Wind Energy

Q1 风力发电机整套系统由哪些部分组成，各自干什么？

Q2 为什么叶片不能是直的，而要从根到尖逐渐扭转？

Q.1 What are the components in a HAWT type wind turbine system? Describe the function of each component.

Gearbox: Increases rotational speed, converting low-speed rotation to a speed suitable for the generator.
Generator: Converts mechanical energy into electrical energy.
Yaw system: Adjusts the direction of the wind rotor to face the wind.
Blade Pitch System: Controls power output and protects the turbine in strong winds by adjusting the blade's angle of attack.

Q.2 Why are wind turbine rotor blades twisted towards the end?

The twist in wind turbine rotor blades is designed to optimize the aerodynamic properties at different radii along the blade. Near the root of the blade, where the speed is slower, a larger angle is required to capture wind energy effectively. At the blade tips, where the speed is much faster, the twist reduces drag and improves efficiency.

Q3 在某个风速下，风本身有多少功率？理论上这台风机最多能拿走多少？

Q.3 What is the specific power in wind at a location with wind speed of 5m/s? Determine the theoretical maximum power output of a 40-m diameter wind turbine generator at this location. Assume density of air to be 1.225Kg/m3. 直径

$V = 5m/s \quad \rho = 1.225 kg/m^3 \quad D = 40m \quad A = \frac{\pi}{4}D^2$

① $P = \frac{1}{2}\rho V^3 = \frac{1}{2} \times 1.225 \times 5^3 = 76.56 W$

② $P_W = \frac{1}{2}\rho A V^3 = \frac{1}{2} \times 1.225 \times \frac{\pi}{4}(40)^2 \times 5^3 = 96211.28 W$

$HAWT: A = (\pi/4) D^2 \quad VAWT: A = \frac{2}{3} D \cdot H$

Betz 极限:

$$P_{max} = 0.593 \times 96.3 \approx 57.1\ \mathrm{kW}$$

Q4 风速随**高度**变化后，风功率会变多少？

Power density (specific power) = power per square meter (Watts/m²)

Q.4 The wind speed in a city area is 5 m/s at a height of 10m. The location has a friction coefficient of 0.4. What is the specific power at a height of 50m? Assume density of air to be 1.225Kg/m3.

$H = 10m \quad V = 5m/s \quad \alpha = 0.4 \quad \rho = 1.225 kg/m^3$

$H_0 = 50m \quad V_0 = ?$

$\left(\frac{V}{V_0}\right) = \left(\frac{H}{H_0}\right)^\alpha \Rightarrow V_0 = \frac{V}{\left(\frac{H}{H_0}\right)^\alpha} = \frac{5}{\left(\frac{10}{50}\right)^{0.4}} = 9.52 m/s$

$P_W = \frac{1}{2}\rho V_0^3 = \frac{1}{2} \times 1.225 \times (9.52)^3 = 528.47 W$

$\left(\frac{P}{P_0}\right) = \left(\frac{V}{V_0}\right)^3 = \left(\frac{H}{H_0}\right)^{3\alpha}$

Q5 已知风速和最佳 TSR，风机应该转多快

Q.5 At tip-speed-ratio of 5, what is the rpm of the wind turbine rotor with a diameter of 40m, if the wind speed is 10m/s?

$\text{tip speed ratio} = \frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{rpm \times \pi D}{60 V}$

$rpm = \frac{5 \times 60 \times 10}{\pi \times 40} = 23.87$

Q6 解释风力涡轮机中的转子叶片如何获得旋转所需的推力。

Q.6 Explain how the rotor blades in a wind turbine get the required thrust to rotate.

Air moving over top of airfoil has more distance to travel →Air pressure on top is lower than under airfoil
→ "Lift" is created

Q7 当风速变化时，有哪些办法能调节风机转速？

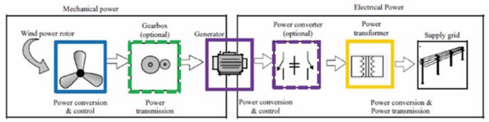
Q.7 What are the various methods used for varying the wind turbine rotor speed based or wind speed?

How: • Adjust angle of attack at the turbine blades • Stall or pitch control	How: • Multiple gearboxes design for different rotor speed to generator speed ratios. • Different generator designs and power converters are used to adjust the voltage frequency to be the same at the grid frequency.

Q8 绘制风能转换系统的框图，说明每个模块功能。

Q.8 Draw the complete block diagram of the wind energy conversion system to convert wind energy to electricity for the grid. Briefly explain the function of each block.

Main Components of Wind Energy Conversion Systems (WECS)



Power extracted by the rotor at low rotational speed, typically at 10-15 rpm.	Gearbox is used to increase rotational speed to a higher rpm to generate 50/60Hz electricity.	Generators and power converters are the main components to make sure that WECS produce high quality voltage supplies.	Transformers are used to step-up the voltage to connect the generator to the grid.

Q9 为什么风机越做越大，在经济上反而更划算？

Q.9 Using appropriate equations, explain why it is economical to increase the size of the wind turbine rotor.

$P_w = \frac{1}{2}\rho A v^3$

The power output of a wind turbine is directly proportional to the swept area of the rotor, which is given by: This means that doubling the blade length results in a fourfold increase in power output, while the cost only increases roughly by a factor of two. Therefore, larger rotors provide significantly higher energy production per unit cost, making them more economical.

The larger the rotor, the more energy it can capture

Q10 大型风机的叶片为什么容易产生应力和疲劳？

Q.10 Explain the cause of rotor stress in large wind turbines.

Rotor Stress

As seen in the previous example, the blade at the top of its rotation can experience much higher wind speeds than at the bottom of its rotation. This results in flexing of the blade.

It can also:
- Increase noise.
- Contribute to blade fatigue, which can lead to blade failure.

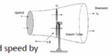
Q11 从基本原理出发，推导出使用风力涡轮机从风中 q 获取最大能量的贝茨定律。

Q.11 From first principle, derive Betz's Law for retrieving maximum energy from wind using a wind turbine.

① Power Extracted

Assume that the velocity of wind v_b is just the average of the upwind and downwind speed,

$$P_b = \frac{1}{2}\rho A\left(\frac{v+v_d}{2}\right)(v^2 - v_d^2)$$



Denote the ratio between upwind and downwind speed by

$$\lambda = \left(\frac{v_d}{v}\right)$$

Substitute v_d, then we have,

$$P_b = \frac{1}{2}\rho A\left(\frac{v+\lambda v}{2}\right)(v^2 - \lambda^2 v^2)$$

$$= \underbrace{\frac{1}{2}\rho A v^3}_{\text{Power in the wind}} \cdot \underbrace{\left[\frac{1}{2}(1+\lambda)(1-\lambda^2)\right]}_{\text{Fraction extracted}}$$

② Rotor Efficiency

Define Rotor efficiency as,

$$C_P = \frac{1}{2}(1+\lambda)(1-\lambda^2)$$

Fundamental relationship for power delivered by the rotor,

$$\boxed{P_b = \frac{1}{2}\rho A v^3 \cdot C_p}$$

③ Maximum Rotor Efficiency

$$\frac{dC_p}{d\lambda} = \frac{1}{2}[(1+\lambda)(-2\lambda) + (1-\lambda^2)] = 0$$
$$= \frac{1}{2}[(1+\lambda)(-2\lambda) + (1+\lambda)(1-\lambda)]$$
$$= \frac{1}{2}(1+\lambda)(1-3\lambda) = 0$$

The blade efficiency will be maximum if it slows the wind to one-third of the upwind speed $\lambda = \frac{v_d}{v} = \frac{1}{3}$

④ We can now find the maximum rotor efficiency,

Substituting λ=1/3 in Efficiency $= \frac{1}{2}(1+\lambda)(1-\lambda^2)$

$$\text{Maximum rotor efficiency} = \frac{1}{2}\left(1+\frac{1}{3}\right)\left(1-\frac{1}{3^2}\right)$$
$$= \frac{16}{27} = 0.593 = 59.3\%$$

Q12 TSR 是什么，会怎样影响风机效率？

Q.12 What is the tip seed ratio (TSR) of wind turbine? How does TSR affect the rotor efficiency of a wind turbine?

TSR is the speed at rotor tip divided by the wind speed.

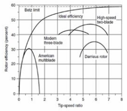
$$\frac{\text{Rotor tip speed}}{\text{Wind speed}} = \frac{\text{rpm} \times \pi D}{60\ v}$$

D: diameter (m)
v: wind speed (m/s)

The optimal TSR gives the maximum efficiency that a turbine can extract wind energy.

Rotor Efficiency vs TSR

- For a given wind speed, rotor efficiency is a function of the rate at which a rotor turns.
  - If Rotor turns too slow letting too much wind to pass => efficiency drops.
  - If Rotor turns too fast causing turbulence =>efficiency drops.



Q13 按照转速控制方式，发电系统可以分哪几类?

Q.13 Describe the various types of wind turbine generators based on type of speed control used.

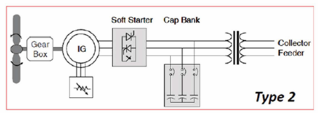
WTGs Classification by Speed Control

Wind turbine generators can be divided into 5 types.
1. Type 1: Fixed speed (1-2% variation)
2. Type 2: Limited variable speed (10% variation)
3. Type 3: Variable speed with partial power electronic conversion (30% variation)
4. Type 4: Variable speed with full power electronic conversion (full variation)
5. Type 5: Variable speed with mechanical torque converter to control synchronous speed (full variation)

Q14 变速风机是如何通过电气方式实现并网的？

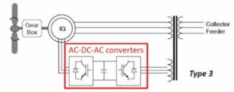
Q.14 Using block diagram, describe the various types of variable speed wind turbine generator systems with electrical control on generator side.

Type 2: Variable Speed Systems

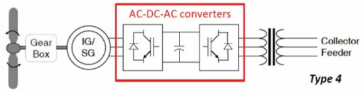


- Variable speed induction generators (VSIG) are often used in wind energy conversion systems to harness energy efficiently from varying wind speeds.
- The rotor resistance control method involves adjusting rotor circuit's resistance to control the generator's speed

Type 3: Doubly Fed Induction Generator(DFIG)



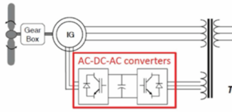
Type 4: Indirect Grid Connection



Q15 DFIG 风机是如何在变速情况下与电网同步的？

Q.15 Using block diagram, explain the operation of wind turbine system with a doubly fed induction generator (DFIG).

Type 3: Doubly Fed Induction Generator(DFIG)



- Instead of variable resistors in Type 2, this Type 3 design adds AC-DC-AC converters to the rotor circuit.
- Rotor frequency is decoupled from grid frequency.
- The machine can still be synchronized with the grid while the wind speed varies.

Q16 使用框图解释带同步发电机的四型风力涡轮机系统的可变转速操作。

Q.16 Using block diagram, explain the operation of variable turbine speed, type 4 wind turbine system with a Synchronous generator.

Type 4: Indirect Grid Connection

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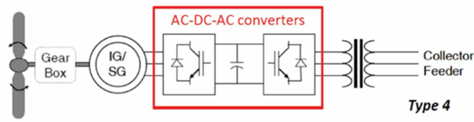

- Allows the turbine to rotate at its optimal speed.
- AC output from generator frequency is different and decoupled from grid frequency.
- AC-DC-AC converter is used to connect the AC output to the grid.
- Full control and flexibility in the design and operation of wind turbine.
- The ratings of power electronics are higher than Type 3.

Q17 真实风机在不同风速区间是如何工作的？

Q.17 Draw the ideal power delivered vs wind speed curve for a wind turbine generator. Clearly explain the operation at different wind speed.

Ideal Power Curve

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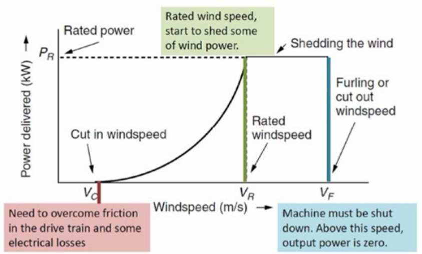


Q18 风太大时，风机如何限制或减少输出功率的？、

Q.18 What is meant by wind shedding? Explain the various methods for shedding wind power?

Wind shedding refers to the intentional reduction of power output to protect the turbine during high winds. Methods include:

How to Shed Wind Power

Pitch-controlled turbines

– Active control by reducing 'angle of attack'

Stall-controlled turbines.

– Passive control using pure aerodynamic design.

Active stall control.

– Induce stall for large wind turbine by increasing 'angle of attack'.

Passive yaw control

– Small kW size turbine, causing axis of turbine to move off the wind.

Q19 在一天中风速不断变化的情况下，这台风机一共能发多少电？

Q.19 The table below gives the measurement of wind speed during one day. Calculate the total energy generated for the day using a 40-m diameter rotor wind turbine generator with rotor efficiency of 40% and generator efficiency of 85%. The cut-in speed is 3 m/s and cut-out speed is 9 m/s. Assume there is no wind shedding.

	Wind speed (m/s)	Number of hours recorded during the day
<3	1	5
	2	3
3~9	4 $i=1$	4
	7 $i=2$	6
	8 $i=3$	4
>9	10	2

$D=40m$

$\rho=1.225\ kg/m^3$

$A=\frac{\pi}{4}D^2=400\pi\ m^2$

$P_w=\frac{1}{2}\rho A v^3$ $\quad P_{w1}=49.26\ kW$ $\quad P_{w2}=264\ kW$ $\quad P_{w3}=394.08\ kW$

$P_{out}=P_w\cdot 0.4\cdot 0.85$ $\quad P_{out1}=16.75\ kW$ $\quad P_{out2}=89.76\ kW$ $\quad P_{out3}=133.99\ kW$

$E=P_{out}\cdot hours$ $\quad E_1=66.99\ kWh$ $\quad E_2=538.57\ kWh$ $\quad E_3=535.95\ kWh$

$E_{all}=\sum_{1\le i\le 3}E$ $\quad E_{all}=E_1+E_2+E_3=1141.51\ kWh$

补充问题

$$CF=\frac{\text{Actual energy delivered}}{\text{Rated power}\times 8760}$$

$$\text{Annual energy (kWh/yr)} = P_R\ \text{(kW)} \times 8760\ \text{(h/yr)} \times CF$$

Actual capacity factor

Estimate of energy delivered from a turbine of diameter D:

$$\text{Annual energy (kWh/yr)} = 8760 \cdot P_R(\text{kW})\left\{0.087\overline{V}(\text{m/s}) - \frac{P_R(\text{kW})}{[D(\text{m})]^2}\right\}$$

Example

The Whisper H900 wind turbine has a 900-W generator with 2.13-m blades.

In an area with 6-m/s average wind speed, estimate the approximated energy delivered.

$$CF = 0.087\overline{V} - \frac{P_R}{D^2}$$

$$= 0.087\times 6 - \frac{0.90}{2.13^2} = 0.324$$

The energy delivered in a year's time

$$\text{Energy} = 8760\ \text{h/yr}\times 0.90\ \text{kW}\times 0.324$$

$$= 2551\ \text{kWh/yr}$$

Other Renewable Energy and Economics

Q1 描述径流式小型水电站的工作原理

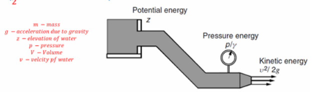
1. Describe how a Run-of-the-rive mini hydro power plant works.

Run-of-the-river (ROR) hydro power plants generate electricity using the natural flow of a river, without requiring a large dam or reservoir. Key steps in the operation:

The energy associated with water manifests itself in three ways:

as potential energy (mgz due to the water level in the dam) pressure energy (pV in the penstock) and kinetic energy ($\frac{1}{2}mv^2$ as water flows).

m – mass
g – acceleration due to gravity
z – elevation of water
p – pressure
V – Volume
v – velcity pf water



2. A Run-of-the-river mini hydro power plant has following operational parameters.

Water Flow rate = 1000 litres/min

Height difference between source of water and the location of the turbine/generator = 50 meter

Length of the PVC pipe = 100m

Diameter of the PVC pipe = 100mm $=0.1m$

Efficiency of the turbine/generator combined = 50%

$1m=100cm$

$1cm=10mm$

$1m^3=1000L$.

a) What is the power output of the plant neglecting the losses in the PVC pipe?

b) How much energy will be produced in a month if the PVC pipe friction loss is 20%?

a) 忽略管道损失时的输出功率：

水力功率公式为：

$$P=\rho gQH\eta$$

其中：

- $\rho=1000\,\mathrm{kg/m^3}$
- $g=9.81\,\mathrm{m/s^2}$
- $Q=\frac{1000}{60}\,\mathrm{L/s}=\frac{1000}{60}\times10^{-3}\,\mathrm{m^3/s}=0.01667\,\mathrm{m^3/s}$
- $H=50\,\mathrm{m}$
- $\eta=0.5$

代入得：

$$P=1000\times9.81\times0.01667\times50\times0.5\approx408.75\,\mathrm{W}$$

b) 考虑 20% 管道摩擦损失时的月发电量：

净有效水头为：

$$H_{\text{net}}=50\times(1-0.2)=40\,\mathrm{m}$$

功率为：

$$P_{\text{net}}=1000\times9.81\times0.01667\times40\times0.5\approx327\,\mathrm{W}$$

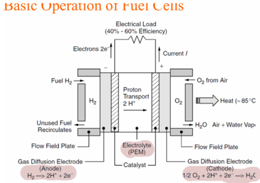
一个月（按 30 天计）发电量为：

$$E=327\times24\times30/1000\approx235.44\,\mathrm{kWh}$$

Q3 使用适当的图表和方程，描述质子交换膜燃料电池的基本工作原理

3. Using appropriate diagram and equation, describe the basic operation of a proton exchange membrane (PEM) fuel cell.

Basic Operation of Fuel Cells



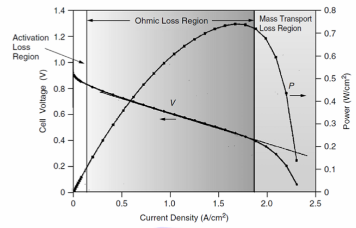
Basic Operation of Fuel Cells

- A single cell consists of two porous gas diffusion electrodes separated by an electrolyte.
- It is the choice of electrolyte that distinguishes one fuel cell type from another.
- The electrolyte consists of a thin membrane that is capable of conducting positive ions but not electrons or neutral gases.
- The entering hydrogen gas has a slight tendency to dissociate into protons and electrons as follows:
$$H_2 \leftrightarrow 2H^+ + 2e^-$$
- This dissociation can be encouraged by coating the electrodes or membrane with catalysts to help drive the reaction to the right.

Q4 绘制 PEM 燃料电池的典型电特性曲线，并标明不同工作区域

4. Draw the typical electrical characteristics of a PEM fuel cell, clearly marking different operating regions.

Electrical Characteristics of Real Fuel Cells



1. **活化极化区**：电流较小时，电压迅速下降，主要由电极反应动力学限制。
2. **欧姆极化区**：电流适中，电压随电流线性下降，主要由电解质和接触电阻引起。
3. **浓差极化区**：电流大时，反应物供应不足，电压急剧下降。

Q5 描述燃料电池中降低其性能的各种损耗类型。

5. Describe various types of losses in a Fuel cell which reduces its performance.

Losses in the Fuel Cell

- *Activation losses* result from the energy required by the catalysts to initiate the reactions. The relatively slow speed of reactions at the cathode, where oxygen combines with protons and electrons to form water, tends to limit fuel cell power.
- *Ohmic losses* result from current passing through the internal resistance posed by the electrolyte membrane, electrodes, and various interconnections in the cell.
- Another loss, referred to as *fuel crossover*, results from fuel passing through the electrolyte without releasing its electrons to the external circuit.
- And finally, *mass transport losses* result when hydrogen and oxygen gases have difficulty reaching the electrodes. This is especially true at the cathode if water is allowed to build up, clogging the catalyst.

- For these and other reasons, real fuel cells, in general, generate only about 60–70% of the theoretical maximum.

Q6 直接甲醇燃料电池相对于 PEM 燃料电池的主要优势是什么？

6. What are the key advantages of Direct Methanol Fuel cell over PEM fuel cell?

Uses liquid methanol, which is easier to store and transport than hydrogen gas. Suitable for portable devices like laptops and phones.

Q7 描述碱性燃料电池的主要特性。

7. Describe the key characteristics of Alkaline Fuel cell?

Electrolyte: Potassium hydroxide (KOH).
Operates at 90–100 °C.
Highly efficient and reliable but sensitive to CO2, requiring pure oxygen.

Q8 燃料电池相对于化石燃料发电厂的主要优势是什么？

8. What are the key advantages of Fuel cell over fossil fuel based power plants?

- Fuel cells convert chemical energy contained in a fuel (hydrogen, natural gas, methanol, gasoline, etc.) directly into electrical power.
- Fuel-to-electric power efficiencies as high as 65% are likely, roughly twice as efficient as the average central thermal power stations.
- The usual combustion products (SOx, particulates, CO, and various unburned or partially burned hydrocarbons) are not emitted.
- They are inherently modular in nature, so that small amounts of generation capacity can be added as loads grow.

Q9 描述水电解制氢的基本过程。

9. Describe Electrolysis of water for production of Hydrogen.

- When an electrical current is forced through water added with an electrolyte, water molecules can be broken apart, releasing hydrogen and oxygen gases: $2H_2O \longrightarrow 2H_2 + O_2$
- De-ionized water introduced into the oxygen side of the cell dissociates into protons, electrons, and oxygen.
- The oxygen is liberated, the protons pass through the membrane, and the electrons take the external path through the power source to reach the cathode where they reunite with protons to form hydrogen gas.

Q10 求风电场的平准化度电成本（LCOE）

10. A wind farm project has fifty (50) 2000-kW turbines with 80-m blades. Capital cost is $100 million and the O&M cost for the first year is $2 million. The O&M cost is escalating at the rate of 5% per year. The project will be financed with a $100 million, 30-yr loan at 8% interest. Turbines are exposed to Rayleigh winds averaging 8.5 m/s. What is LCOE for the wind farm?

$\to e$ $\quad P$ $\quad n=30$ $\quad g$ $\quad G=10^9$

The ratio of the equivalent annual cost ($/yr) to the annual electricity generated (kWh/year) is called the levelized cost of electricity (LCOE).

① $CF=0.087\overline{V}-\frac{P_R(kW)}{[D(m)]^2}=0.087\times8.5-\frac{2000}{80^2}=0.427$

② For 50 such turbines, the annual electrical production will be

Annual energy $=50\times2000kW\times8760\ h/yr\times0.427=374\times10^6\ kWh/yr$

③ The debt payments will be $(i=g=0.08)$

$A=P\cdot\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]=100{,}000{,}000\times\left[\frac{0.08(1+0.08)^{30}}{(1+0.08)^{30}-1}\right]=\$8.8\times10^6/yr$

④ The levelized O&M cost is $=2\times10^6\times\left[\left(\frac{1.328}{0.0665}\right)\cdot\left(\frac{0.805}{9.0626}\right)\right]=3.55\times10^6\ \$$

O&M cost $=A_0[PVF(d',n)\cdot CRF(d,n)]=2\times10^6\times\left[\left[\frac{(1+d')^n-1}{d'(1+d')^n}\right]\cdot\left[\frac{d(1+d)^n}{(1+d)^n-1}\right]\right]$

⑥ The levelized price at which electricity needs to be sold is

Selling price $=\frac{8.8\times10^6\times30+3.55\times10^6}{30\times374\times10^6\ kWh/year}=0.238\ \$/kWh=23.8\ ¢/kWh$

NPV and IRR with Fuel Escalation

- The chances are that the cost of fuel in the future will be higher than it is today.
- Fuel price escalation factor (e) is used in the present worth analysis:

$$PVF(d,n)=\frac{1+e}{1+d}+\frac{(1+e)^2}{(1+d)^2}+\cdots+\frac{(1+e)^n}{(1+d)^n}=\frac{(1+d')^n-1}{d'(1+d')^n}$$

- The fuel price escalation can be captured through the equivalent discount rate.

$$\frac{1+e}{1+d}=\frac{1}{1+d'}\ \text{where}\ d'=\frac{d-e}{1+e}$$

Annualizing the Investment

- Extra capital required for an energy investment will be borrowed from a lending company.
- The extra capital cost is converted into a series of n equal annual payments (A) that eventually pay off the loan(P) with interest (i),

$$A = P \times CRF(i,n)$$

$$CRF(i,n) = Capital\ recovery\ factor(yr^{-1}) = \frac{i(1+i)^n}{(1+i)^n-1}$$

$$CRF(i,n)\ per\ month = \frac{(i/12)[1+(i/12)]^{12n}}{[1+(i/12)]^{12n}-1}$$

Levelized Costs

- The cost of a power plant has two key components - an up-front fixed cost to build the plant plus an assortment of costs that will be incurred in the future.
- In the usual approach to cost estimation, a present value calculation is first performed to find an equivalent initial cost, and then that amount is spread out into a uniform series of annual costs.
  - Levelized annual costs = A_0[PVF(d', n) · CRF(d, n)]
- The ratio of the equivalent annual cost ($/yr) to the annual electricity generated (kWh/year) is called the levelized cost of electricity (LCOE).

Levelizing Factor

$$\text{Levelizing factor (LF)} = \left[\frac{(1+d')^n-1}{d'(1+d')^n}\right]\cdot\left[\frac{d(1+d)^n}{(1+d)^n-1}\right]$$

Price of Electricity from a Wind Farm - Example

A wind farm project has 40 1500-kW turbines with 64-m blades. Capital costs are $60 million and the levelized O&M cost is $1.8 million/yr. The project will be financed with a $45 million, 20-yr loan at 7% plus an equity investment of $15 million that needs a 15% return. Turbines are exposed to Rayleigh winds averaging 8.5 m/s.

What levelized price would the electricity have to sell for to make the project viable?

Solution

$$CF = 0.087\overline{V}\ (m/s) - \frac{P_R(kW)}{[D(m)]^2} = 0.087\times 8.5 - \frac{1500}{64^2} = 0.373$$

For 40 such turbines, the annual electrical production will be

$$\text{Annual energy} = 40\ \text{turbines}\times 1500\ kW\times 8760\ h/yr\times 0.373 = 196\times 10^6\ kWh/yr$$

The debt payments will be

$$A = P\cdot\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] = \$45{,}000{,}000\cdot\left[\frac{0.07(1+0.07)^{20}}{(1+0.07)^{20}-1}\right] = \$4.24\times 10^6/yr$$

The annual return on equity needs to be

$$\text{Equity} = 0.15/yr\times \$15{,}000{,}000 = \$2.25\times 10^6/yr$$

The levelized O&M cost is $1.8 million, so the total for O&M, debt, and equity is

$$\text{Annual cost} = \$(4.24+2.25+1.8)\times 10^6 = \$8.29\times 10^6/yr$$

The levelized price at which electricity needs to be sold is therefore

$$\text{Selling price} = \frac{\$8.29\times 10^6/yr}{196\times 10^6\ kWh/yr} = \$0.0423 = 4.23¢/kWh$$

Q11

11. A photovoltaic system that generates 8000 kWh/yr costs $15,000. It is paid for with a 6%, 20-year loan.

$L=15000$ $r=0.06$ $n=20$

a) Ignoring any tax implications, what is the cost of electricity from the PV system?

b) With local utility electricity costing 11¢/kWh, at what rate would that price have to escalate over the 20-year period in order for the levelized cost of utility electricity be the same as the cost of electricity from the PV system?

a) $P=\frac{L\cdot r\cdot(1+r)^n}{(1+r)^n-1}=\$1307.3/yr$

the cost of electricity:

$$LCOE = \frac{\text{Annual Loan Payment}}{\text{Annual Electricity Generation}}$$

$$LCOE = \frac{1{,}307.3}{8000} = 0.1634\ \$/kWh = 16.34¢/kWh$$

b) $P_{final} = P_{initial}\cdot(1+g)^n$

$16.34 = 11\cdot(1+g)^{20}$

$g\approx 2.01\%$

The utility price must escalate at 2.01% per year.

Q12 分时电价与需量电价计算

12. A small business uses 100 kW of power and 24,000 kWh/month during peak period. It uses 20 kW peak power and 10,000 kWh/month during off-peak period. Calculate its monthly electricity bill if:

a) Time of Use (TOU) rate schedule is used
On-peak : 12¢/kWh and Off-peak 7¢/kWh.

b) Demand Charge Schedule is used with
Energy charge 6¢/kWh and demand charge of $9/mo-kW.

a) 分时电价:
高峰电费: $24000\times 0.12 = 2880$ 美元
低谷电费: $10000\times 0.07 = 700$ 美元
总电费: $2880+700=3580$ 美元

b) 需量电价:
电量费: $(24000+10000)\times 0.06 = 2040$ 美元
需量费: $100\times 9 = 900$ 美元(按高峰需量计算)
总电费: $2040+900=2940$ 美元

Q13 需量电价变化问题

13. A commercial customer uses demand charge schedule and consumes 20,000 kWh power month with a peak demand charge of 100kW. The rate schedule used is energy charge 6¢/kWh and demand charge of $9/mo-kW. A sales engineer proposes to install an equipment that would reduce the peak demand to 80kW and increase energy efficiency by 10%. What should be cost of the equipment if the pay-back period is less than 3 years?

$$\text{Simple payback} = \frac{\text{Extra first cost } \Delta P\ (\$)}{\text{Annual savings } S(\$/yr)}$$

① Energy reduction → Energy savings: 20000×0.1 = 2000 kWh/mo
Energy cost savings: 2000×0.06 = 120 $/mo

② Demand reduction → Demand savings: (100−80)×9 = 180$/mo

③ Total savings: (120+180)×12 = 3600$/year

④ cost = 3600×3 = 10800$

Q14 负荷率相关问题

$$\text{Load factor (\%)} = \frac{\text{Average Power}}{\text{Peak Power}}\times 100\%$$

14. Two customers use 10,000kWh per month and pay according to a demand charge schedule with energy charge 6¢/kWh and demand charge of $9/kW-mo. One customer has a load factor of 15% whereas the other has a load factor of 60%. What is difference in their monthly energy bills?

$$Peak(A) = \frac{10000\ kWh/mo}{15\%\times 24h/day\times 30\ day/mo}\times 100\% = 92.59\ kW$$

which, at $9/mo-kw, will incur demand charges of $833.31/mo

Bill(A) = (10000×0.06) + (92.6×9) = 1433.4$

$$Peak(B) = \frac{10000\ kWh/mo}{60\%\times 24h/day\times 30\ day/mo}\times 100\% = 23.15\ kW$$

costing $208.35/mo

Bill(B) = (10000×0.06) + (23.15×9) = 808.4$

差异: $1433.31 - 808.35 \approx 624.96$ 美元

补充问题(NPV 是一个项目未来所有现金流的当前总价值,减去初始投资后得到的净值)

Example 5.7 Net Present Value of Premium Motor with Fuel Escalation. The premium motor in Example 5.6 costs an extra $500 and saves $192/yr at today's price of electricity. If electricity rises at an annual rate of 5%, find the net present value of the premium motor if the best alternative investment earns 10%.

e

d

Solution. Using (5.15), the equivalent discount rate with fuel escalation is

$$d' = \frac{d-e}{1+e} = \frac{0.10-0.05}{1+0.05} = 0.04762$$

From (5.9), the present value function for 20 years of escalating savings is

n=

$$PVF(d',n) = \frac{(1+d')^n-1}{d'(1+d')^n} = \frac{(1+04762)^{20}-1}{0.04762(1+0.04762)^{20}} = 12.717\ yr$$

From (5.10), the net present value is

$$NPV = \Delta A\times PVF(d',n) - \Delta P \quad = \$192/yr\times 12.717\ yr - \$500 = \$1942$$

TOU 电价和 Demand charges

TABLE 5.2 Example Residential Time-of-Use (TOU) Rate Schedule

	November–April		May–October	
On-peak	7–10 A.M., 5–8 P.M.	8.335 ¢/kWh	2–8 P.M.	19.793 ¢/kWh
Off-peak	All other times	7.491 ¢/kWh	All other times	8.514 ¢/kWh

Example 5.2 PVs, TOU Rates, and Net Metering. During the summer a rooftop PV system generates 10 kWh/day during the off-peak hours and 10 kWh/day during the on-peak hours. Suppose too, that the customer uses 2 kWh/day on-peak and 18 kWh/day off-peak. That is, the PVs generate 20 kWh/day and the household consumes 20 kWh/day.

	PV supply	Demand
On-peak	10kWh	2kWh
Off-peak	10kWh	18kWh
Total	20kWh/day	20kWh/day

For a 30-day month in the summer, find the electric bill for this customer if the TOU rates of Table 5.2 apply.

Solution During the on-peak hours, the customer generates 10 kWh and uses 2 kWh, so there would be a credit of

$$\text{On-peak credits} = 8\ kWh/day\times \$0.19793/kWh\times 30\ day/mo = \$47.50$$

During the off-peak hours, the customer generates 10 kWh and uses 18 kWh, so the bill for those hours would be

$$\text{Off-peak bill} = 8\ kWh/day\times \$0.08514/kWh\times 30\ day/mo = \$20.43/mo$$

So the net bill for the month would be

$$\text{Net bill} = \$20.43 - \$47.50 = -\$27.07mo$$

That is, the utility would owe the customer $27.07 for this month. Most likely in other months there will be actual bills against which this amount would be credited.

Notice that the bill would have been zero, instead of the $27.07 credit, had this customer elected the standard rate schedule of Table 5.1 instead of the TOU rates.

For a 30-day month in the summer, find the electric bill for this customer if the TOU rates of Table 5.2 apply.

TABLE 5.3 Electricity Rate Structure Including Monthly Demand Charges

	Winter Oct–May	Summer June–Sept
Energy charges	$0.0625/kWh	$0.0732/kWh
Demand charges	$7/mo-kW	$9/mo-kW

Example 5.3 Impact of Demand Charges. During the summer, a small commercial building that uses 20,000 kWh per month has a peak demand of 100 kW.

a. Compute the monthly bill (ignoring fixed customer charges).
b. How much does the electricity cost for a 100-W computer that is used 6 h a day for 22 days in the month? The computer is turned on during the period when the peak demand is reached for the building. How much is that in ¢/kWh?

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Solution

a. The monthly bill is made up of energy and demand charges:

$$\text{Energy charge} = 20{,}000\ kWh\times \$0.0732/kWh = \$1464/mo$$
$$\text{Demand charge} = 100\ kW\times \$9/mo\text{-}kW = \$900/mo$$

For a total of $1464 + $900 = $2364/mo (38% of which is demand)

b. The computer uses 0.10 kW × 6 h/d × 22 day/mo = 13.2 kWh/mo

$$\text{Energy charge} = 13.2\ kWh/mo\times \$0.0732/kWh = \$0.97/mo$$
$$\text{Demand charge} = 0.10\ kW\times \$9/mo\text{-}kW = \$0.90/mo$$
$$\text{Total cost} = \$0.97+\$0.90 = \$1.87/mo$$

On a per kilowatt-hour basis, the computer costs

$$\text{Electricity} = \frac{\$1.87/mo}{13.2\ kWh/mo} = \$0.142/kWh$$

Notice how the demand charge makes the apparent cost of electricity for the computer (14.2¢/kWh) nearly double the 7.32 ¢/kWh price of electric energy.

Ratchet Clause(阶梯/追溯条款)某月最高需量将作为后续数月的最低计费需量。

Example 5.4 Impact of Ratcheted Demand Charges on an Efficiency Project. A customer's highest demand for power comes in August when it reaches 100 kW. The peak in every other month is less than 70 kW. A proposal to dim the lights for 3 h during each of the 22 workdays in August will reduce the August peak by 10 kW. The utility's energy charge is 8¢/kWh and its demand charge is $9/kW-mo with an 80% ratchet on the demand charges.

a. What is the current annual cost due to demand charges?
b. What annual savings in demand and energy charges will result from dimming the lights?
c. What is the equivalent savings expressed in ¢/kWh?

Solution

a. At $9/kW-mo, the current demand charge in August will be

$$\text{August} = 100\ kW\times \$9/kW\text{-}mo = \$900$$

For the other 11 months, the minimum demand charge will be based on 80 kW, which is higher than the actual demand:

$$\text{Sept–July demand charge} = 0.8\times 100\ kW\times \$9/kW\text{-}mo\times 11\ mo = \$7920$$

So the total annual demand charge will be

$$\text{Annual} = \$900+\$7920 = \$8820$$

b. By reducing the August demand by 10 kW, the annual demand charges will now be

$$\text{August} = 90\ kW\times \$9/kW\text{-}mo = \$810$$
$$\text{Sept–July} = 0.8\times 90\ kW\times \$9/kW\text{-}mo\times 11\ mo = \$7128$$
$$\text{Total annual demand charge} = \$810+\$7128 = \$7938$$
$$\text{Annual demand savings} = \$8820-\$7938 = \$882$$

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e.g. The demand charge for every month may be based on 80% of the annual peak demand.

$$\text{August energy savings} = 3\ h/d\times 10\ kW\times 22\ days\times \$0.08/kWh = \$52.80$$

$$\text{Total Annual Savings} = \$882+\$52.80 = \$934.80$$

Notice that the demand savings is 94.4% of the total savings!

c. Dimming the lights saved 3 h/d × 10 kW × 22 d = 660 kWh and $934.80, which on a per kWh basis is

$$\text{Savings} = \frac{\$934.80}{660\ kWh} = \$1.42/kWh$$

In other words, the business saves $1.42 for each kWh that it saves, which is about 18 times more than would be expected if just the $0.08/kWh cost of energy is considered.

Smart grid

What is a Microgrid?

- Micro grids comprise LV distribution systems with distributed energy resources (DER) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads.
- Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid.
- The operation of micro sources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently.
- Microgrid is an integration platform for supply-side (microgeneration), storage units and demand resources (controllable loads) located in a local distribution grid.
- A microgrid should be capable of handling both normal state (grid-connected) and emergency state (islanded) operation.

Importance of Storage System

During renewable excess/deficit

In grid connected mode batteries can store excess of renewable energy when demand is less and supply the required deficit power when renewable generation is less

During Islanded mode

Grid support action: Helps to regulate the grid voltage by its charging/discharging action.

To flatten load curve

Since both renewable generation and loads are variable by nature, usage of batteries can flatten the load curve.

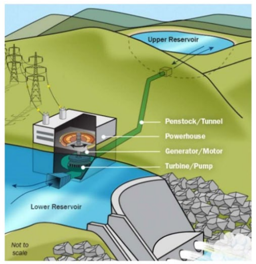
Performance factors for energy storage systems

- Energy capture rate and efficiency
- Discharge rate and efficiency
- Dispatchability and load following characteristics
- Scale flexibility
- Durability – cycle lifetime
- Mass and volume requirements – footprint of both weight and volume
- Safety – risks of fire, explosion, toxicity
- Ease of materials recycling and recovery

Pumped Hydro System(抽水蓄能)

Pumped Hydro System

- Water is pumped from a lower reservoir uphill and then allowing it to flow downhill to through turbines to produce electricity.
- Readily available and widely used in high power applications
- Lower cost of power, frequency regulation on the grid, and reserve capability
- Can only be implemented in areas with hills .



Flywheels(飞轮储能)

A cylinder that spins at a very high speed, storing kinetic energy.

Advantages of Flywheels

- Charge and discharge rapidly
- Affected little by temperature fluctuations
- Take up relatively little space
- Long life span
- Tolerant of abuse
- Lower maintenance requirements than batteries
- Flywheels with magnetic bearings and high vacuum can maintain 97% mechanical efficiency, and 85% round-trip efficiency
- Flywheels may be used to store energy generated by wind turbines during off-peak periods or during high wind speeds.

- Disadvantage: Power loss faster than batteries.

Compressed Air Energy Storage (CAES) 压缩空气储能

Compressed Air Energy Storage (CAES)

- Utilities use electricity generated during off-peak hours (i.e., storage hours) to compress air and store it in airtight underground caverns.
- When the air is released from storage, it expands through a combustion turbine to create electricity.
- Conserves some natural gas by using low-cost, heated compressed air to power turbines and create off-peak electricity.
- Has low efficiency due to the extra reheating energy needed to turn on the turbines.
- For every kWh of energy going in, only 0.5 kWh of energy can be taken out.

电池

Batteries

Lead Acid Batteries
- Suitable for large storage application
- Low cost but high maintenance

Sodium Sulphur (NaS)
- High energy density (Four times of lead acid),
- Long cycle capability
- Suitable for stationary energy storage applications

Lithium-Ion
- Environmental friendly
- Suitable for portable devices like mobile phones, laptops, power tools and also in Electric vehicles

Lithium-Ion Polymer
- Higher specific energy than other lithium battery types and are being used in applications where weight is a critical feature
- Suitable for portable devices like mobile phones and notebook computers

DC Microgrid

Importance of DC

- Various conversion stages like AC-DC/DC-AC can be avoided by forming DC Grid and Overall System efficiency can be improved.
- No problem of reactive power, harmonics, frequency control.
- No synchronization issues and Controlling becomes easier.
- Eddy current, hysteresis losses and skin effect are absent.
- Reduces stress on conventionally grid, congestion of transmission line will be reduced.

DC operation based on Voltage Level

HVDC
- Operating voltage range 500kV and above, Economical and efficient over AC at long distance transmission.
- Power transfer between two separate AC networks.

MVDC
- Operating voltage level is 11kV and 33kV
- Can provide controlled power transfer between two 11kV and 33kV networks for better utilization of existing network.

LVDC
- Operating voltage levels are 48V/380V/600V
- Reduces dependency on main grid, reliability to the consumer can be improved, and provide supply to remote villages.

Single-bus DC Microgrid

Simple, suitable for low-voltage DC systems

Direct storage: low cost, poor controllability

Converter-interfaced storage: flexible control, higher reliability

Multi-bus DC Microgrid

Multiple buses improve efficiency and flexibility

Dual-bus reduces single-point failure

Microgrid clustering enables energy sharing

SST enables intelligent low-voltage energy management

Reconfigurable DC Microgrid

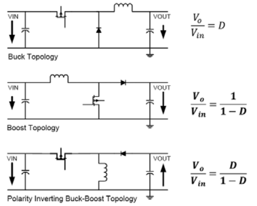
Topology can be reconfigured

Ring bus provides redundancy

Zonal structure enables fault isolation

Multi-terminal DC offers multiple power paths

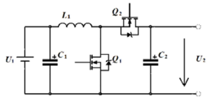
Buck, Boost, Buck-Boost Converters



Bi-Directional DC-DC converters

The key constraints of bidirectional DC-DC converter are:
- Single converter
- Simplicity using minimal storage elements.
- Allow bi-directional power flow from one source to other and vice versa.

Non-isolated bi-directional converter topology
- Half-bridge converter
- Cascaded half-bridge converte



Protection Devices in LVDC（常见的直流保护器件）

Fuses/LV power CBs/Moulded Case Circuit

Brèakers/Isolated case CBs

Challenges in DC Microgrid

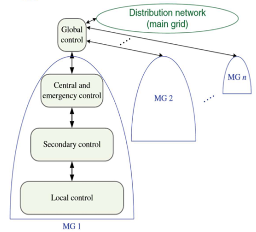
- Lack of Standards
- Protection issues : no DC circuit breaker
- Lack of DC infrastructure
- Circulating currents in parallel operation, Grounding issues.
- Unable to feed AC loads of Industries, Commercial and Residential applications.

MG Control

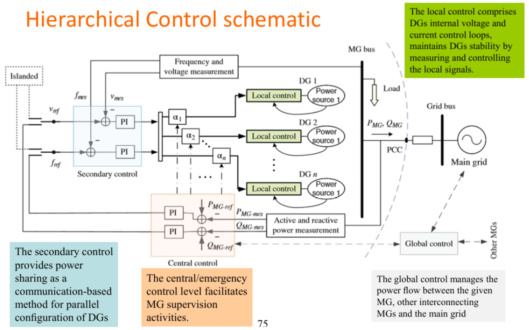
- MGs should be able to not only operate autonomously but also interact with the main grid.
- In the grid-connected operation mode, the MGs are integrated into a constantly varying electrical grid with changing tie-line flow, voltages, and frequency. To cope with those variations, to respond to grid disturbances, and to perform active power/frequency regulation, as well as reactive power/voltage regulation, MGs need to use proper control loops.
- Furthermore, suitable islanding detection feedbacks/algorithms are needed to ensure a smooth transition from the grid-connected to islanded mode to avoid cascaded failures.

Hierarchical Control Strategy

Consists of four levels:
1. local (primary) controls,
2. secondary controls,
3. central/emergency controls, and
4. global controls



Hierarchical Control schematic



Time scales of control levels

global control: several of minutes to hour

Central control: a few minutes

Secondary control: a few seconds to minute.

local controls ： instantaneously

Microgrid Control (P77–80) – Compact Summary

Local (Primary) Control: Ensures stability of individual DG units through inner voltage/current control loops; depends on DG type (synchronous, induction, inverter-based); no communication required; fastest response (ms); provides stability but allows steady-state voltage/frequency deviations.

Secondary Control: Complements local control by removing steady-state voltage and frequency deviations caused by load changes; generates reference signals E^*, ω^*; requires low-bandwidth communication; slower dynamics than local control (seconds to minutes).

Central / Emergency Control: Supervises overall microgrid operation and resource scheduling; activated during abnormal conditions such as faults or limit violations; coordinates corrective actions to maintain system security; operates on a minutes timescale.

Global Control: Highest-level control coordinating power exchange between microgrids and the main grid; manages active/reactive power at system level and treats a microgrid as a dispatchable unit; operates on minutes-to-hours timescale with full communication support.

本地（一次）控制：通过内部电压/电流控制环保证单个分布式电源（DG）的稳定运行，控制方式取决于 DG 类型（同步机、感应机、逆变器型电源）；无需通信，响应速度最快（毫秒级）；可保证稳定性，但会引入稳态电压和频率偏差。

二次控制：用于补偿一次控制造成的稳态电压与频率偏差，在负载变化或运行状态调整时提供参考信号 E^* 和 ω^*；需要低带宽通信，动态响应慢于本地控制（秒到分钟级）。

集中 / 应急控制：负责微电网整体运行的监视与调度，在故障、越限或异常工况下介入，协调各单元采取纠正措施以维持系统安全，运行时间尺度为分钟级。

全局控制：最高层控制，用于协调微电网与主电网或多个微电网之间的功率交换，在系统层面进行有功/无功管理，将微电网视为可调度单元，运行时间尺度为分钟到小时级。

Stability of Microgrid

- MG can have small signal instability, transient instability, voltage instability, and frequency instability problem.
- Dynamic impacts of feedback controllers, continuous load switching and oscillation modes are causes of small signal stability.
- Unexpected islanding, DG outage, large and sudden load change, and cascaded faults are known as reasons of the transient instability problems.
- Reactive power limits, load dynamics, and tap changers create most of the voltage stability problems.
- Load-generation imbalance and active power limits can be considered as the main reasons for frequency instability in an MG.

1 小信号稳定
- 控制器动态
- 频繁负载变化

2 暂态稳定
- 突发事件
- DG 跳闸
- 突然孤岛

3 电压稳定
- 无功不足
- 负载特性

4 频率稳定
- 有功失衡
- 惯量不足

Low inertia of MGs

- Compared to conventional power systems with bulk power plants, microgrids (MGs) with DG/RES units have either small or no rotating mass and damping property.
- Relatively high integration of inverter-based distributed generators (DGs) and renewable energy sources (RESs) will have some impacts on power grid dynamics, frequency, and voltage regulation, as well as other control and operation issues.

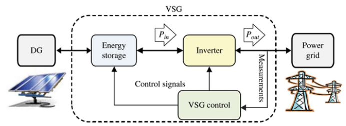
为什么微电网惯量低?
- 少同步机
- 多逆变器
- 几乎没有旋转质量

带来的问题
- 频率变化快
- 系统更"脆"

"解决低惯量"的关键方案

Virtual Synchronous Generators : Dynamic Performance and Characteristics

- A solution towards stabilizing a grid/MG with numerous low-inertia DGs is to fortify the system with additional inertia, virtually.
- Virtual inertia can be established by using short-term energy storage together with a power electronics inverter/converter and a proper control mechanism in a system that is called virtual synchronous generator(VSG).



Microgrid Protection

- Protection of Microgrid especially when it is islanded is quite challenging
- The first and foremost challenge is to detect the islanding of the microgrid
- The second important challenge is how to provide segments of the microgrid with sufficient coordinated fault protection while operating as an island separated from the utility

两大核心挑战

1 孤岛检测
- 必须快、准
- 防止误动作

2 孤岛下保护协调
- 故障电流小
- 方向变化
- 传统保护失效