots,nd-1; \quad i \neq j; \quad j = 1,\dots,nd$

The wind power generation output in each time interval of the unit should be between its minimum and maximum technical limits. The minimum limit is calculated or estimated for avoiding damage and harm of the wind generator form mechanical standpoint. The maximum limit the power generation produced by wind turbine is constrained by local wind speed forecasting and technical characteristics of the equipment.

Wind power generation limits in each time interval “*t*”

$$P_{Wmin_i}(t) \leq P_{w_i}(t) \leq P_{Wmax_i}(t); \quad t = 1,\dots,n;\; i = 1,\dots,nd-1 \quad (3)$$

PV is assumed to produce electricity in proportion to the capacity limit of the installed system and the amount of solar irradiation. Thus, the Photovoltaic power generation output of the unit should be between its minimum and maximum power limits provided by the manufacturer on the considered time interval. These limits are assumed to be calculated in advance according to a certain solar irradiation on lieu where the equipment is installed.

Photovoltaic power generation limits in each time interval "t"

$$0 \leq P_{V_i}(t) \leq P_{Vmax_i}(t); \quad t = 1, \dots, n; \quad i = 1, \dots, nd - 1 \tag{4}$$

The Fuel Cell power generation output should be minor or equal to its maximal power limit provided by the manufacturer on the considered time interval. This generation output should also be positive.

Fuel Cell power limits capacity in each time interval "t"

$$0 \leq P_{Fc_i}(t) \leq P_{Fcmax_i}(t); \quad t = 1, \dots, n; \quad i = 1, \dots, nd - 1 \tag{5}$$

Regarding the storage systems, there are two battery banks. Each battery bank is formed by 12 units connected in series forming a unique batteries bank with 24 V and 190 Ah. For simplicity, each batteries bank is treated as one battery. In this paper, these storage systems are considered independently. However, they have equal characteristics. Therefore, each system has its proper technical constraints.

For the storage system 1 or batteries bank 1 or simply battery 1:

Storage battery 1capacity limits in each time interval "t"

$$0 \leq P_{S_i}(t) \leq P_{Smax_i}(t); \quad t = 1, \dots, n; \quad i = 1, \dots, nd - 1 \tag{6}$$

Storage battery 1 maximal power discharge limits in each time interval "t"

$$P_{Sd_i}(t) \leq P_{Sdinitial_i}(1) \cdot X_i(t); \quad t = 1, \dots, n; \quad X_i = 0 \; or \; 1; \quad i = 1, \dots, nd - 1 \tag{7}$$

Storage battery 1 maximal power charge limits in each time interval "t"

$$P_{Sc_i}(t) \leq P_{Scmax_i}(t) \cdot Y_i(t); \quad t = 1, \dots, n; \quad Y_i = 0 \; or \; 1; \quad i = 1, \dots, nd - 1 \tag{8}$$

The battery 1 cannot charge and discharge power at the same time in each time interval "t"

$$X_i(t) + Y_i(t) \leq 1; \quad t = 1, \dots, n; \quad X_i, Y_i = 0 \; or \; 1; \quad i = 1, \dots, nd - 1 \tag{9}$$

Storage battery 1 maximal power discharge limits in each time interval "t" considering the battery state storage in period *t-1*

$$P_{Sd_i}(t) - P_{S_i}(t-1) \leq 0; \quad t > 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{10}$$

Storage battery maximal power charge limits in each period "t" considering the battery state storage in time interval*t-1*

$$P_{Sc_i}(t) + P_{S_i}(t-1) \leq P_{Smax_i}(t); \quad t > 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{11}$$

Power balance state of the battery on the initial state

$$P_{S_i}(t) = P_{s_{0_i}} - P_{Sd_i}(t) + P_{Sc_i}(t); \quad t = 1; \quad i = 1, \dots, nd-1 \tag{12}$$

Power balance state of the battery 1 in each time interval "t"

$$P_{S_i}(t) = P_{S_i}(t-1) - P_{Sd_i}(t) + P_{Sc_i}(t); \quad t = 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{13}$$

Power storage battery limit on the initial state

$$P_{S_i}(t) + P_{s_{0_i}} \leq P_{Smax_i}; \quad t = 1; \quad i = 1, \dots, nd-1 \tag{14}$$

Initial power state of the battery 1

$$P_{Sd_i}(t) = P_{Sinitial_i}(0)\,; \quad i = 1, \dots, nd-1 \tag{15}$$

For the storage system 2 or battery 2:

Power storage battery 2 limits in each time interval "t"

$$0 \leq P_{S_{2_i}}(t) \leq P_{Smax_{2_i}}(t); \quad t = 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{16}$$

Power storage battery 2 maximal discharge limits in each time interval "t"

$$P_{Sd_{2_i}}(t) \leq P_{Sdinitial_{2_i}}(1) \cdot X_{2_i}(t); \quad t = 1, \dots, n; \quad X_{2_i} = 0 \; or \; 1; \quad i = 1, \dots, nd-1 \tag{17}$$

Power storage battery 2 maximal charge limits in each time interval "t"

$$P_{Sc_{2_i}}(t) \leq P_{Scmax_{2_i}}(t) \cdot Y_{2_i}(t); \quad t = 1, \dots, n; \quad Y_{2_i} = 0 \; or \; 1; \quad i = 1, \dots, nd-1 \tag{18}$$

The battery 2 cannot charge and discharge power at the same time in each time interval "t"

$$X_{2_i}(t) + Y_{2_i}(t) \leq 1; \quad t = 1, \dots, n; \quad X_{2_i}, Y_{2_i} = 0 \; or \; 1; \quad i = 1, \dots, nd-1 \tag{19}$$

Storage battery 2 maximal power discharge limits in each time interval "*t*" considering the battery 2 state storage in time interval*t-1*

$$P_{Sd_{2_i}}(t) - P_{S_{2_i}}(t-1) \le 0; \quad t > 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{20}$$

Storage battery 2 maximal power charge limits in each time interval "*t*" considering the battery 2 state storage in time interval*t-1*

$$P_{Sc_{2_i}}(t) + P_{S_{2_i}}(t-1) \le P_{Smax_{2_i}}(t); \quad t > 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{21}$$

Power balance state of the battery 2 on the initial state

$$P_{S_{2_i}}(t) = P_{s_{20_i}} - P_{Sd_{2_i}}(t) + P_{Sc_{2_i}}(t); \quad t = 1; \quad i = 1, \dots, nd-1 \tag{22}$$

Power balance state of the battery 2 in each time interval "t"

$$P_{S_{2_i}}(t) = P_{S_{2_i}}(t-1) - P_{Sd_{2_i}}(t) + P_{Sc_{2_i}}(t); \quad t = 1, \dots, n; \quad i = 1, \dots, nd-1 \tag{23}$$

Power storage battery 2 limit on the initial state

$$P_{S_{2_i}}(t) + P_{s_{20_i}} \le P_{S_2max_i}; \quad t = 1; \quad i = 1, \dots, nd-1 \tag{24}$$

Initial power state of the battery

$$P_{Sd_{2_i}}(t) = P_{S_2initial_i}(0); \quad i = 1, \dots, nd-1 \tag{25}$$

Capacity limits of distribution lines (Direct current constraint)

$$P_{ijmax}(t) \le V_i(t) * I_{ijmax}; \; t = 1, \dots, n; i = 1, \dots, nd-1; \quad i \ne j; \quad j = 1, \dots, nd \tag{26}$$

For the succeeding time slices the constraints are the same. The existent storage energy (P_S) is updated between time slices. If a large number of time slices is considered, it is possible to minimize the operation costs and optimize the storage management systems.

The Distribution Network constraints and active power losses are taken into account in the formulation. In this particular case, the active power loss is a squared function of the current flowing through the lines. This function can be linearized in the objective function if necessary. However, if it is necessary to carry out the study without linearization, other optimization techniques can be used. In this case, the Mixed–Integer Quadratic Programming (MIQP)is used. However, there are other optimization techniques, for example, the Benders decomposition is a suitable technique for solving the non–linear model using the most adequate solver in platform of GAMS system. Benders decomposition [19]is a solution technique for solving certain large–scale combinatory optimization problems. Instead of considering all decision variables and constraints of a large–scale problem simultaneously, Benders decomposition partitions the problem into multiple smaller problems easy to solve separately, but they are related by means of Benders linear cuts. Since computational difficulty of optimization problems increases the number of binary variables and constraints, solving these smaller problems iteratively can be more efficient than solving a single large problem. Hence, this technique can be used for future developments of the proposed methodology and its application to larger power system, where the batteries can be considered as electric vehicles.

4. Mathematical Optimization Solution Methods

The optimal distributed generation dispatch problem formulated in Section 3 is an MIQP model with two types of variables that are continuous which represent the output power generation of each unit and decision binaries that are the decision off–on of each generation unit. The nature of the formulated problem is combinatorial. As a consequence, in the specialized literature, several solution techniques have been proposed to solve the unit commitment problem which may be adopted to solve the proposed problem such as heuristics [20]–[22], dynamic programming [23]–[25], mixed–integer linear programming [26], [27], Lagrangian relaxation [28], simulated annealing [29] and evolution–inspired approaches [30]–[32] can also be adopted to solve the intelligent micro–grid optimal scheduling. In this paper, the MIQP has been chosen firstly to obtain a global optimal solution. On the other hand, "to solve complex real–world optimization problems, researchers and scientists have been searching into existing natural processes and creatures–both as optimization model and metaphor–for many years. Mathematical optimization techniques are at the heart of many existing natural processes including Darwinian evolution theory, social group behavior, customs and foraging strategies. Over the last decades, there has been remarkable increase in the field of nature–inspired meta–heuristics search and optimization algorithms. Currently these meta–heuristic optimization techniques are applied to a variety of real world optimization problems, ranging from scientific research in any field to industry process and commerce trading. The two most important families of heuristics algorithms that primarily constitute this field of meta–heuristic techniques today are the evolutionary computation methods and the swarm intelligence algorithms that also may be an evolutionary. Although both families of algorithms are generally dedicated towards solving the best global search and optimization problems, they are certainly not equivalent, and each has its own distinguishing procedures features. Reinforcing each other's performance makes powerful hybrid heuristics algorithms capable of solving many intractable global search and optimization problems [33]".

In [14], [15], [34], it has been proved that meta–heuristics techniques are also very attractive to solve this kind of problem in a sense; it has the capability to escape from a local minimum if its parameters are very well tuned. It allows the search process to find out the best and acceptable solutions. However, deterministic optimization technique like MILP has been proven to be the adequate solution of the sated MILP optimization problem handling efficiently the decision to be taken expressed on the binary variables [13]. In all these references, the problem has been formulated as MILP; the micro–grid has islanding operation and without taken into accounts the distribution active power losses and the buses voltage of the distribution power grid. The formulation in this paper is a non–linear problem. To solve this problem the MIQP optimization technique has been used on this paper, which is still to be very efficient to solve this kind of problem fully handling the binary variables. The micro–grid can operate isolated and connected to distribution network and the distribution network active power losses has been taken into account.

A) Mixed Integer Linear Programming (MIQP)

The MIQP optimization technique has been chosen for solving the optimal dispatch of renewable distributed energy park problem at the laboratory. The main reason for it is the convergence guarantee to the global optimal solution in a finite number of steps [35] while providing a flexible and accurate modeling framework. In addition, during the search of the problem tree, information on the proximity to the optimal solution is available. Efficient mixed–integer quadratic programming such as the branch–and–cut algorithm based on GAMS platform under CPLEX name is used in this paper. However, other optimization techniques can also be used instead of this technique [36].

5. Conclusions

In this paper the mathematical formulation of the optimal operation of an intelligent micro–grid based on renewable energy resources managed by a VPD is formulated, presented and later in the second part of this research work will be discussed. The main goal is to decide the best VPD management strategy to minimize the generation costs of wind energy, photovoltaic energy, fuel cell energy and optimize power storage charging and discharging time subjected to all the operation technical constraints controlled by the VPD developed software.

The optimal dispatch is formulated as a MIQP problem which is solved by a deterministic optimization technique in the second part of this research work. The proposed method is applied to a real case system at the micro–grid laboratory, and the results are graphically illustrated in part II of this research work. Performance of used optimization technique is studied demonstrating that the MIQP is a powerful technique to solve this kind of problem, handling effectively not only the binary decision variables but also the whole optimization problem with a very low execution time, as will be seen in the next part II of this research work.

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التوزيع الأمثل لمصادر الطاقة المتجددة في شبكات القوى الصغيرة الذكية
الجزء الأول

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ملخص البحث. يتناول هذا البحث جدولة وحدات مصادر الطاقة المتجددة التي تغذى الأحمال الصغيرة في الشبكات متناهية الصغيرة أخذة في الاعتبار القيود التقنية. و نتيجة صعوبة تمثيل المتغيرات و التي تتكون من خليط من المتغيرات المستمرة و الصحيحة فقد تم تمثيل المشكلة رياضا بدالة هدف تعمل على تصغير التكلفة الهامشية للوحدات و تحقيق مجموعه من القيود التقنية التي تحافظ على الحدود الأمنه للتشغيل واتخاذ القرار الصحيح لتحقيق الحل الأمثل للمشكلة. تم حل الصيغة الرياضية المقترحة عن طريق تقنية الحل الأمثل المحددة باستخدام محسن CEPLEX و تم تنفيذها بواسطة نظام النمذجه الجبري العام.