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Power-to-Gas Storage Optimization Through Power Pinch Analysis

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This work focuses on the optimization of an innovative power storage technology Power-to-Gas using pinch analysis. The concept of Power -to-gas storage is the conversion of power into gas that can be stored in the natural gas network. This concept incurs considerable power losses compared to other storage technologies. Besides, it has a long start time and a long stand-by recovery time that need to be studied. Graphical and numerical approaches have been developed for power optimization. A first graphical approach is presented. Then a numerical approach will facilitate more targeted responses to the problems experienced with the graphical one. This work acknowledges losses of the rectifier AC (alternating current) to DC (direct current), of the inverter (DC to AC), of the charging and the discharging process. This work proposes a new approach of Pinch Analysis Method for the optimization of Power-to -gas storage of a hybrid power system using intermittent and renewable energy. Graphical and numerical tools take into consideration new parameters (standby time, start time) and were applied to determine:

- The temporal time ratio of charging, discharging, stand-by time and rest;
- The minimum of outsourced electricity and the maximum of storage capacity.

Different scenarios for energy farms are presented and allow the designers to choose the best alternative for energy systems in a French City. Results show that the best alternative is an onshore wind farm. A sensitive analysis allows us to apprehend the importance of the source's type in the optimization of the storage system.

1. Introduction

Renewable energy has known a rapid growth. This interest is explained by the challenge of meeting growing energy demand. A renewable energy system, by itself, does not guarantee the satisfaction of such demand. In fact, it uses natural resources such as wind energy and solar energy that are intermittent. A storage technology is required to solve the mismatch between renewable energy production and an irregular load demand. Different storage technologies lead to different types of parameters to be considered in the design of power storage. In previous papers, pinch analysis method has been extended in different ways to energy storage problem. The method has been introduced for the first time by (Bandyopadhyay, 2011) integrating the design space for sizing the battery. (Wan Alwi et al., 2012) developed POPA, a graphical tool, to determine the outsourced electricity and the stored energy of a battery system. (Rozali et al., 2012), on the other hand, implemented the SCT to determine the stored and outsourced electricity at each time period using a battery system. Later on, (Rozali et al., 2013) improved his approach by considering losses in the optimization of pumped-hydro storage system for hybrid power system. (Ho et al., 2014) proposed another numerical approach ESCA (Electric System Cascade Analysis) for sizing of the inverter of a power system using intermittent power generation. Those papers considered in general a battery as a storage technology. Pumped- hydro storage was considered by (Rozali et al., 2013).

Our work focuses on the optimization of an innovative power storage technology Power to gas (PTG) using pinch analysis. The concept of Power to gas storage is the conversion of power into gas that can be stored in the natural gas network (De Saint-Jean et al., 2014). This concept incurs considerable power losses compared to other storage technologies. Besides, it has a long start time and a long stand-by recovery time

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that need to be studied. Graphical and numerical approaches have been developed for power optimization (Rozali et al., 2013). At first a graphical approach is presented. Then a numerical approach will facilitate more targeted responses to the problems experienced with the graphical one. This work acknowledges losses of the rectifier (AC to DC), of the inverter (DC to AC), of the charging and the discharging process (Rozali et al., 2012). Eleven recent studies have been selected and compared to the present work, in order to offer a clear vision of the research advance present in this paper.

2. Methodology

For both approaches, the first step consists in data extraction of hardware components efficiency (Rozali et al., 2012) and power sources and power demands. Table 2 and Table 3 show an illustrative case taken from (Wan Alwi et al., 2013). The type of power source and power demand weren't specified in the work by Wan Alwi et al. (2013). We will consider an AC type for all data. Start time and standby recovery time (Table 1). It is important to note that the type of current cannot be considered in the graphical approach. What is presented here is the required data for the methodology.

Table 1: Parameters of the PTG storage system

Converter efficiency	85 %
Inverter efficiency	85 %
Charging efficiency	61 %
Discharging efficiency	53 %
Start time	30 min
Standby recovery time	10 min

Table 2: Illustrative case (Power source)

Power Source	Time From (h)	To (h)	Electricity Generation (kWh)	Power Rating (kW)	Type (AC/DC)
1	8	18	500	50	AC
2	0	12	480	40	AC
3	12	24	720	60	AC

Table 3: Illustrative case (Power demand)

Power Demand	Time From-to (h)	Electricity Generation (kWh)	Power Rating (kW)	Type (AC/DC)
1	6-12	180	30	AC
2	8-18	350	35	AC
3	8-12	200	50	AC
4	0-12	420	35	AC
5	12-24	600	50	AC

Table 4: Results of applying graphical approach to the illustrative case

Storage capacity (kWh)	176.9
Minimum outsourced electricity (kWh)	413.8
Standby time (h)	0
Charging time (h)	17.5
Discharging time (h)	6
Temporal ratio of standby	0
Temporal ratio of charging	72.91
Temporal ratio of discharging	25
Temporal ratio of rest	2.09

2.1 Graphical approach

Step 1. Constructing PCC and determining charging, discharging, start and standby times

The PCC are constructed applying the methodology of Wan Alwi et al. (2012) where x axis represents time and y axis electricity. The SCC is constructed by affecting source electricity to the corresponding time period while the DCC is constructed by affecting demand electricity to the corresponding time period (Ho et al., 2012). Figure 1 shows the PCC related to the illustrative case with a SCC on the right and a DCC on the left. Starting time period corresponds to the period from time 0 h to start time h. Charging and discharging times can be determined by two approaches; by a direct one or by decomposing the SCC at suitable times (Ho et al., 2014). In this paper, the direct approach is applied. For each time interval, energy capacity E (t+ Δt) at the end is compared to energy capacity at starting E (t) using E (t+ Δt) - E (t). A positive value shows a charging period, while a negative value indicates a discharging one. Figure 1 shows a discharging period between 8 h and 12 h and two charging periods: Between time 0.5 h to 6 h and time 12 h to 24 h. Working of storage is not instant and necessitates 30 min to start charging in an effective way.

Step 2. Determining the maximum of storage capacity and the minimum of outsourced electricity

The maximum of storage capacity is the maximum of energy charged into the storage system. It is determined by the largest horizontal distance E_{max} between a point on the DCC and a point on the SCC (Ho et al., 2014). It can be calculated using Eq (1):

$$\textit{Maximum of storage Capacity} = E_{max} \times \textit{Charging efficiency} \quad (1)$$

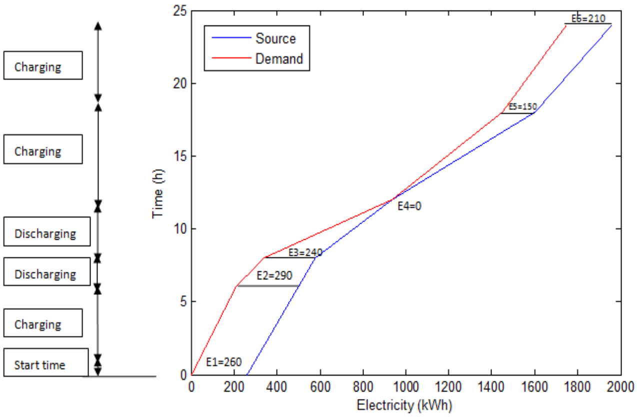

Figure 1: PCC of the illustrative case

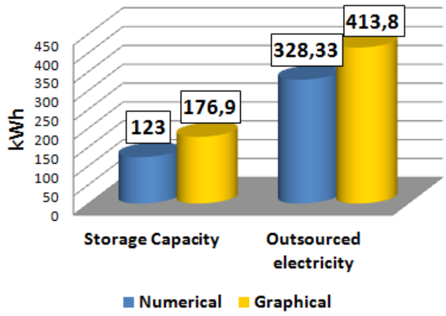

Figure 2: Comparison of approaches

According to the Figure 1, it equals 290 × 0.61 = 176 kWh. The minimum outsourced electricity can be determined by the overshoot of the DCC from the SCC at time t = 0 h (Ho et al., 2014). In the illustrative case, it equals 260 kWh. However, the process needs start time to work effectively. An added amount is outsourced at start time using Eq (2) :

$$\textit{Added outsourced electricity at start time} = \textit{Power rating demand (First period)} \times \textit{start time} \quad (2)$$

In this illustrative case, it equals 17.5 kWh. Besides, Power to gas technology incurs discharging efficiency. To respond to the demand, added electricity is outsourced at each discharging period using Eq (3):

$$\textit{Added outsourced electricity at discharging period } [t, t+\Delta t] = (E(t) - E(t+\Delta t)) \times (1 - \textit{Discharging efficiency}) \quad (3)$$

Figure1 shows two discharging periods. The added outsourced quantities of electricity related to the period [6 h, 8 h] and [8 h, 12 h] are respectively 23.5 kWh and 112.8 kWh. The minimum required outsourced electricity equals 413.8 kWh. Considering start time and the important power losses of Ptg technology are inevitable. Storage capacity in this work is 39 % inferior to the storage capacity in (Wan Alwi et al., 2013) which is 290 kWh and outsourced electricity in this work is 59 % superior to outsourced electricity in (Wan Alwi et al., 2013) which is 260 kWh. Table 5 illustrates the main results of applying the graphical approach to (Wan Alwi et al., 2013) case. However, constructing composite curves cannot deal with the difference of type of power sources and power demands. The numerical approach will respond to this problem.

Table 5: Energy cascade (Illustrative case)

1		2		3		4		5		6	
Date (h)		Σ Power source rating (kW)		Σ Power demand rating (kW)		Σ Electricity source (kWh)		Σ Electricity demand (kWh)		Σ Electricity surplus/deficit (kWh)	
From	To	DC	AC	DC	AC	DC	AC	DC	AC	DC	AC
0	6	0	40	0	35	0	240	0	210	0	30
6	8	0	40	0	65	0	80	0	130	0	-50
8	12	0	90	0	150	0	360	0	600	0	-240
12	18	0	110	0	85	0	660	0	510	0	150
18	24	0	60	0	50	0	360	0	300	0	60

2.2 Numerical approach

The numerical approach consists in extending the modified storage cascade (Rozali et al., 2014) to Power-to-gas storage by involving start time and standby recovery time. The first 6 columns of the Table 5 are calculated as in the study of Rozali et al, 2014. In this work, we will focus on the next calculations. Then, two binary variables are introduced ts and td using as follows:

i. ts = 1 if stand, 0 else

ii. td=1 if start time, 0 else

Here **ts** and **td** are Initialized to 0 and 1 respectively because at start time the process needs start time and not standby recovery time to work. It is necessary to note that the process will only be used if there is a need for charging or discharging. Unless, the variables would keep the same values.

For each time period [t, t+ *Δt]*, two other time variables are introduced **aa** and **nn** using Eq (4) and Eq (5) Where **trets** is standby recovery time and **tretd** is start time:

$$aa = (\Delta t - trets \times ts \times (1-td) - td \times tretd)/ \Delta t \quad (4)$$

$$nn = 1 - aa \quad (5)$$

Table 6: Continued storage cascade (Illustrative case)

7		8	9	10	11		12	13	14
Converted surplus (kWh)		Charging/ discharging quantity DC (kWh)	Discharge for AC Deficit (kWh)	Energy capaci-ty	Outsourced electricity(kWh)		Standby Time (h)	Chargi-ng time (h)	Discharg-ing Time (h)
AC to DC	DC to AC				DC	AC			
25.5	0	25.5	0	0	0	0	0	0	0
0	0	0	58.82	14.25	0	52.39	0	5.5	0
0	0	0	282.35	14.25	0	275.93	0	0	2
127.5	0	127.5	0	14.25	0	0	0	0	4
51	0	51	0	92.03	0	0	0	6	0

If there is an electricity deficit, three possibilities are available (Table 6):

i. The electricity is fulfilled by converting electricity surplus:

For DC deficit, if there is AC electricity surplus, it will be converted to DC using Eq (6):

Amount of converted AC electricity to DC (col 7) = AC electricity surplus × Rectifier efficiency (6)

For AC deficit: If there is a remaining DC deficit, the electricity will be discharged from storage using Eq (7):

Amount of converted DC electricity to AC (col 7)= AC electricity deficit / Inverter efficiency (7)

ii. If there is remaining electricity deficit, the electricity is discharged from storage: The calculations will be specified after for surplus and deficit electricity

iii. If there is remaining electricity deficit, it will be outsourced.

Two amounts are then calculated to determine storage capacity at the end of time period E(t+ *Δt) using Eq (8) and Eq (9)*:

Q1 = Charging/Discharging electricity (col 8)= DCsd + ACconv- DCconv (8)

Q2 = DC Electricity to be discharged for AC deficit (col 9)= (DCconv + AC deficit)/Rectifier efficiency (9)

Where

DCsd: DC electricity surplus/deficit, ACconv: Converted AC electricity surplus, DCconv : Converted DC electricity surplus.

The storage capacity at the end of time period, standby time, discharging time and charging time are calculated by analyzing Q1, Q2 and storage capacity (Col(10)) at the beginning of the period E (t):

a. In case of having Q1 <0 and AC electricity deficit, the storage capacity (Col(10)) is calculated using Eq (10):

$$E(t+\Delta t) = E(t) + (Q1 \times aa)/ \text{Discharging efficiency} + (Q2 \times aa)/ (\text{Discharging efficiency} \times \text{inverter efficiency}) \quad (10)$$

The outsourced electricity is calculated by using Eq (13) and Eq (14):

Outsourced DC electricity = Abs (Q1 ×nn) (13)

Outsourced AC electricity = Abs (Q2×nn) (14)

The discharging time in the time period (t, Δt) is equal to *aa*× *Δt*. Then, the variable ts and td turn to zero.

b. In case of having Q1>0 and AC electricity surplus, there is no outsourced electricity and the energy storage (Col(10)) is calculated using Eq (15):

$$E(t+\Delta t) = E(t) + (Q1 \times aa) \times \text{Charging efficiency} + (Q2 \times aa) \times (\text{Charging efficiency} \times \text{converter efficiency}) \quad (15)$$

The charging time in the time period (t, Δt) is equal to *aa*× *Δt*.Then, the variables ts and td turn to zero.

c. Other cases are treated with the same logic. However, It is important to note that in case of having storage capacity empty at the beginning of the time period, the necessary AC and DC electricity are directly outsourced and the storage capacity at the end of the time period remains equal to zero. Then, the value of **ts** is 1-td. The standby time in the time period (t, Δt) is equal to Δt.

Table 7 shows the results of applying the numerical approach to the illustrative case.

Figure 2 shows a higher storage capacity (45.36 %) in the graphical approach than in the numerical one and higher outsourced electricity (26 %) in the graphical approach than in the numerical one. This is due to the notion of priority in responding to electricity deficit in numerical approach that allows a higher optimization of energy storage.

Table 7: Results of applying the numerical approach to the illustrative case

Storage capacity (kWh)	123.14
Minimum outsourced AC electricity (kWh)	328.33
Minimum outsourced DC electricity (kWh)	0
Standby time (h)	0
Charging time (h)	17.5
Discharging time (h)	6
Temporal ratio of standby	0
Temporal ratio of charging	72.91
Temporal ratio of discharging	25
Temporal ratio of rest	2.09

3. French City: Case studies

Four different case studies are presented related to a French city. Every case study is described by a power farm. In order to compare them and to determine the best power farm, all the farms have the same capacity of electricity generation (220 MW). 220 MW corresponds to the maximum of energy demand of the French city. The power farms are:

i. On-Shore Wind energy farm : composed of 110 on-shore wind turbines (Cap_gen/ Turbine = 2 MW).
Off-Shore Wind energy farm : composed of 44 on-shore wind turbines (Cap_gen/ Turbine = 5 MW).

ii. Solar energy farm : composed of 44 solar panels (Cap_gen/ Solar panel = 3.6 MW).

iii. Mixed energy farm : composed of 22 solar panels and 55 on-shore wind turbines. The generators have the same capacity as generators above.

Power source data has been obtained from (Soda, 2004) data basis and demand power source has from (UCTE, 2009) data basis. Power data is supposed to have changed faintly for this last ten years.

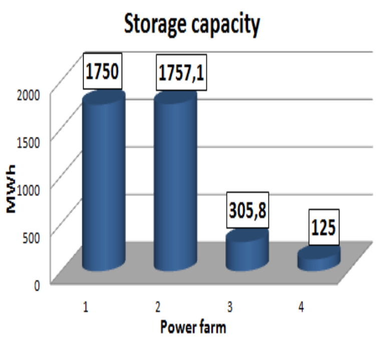

Figure 3: Storage capacity of energy farms

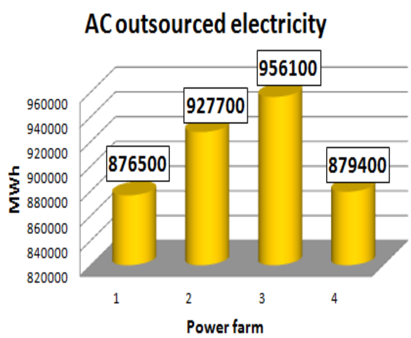

Figure 4: AC outsourced electricity of energy farms

An effective determination of the power farm should be based on comparing both the maximum of capacity storage and the minimum of outsourced electricity. A high amount of outsourced electricity incurs high level of energy consumption while a high storage capacity incurs high investment on energy system. Considering Figure 3 and Figure 4, the lowest amount of outsourced energy is provided by the on-shore energy farm. The lowest capacity is provided by the mixed energy farm. By analyzing the discharging rate for both energy systems, it is important to note that the on-shore energy farm has used its storage system approximately eight times more than the mixed energy farm. The mixed energy farm spent only 3.46 % of time on charging and 0.274 % on discharging. That explains the small storage capacity needed for the mixed energy farm. The on-shore energy is the best alternative for the French city.

4. Conclusions

As two approaches were presented, numerical approach was chosen to optimize energy storage because it takes into account all the parameters of energy storage and is lighter to implement on software (Matlab etc.). The numerical approach results are in favor of an on-shore energy farm for the French city for AC and DC demand. Considering the importance of every parameter contributing in energy storage optimization, it emphasizes the need of more thorough investigation on a suitable capacity of electricity generation and the financial feasibility of each of the energy farms.

Abbreviations

AC	Alternating current	SCC	Source composite curve
ACconv	Converted AC electricity surplus	DCC	Demand composite curve
DC	Direct current	Δt	Length of time interval
DCsd	DC electricity surplus/deficit	Trets	Standby recovery time
DCconv	Converted DC electricity surplus	Tretd	Start time
PCC	Power composite curves	col	Column
		Cap_gen	Capacity of generation

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