The Journal of Engineering

The 7th International Conference on Renewable Power Generation (RPG 2018)

Smart energy coordination of a hybrid wind/PV with battery storage connected to grid

eISSN 2051-3305
Received on 26th October 2018
Accepted on 5th December 2018
E-First on 18th June 2019
doi: 10.1049/joe.2018.9235
www.ietdl.org

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Abstract: This study presents a smart power strategy coordination for optimal electricity supply. It aims to coordinate the energy flow on the electrical system for a residential application in the southern area of the African continent, in conjunction with an intelligent demand management control strategy. It has been observed that there is a potential for renewable energy resources that can enhance the energy and development of the African continent if used efficiently. In addition, the continent is suffering from several energy crises, which could be resolved by appropriate energy control approaches. It has been observed that incorporating an autonomous smart strategy that can coordinate a hybrid energy supply for a residential energy demand could improve the power grid performance of the Southern African region. In this paper, a smart strategy that develops a dynamic real-time energy structure control is proposed. This approach uses the ability of smart metering to create a flexible communication control strategy (FCCS), which will manage the demand and the supply of energy. It ensures the consumer's optimal power supply while ensuring stability and good performance on the utility side.

1 Introduction

The energy management strategy is the principal manner of creating flexibility on the electrical system. However, the flexibility of the energy flow on the electrical system that can enhance the power system is more complex due to the diversity of the demand behaviour, the quality issue of the traditional power generation and the uncertainty of the renewable resources integration [1–5]. Moreover, when the electrical system requires more efficiency, the power grid becomes more complex in terms of fast communication and control strategy. Nowadays, the smart grid approaches try to resolve the complexity of the electrical system and to introduce more efficiency and resilience of the energy flows.

Through smart grid development, the power grid becomes more and more flexible, which satisfies both the consumers and suppliers of the energy. The smart grid environment can be designed in different sizes of a microgrid, i.e. from nanogrid (less than 100 kVA/low-voltage distribution) to megagrid (more than 100 MVA/ high voltage distribution above 120-kV). When the intelligence strategy is implemented in any type of electrical system or microgrid, it brings autonomy, stability, compatibility, flexibility, scalability, efficiency, cost effectiveness, and peer-to-peer mode. These advantages solve the complexity and the flexibility problems of the electrical network through smart metering system.

Currently, several strategies use the smart metering system to manage the energy flow into the electrical system and to optimise the operation and consumer cost. This consists of funding the performance index of the electrical system in a specific time interval that can satisfy both the end user and supplier. In [6] a grid integration and optimisation through the smart metering environment is proposed for residential application. This strategy tries to create a smart optimal management communication by using the advantages that the advanced metering infrastructure (AMI) offers to enhance the resilience of the energy flow on the electrical system.

In [7] a new generation smart metering system is presented that can dynamically manage the energy on the demand side. This strategy consists of creating a control behaviour that can follow the consumer requirement. Based on the proposed real-time electricity-pricing environment of the predictive energy demand management developed in [8,9], this novel smart metering strategy is designed. An advanced model of predicting energy management approach, which consists of integrating grid with a hybrid PV-wind-battery for an industrial load, is presented in [10]. This strategy uses the approach of real-time electrical pricing to optimize the cost of energy consumption.

Siti *et al.* [11] proposed an optimisation strategy for grid-connected solar-wind-pumped hydro storage using model predictive control to minimise the cost of the utility grid. In [12] an optimal planning method of battery energy storage system for a wind-diesel off-grid is designed. This study aims to maximize the economic, environmental and reliability benefits of the electrical system, which can consider all uncertainty impacts of renewable energy generation. In [13], an optimal schedule of power flow for a distributed generation using solar-wind-diesel for the residential load is proposed. The system uses battery storage to cover the uncertainty variation of renewable energy resources. The overall goal of this hybrid model is to minimise the operating cost of the system.

Unlike the above-mentioned research, this study looks at the flexibility strategy of the energy flow of a hybrid PV-wind-battery connected to the grid for residential application. The work aims to develop a control strategy under smart metering communication using the real-time electricity-pricing framework to create an energy cost optimisation method. This system does not consider the opportunity cost, which consists of supplying the energy to grid in case of surplus energy generation from renewable energy resources. The optimisation approach used in this study is designed under an open loop method to test the proposed FCCS scheme.

2 System configurations

Fig. 1 describes the system model of the proposed FCCS for energy flow optimisation of residential load. This system consists of a hybrid PV-wind-battery connected to the grid. Table 1 describes the daily load demand and the daily generation of renewable energy resources, i.e. wind speed and solar irradiance.

2.1 Hybrid configuration

It is assumed that the inverter efficiency of each component of the hybrid resources, i.e. PV, wind, battery storage, is equal. Fig. 2 depicts the operating strategy of the hybrid renewable energy flow system and E_i (with i equals 1–4) represents the energies seen on

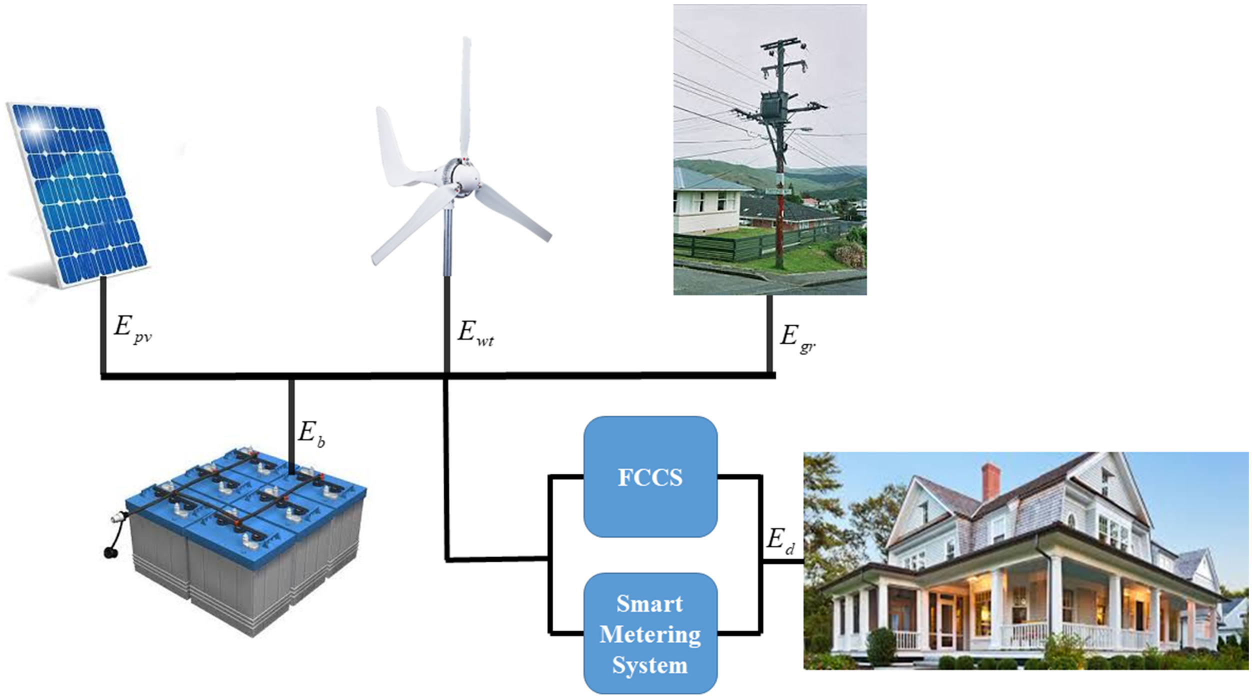


Fig. 1 *Smart-home energy flexible communication control strategy layout*

Table 1 Daily load demand, wind speed and solar irradiance

Daily Time hour	Energy demand kWh	Wind Speed m/s	Solar Irradiance W/m^2	Daily Time hour	Energy demand kWh	Wind Speed m/s	Solar Irradiance W/m^2
00:00	0.6	0.82	0	12:00	0.84	1.766	494.023
01:00	1.72	1.665	0	13:00	0.62	2.576	472.315
02:00	0.46	0.998	0	14:00	0.56	2.017	418.492
03:00	0.9	0.956	0	15:00	4.34	2.282	308.193
04:00	2.18	2.549	0	16:00	7.02	3.116	198.642
05:00	5.72	2.558	0	17:00	2.82	2.626	82.118
06:00	6.98	2.775	15.418	18:00	2.48	3.427	4.934
07:00	4.82	3.754	119.344	19:00	8.48	2.972	0
08:00	1.44	2.948	233.282	20:00	3.66	2.543	0
09:00	4.24	2.828	336.534	21:00	3	2.336	0
10:00	1.16	2.87	438.693	22:00	2.58	1.863	0
11:00	4.6	2.522	482.247	23:00	0.68	1.231	0

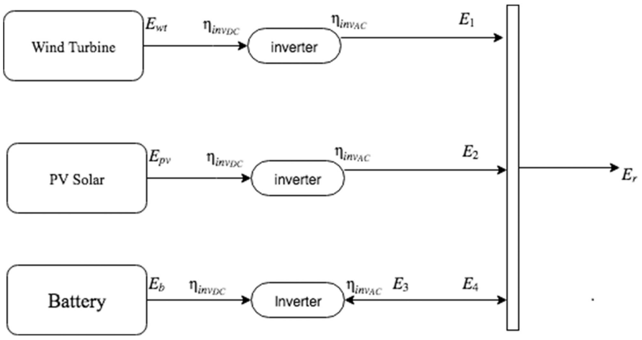


Fig. 2 *Hybrid PV-wind-battery layout*

the wind, solar, charging and discharging of the battery. The FCCS strategy, as described in Fig. 1, communicates with the hybrid system to connect to the grid for optimal energy flow. It is worth noting that the utility grid does not charge the battery and the hybrid does not supply to the grid. Therefore, E_r represents the renewable energy that supplies the load which is a function of E_i (with $i = 1$, 2, and 4). If it is assumed that the efficiency of the inverter is equal to unity, the energy flow on the hybrid system can be expressed as follows:

$$E_r = E_1 + E_2 + E_4 \tag{1}$$

The charging strategy of battery is described as

$$E_3 = E_1 + E_2 \tag{2}$$

Equations (1) and (2) give the mathematical expression of the energy flow strategy into the hybrid during discharging and charging process respectively.

When the efficiency of the inverter is considered as described in Fig. 2, the relation between AC-DC inverter efficiency is expressed as

$$\eta_{invAC} = \eta_{invDC}^{-1} \tag{3}$$

Equation (3), therefore, can introduce a new parameter on (1), where charging and discharging energy flow of the hybrid system can be defined.

During the discharging period of the battery, the energy flow on the hybrid bus is a function of (1). The energies generated by the PV, wind and battery storages, seen in the hybrid bus as shown in Fig. 2, are expressed as

$$E_{wt} = \eta_{invAC}E_1 \tag{4}$$

$$E_{pv} = \eta_{invAC}E_2 \tag{5}$$

$$E_b = \eta_{invAC}E_4 \tag{6}$$

Using (1), it is worth noting that the energy flow on the battery on discharging state, can be expressed as

$$E_b = E_{wt} + E_{pv} - E_r \tag{7}$$

By substituting (4)–(6) into (7), the discharge energy that is seen on the hybrid bus is determined as

$$E_4 = E_1 + E_2 - E_r/\eta_{inv} \tag{8}$$

with $\eta_{inv} = \eta_{invAC}$

During the charging state, based on Fig. 2, the energy seen on the battery side can be described as follows

$$E_b = \eta_{invDC}^{-1}E_3 \tag{9}$$

When (3) is substituted in (9), this relation becomes

$$E_b = \eta_{invAC}E_3 \tag{10}$$

Equation (11) defines the energy flow on the hybrid during the charging process as

$$E_3 = E_r - E_1 - E_2 \tag{11}$$

By substituting (4), (5), and (10) into (11), the energy flow on charging state of the battery can be written as

$$E_3 = \frac{E_r}{\eta_{inv}} - E_1 - E_2 \tag{12}$$

It can also be assumed that $\eta_{inv} = \eta_{invDC}$

2.2 Wind turbine energy generation

The energy produced by the wind turbine as described in Table 1 depends on the speed of the wind. Equation (13) defines the energy generated from the wind as

$$E_{wt} = \frac{6}{\pi}\eta_{wt}\rho_{\mathrm{air}}C_pA\Delta t\sum_{k=1}^{N}V_k \tag{13}$$

where η_{wt}, φ_{air}, C_p, A, Δt, N and V_k and are respectively wind turbine efficiency, air density (kg/m^3), coefficient of wind turbine performance, wind turbine swept area (m^2), time variation (hour), control horizon, and hourly average wind velocity (m/s). It is important to note that k is the sampling time which is set in hourly range.

2.3 Solar panel energy generation

Equation (14) defines the energy generated by solar PV, which is a function of solar irradiance that the panel can capture in a given surface.

$$E_{pv} = \eta_{pv}A_p\Delta t\sum_{k=1}^{N}I_k \tag{14}$$

where η_{pv}, A_p, and I_k are respectively solar panel efficiency, the surface of PV (m^2) and solar irradiance (W/m^2).

2.4 Grid system

Suppose that the utility grid supplies the energy demand given in Table 1, the hourly energy flow, in this case, can be expressed as a function of the electricity tariff. This energy is expressed as

$$E_{gr} = \Delta t\sum_{k=1}^{N}p_uP_k \tag{15}$$

where p_u, and P_k are utility energy price (R/kWh) and load power demand (kWh), respectively.

3 System design

This strategy consists of creating an optimal control strategy that can allow the energies to flow that may reduce the cost of energy from the utility grid and maximise the energy supply from the hybrid side. The performance index of the system design is described in Fig. 1. This is considered as the energy cost that the consumer can pay, which can be written as a multi-objective function. It is worth noting that the consumer takes the full responsibility of the hybrid energy cost. Therefore, the system objective function can be written as follows:

$$J = \sum_{i=1}^{N}\left[(p_uE_{5_i} - p_r(E_{2_i} + E_{1_i})\right] \tag{16}$$

where E_5 and p_r are the energy from the utility grid and the price of electricity from renewable energy resources, respectively. With i the sampling of time which replaces k and N is the system horizon. The performance index is subjected to the constraint below as

$$E_{di} = E_{ri} + E_{5i} \tag{17}$$

$$E_{3i} = E_{1i} + E_{2i} \tag{18}$$

$$0 \le E_{5i} \le E_{d\max} \tag{20}$$

$$0 \le E_{1i} \le E_{wt\max} \tag{21}$$

$$0 \le E_{2i} \le E_{pv\max} \tag{22}$$

$$SOC_{\min} \le SOC_i \le SOC_{\max} \tag{23}$$

where SOC is the state of charge of battery.

3.1 System method

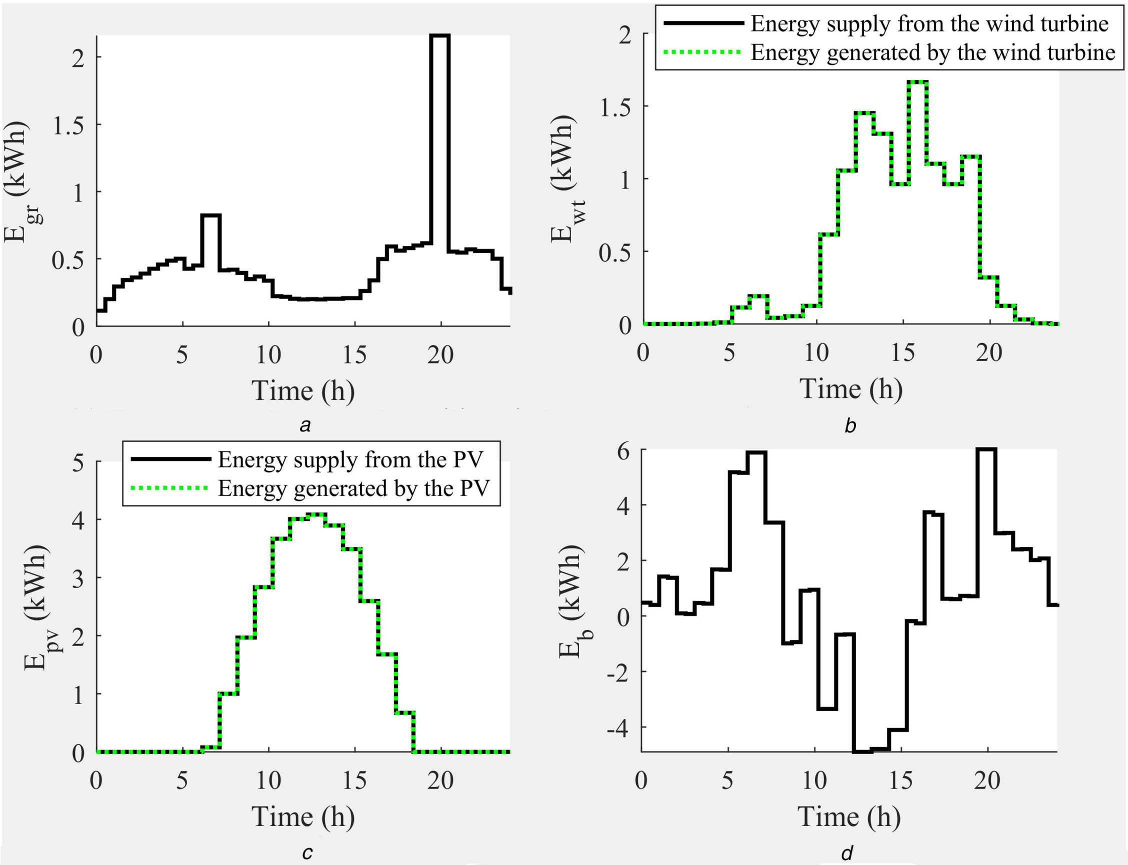
The system algorithm is designed under the fmincon optimal structure, which is based on open loop control model.

The approach is as follows.

Step-1: Read the electricity price from the grid and from the renewable energy resources under real-time electricity pricing structure.

Step-2: Measure the energy flow of each component into the FCCS structure.

Step-3: Compute the objection function (16) for a given period i and find the optimal control strategy.



a *b* *c* *d*

Fig. 3 *Energy flow system of FCCS structure*

Step-4: Compute the objection function (16) at a given period $i + 1$ to reach the system horizon N.

4 Results and discussion

This study uses the daily renewable energy generation, i.e. energy from wind and PV system for simulation analysis. The installed capacity of the wind turbine and solar panel are respectively 1.5 and 5 kW. The maximum demand from the consumer is fixed at 8.5 kW. Table 1 describes the system behaviour, which may be operated under the proposed FCCS to reach the specified system objective. The state of charge of the battery is fixed between 40 and 95 percent.

4.1 Simulation results

Considering the daily data given in Table 1, the simulation horizon may be fixed at 24 h to test the performance of the proposed optimal strategy. It is assumed that in this study the inverter efficiency value of the hybrid system is equal to unity. When the utility electricity pricing and renewable energy tariff are set to be 1.2196 and 0.65 rand per kilowatt-hour, respectively [7, 14], the system objective function (16) can be computed by taking into consideration the system constraints as described from (17) to (23).

Fig. 3 presents the optimal strategy of the energy flow using the proposed FCCS method. This describes the energy supply from the grid, wind energy flow, PV energy flow and energy flow into the storage system. Fig. 4 describes the behaviour of the proposed control strategy in terms of managing the energy flow.

4.2 Discussion

As shown in Fig. 3(a), compared to the energy demand in the consumer side Table 1, the energy demand from the utility grid is reduced, which leads to cost reduction. Renewable energy generations are optimally used to reach the system requirement. Fig. 3(b) shows that the energy from the wind turbine generated is the same as the energy supplied by the wind. The same observation is also made for the solar panel generation. The energy measured into the battery during the charging and discharging period of the hybrid system is shown in Fig. 3(c). At the discharging state, this energy is positive, while during the charging period it becomes negative.

It can be observed that the utility grid is supplying the load during the system given horizon *N*. This is shown in Fig. 4(a). However, this energy supply is of low demand as depicted in Fig. 3(a). The switching system of the hybrid structure follows the performance index requirement, which consists of satisfying the system constraint. This control strategy is shown in Fig. 4 (b–d).

Table 2 presents the different cost of energy that the consumer may pay. It contains the utility cost with and without the FCCS structure. Through the FCCS design, it is observed that the cost of energy that the consumer can pay the utility grid is reduced by about 15.72% of total energy cost.

5 Conclusion

It is observed that the developed model of this study could be developed in any Nano grid configuration where the flow optimisation is required. This strategy can be efficiently implemented into another electrical grid configuration. In this study, through the simulation results, it was observed that the proposed FCCS has the possibility of managing the energy flow on the electrical system. The control strategy that the designed system offers gives an excellent optimal structure in terms of energy coordination between the hybrid and the grid as well as the utility cost reduction. The future research study will focus on the system design where the opportunity cost is taken into consideration. This work may be done in the framework of a closed loop control strategy to compare the results with the present FCCS structure.

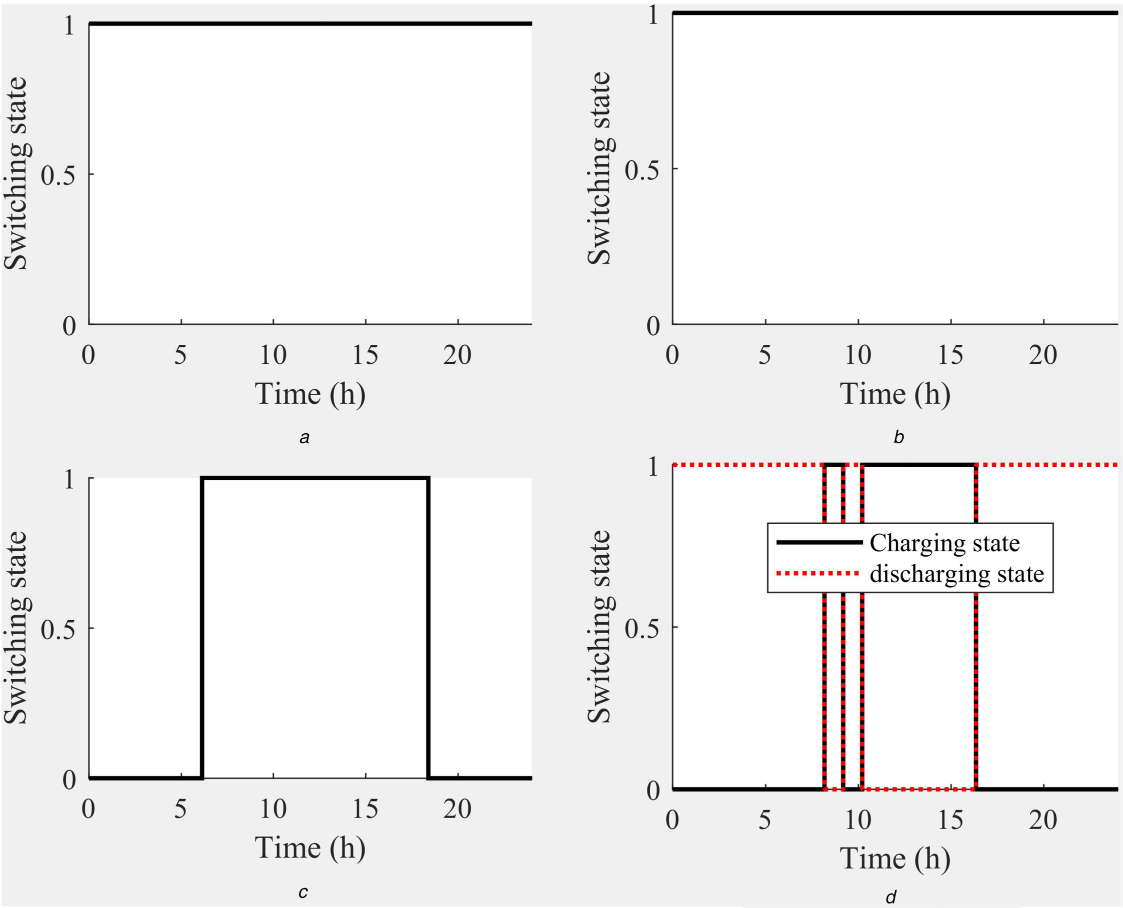


Fig. 4 *Switching system of FCCS*

Table 2 *Cost of energy consumption to pay the utility grid*

Cost without FCCS method	Cost with FCCS method
R87.6892	R13.7830

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