06-Off-Grid Generators and Gen Sets

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 6

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries, 2nd Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
- Inquiries about guest lectures, seminars, or trainings can be made to hlouie@ieee.org
- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

Learning Outcomes

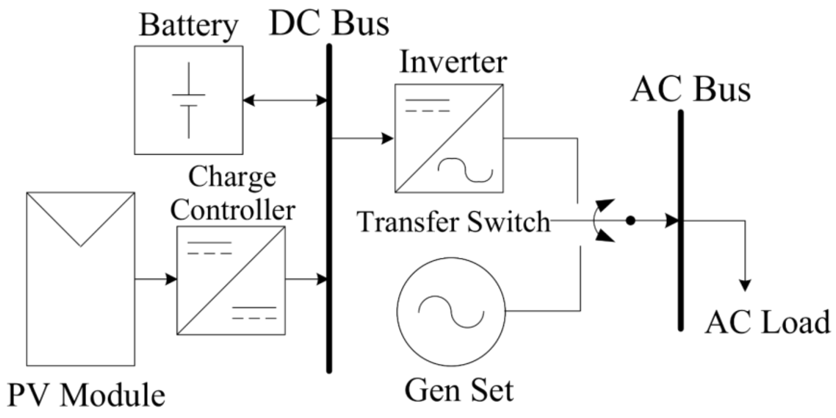
At the end of this lecture, you will be able to:

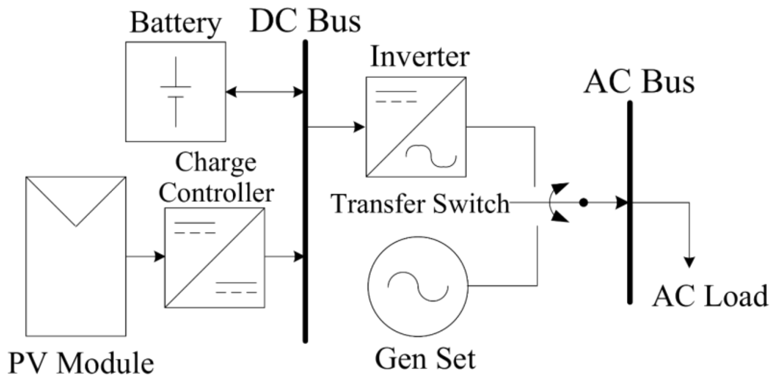
- ✓Describe the use of generator sets (gen sets) in off-grid electrification, emphasizing the key technical, economic, environmental, and social considerations
- ✓Apply the appropriate mathematical and circuit models to explain the mechanical and electrical behavior of synchronous generators
- ✓Explain the components and core principles of operation of internal combustion engine gen sets
- ✓Calculate the efficiency, fuel consumption, emissions, and other design and operation considerations for gen sets in off-grid applications

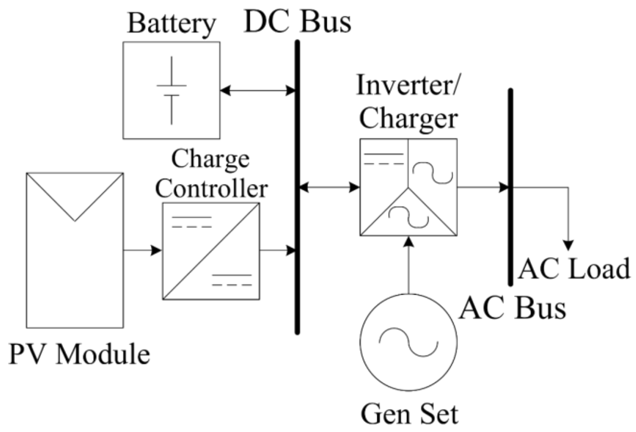
Introduction

- Electrical generators are found in wind energy conversion systems, micro hydro power systems, and fossil- and biomass-fueled generator sets
- Generator Sets (gen sets): electrical generators powered by internal combustion engines
- Commonly used in off-grid electrification (and as backup generation when the grid has unreliable power)

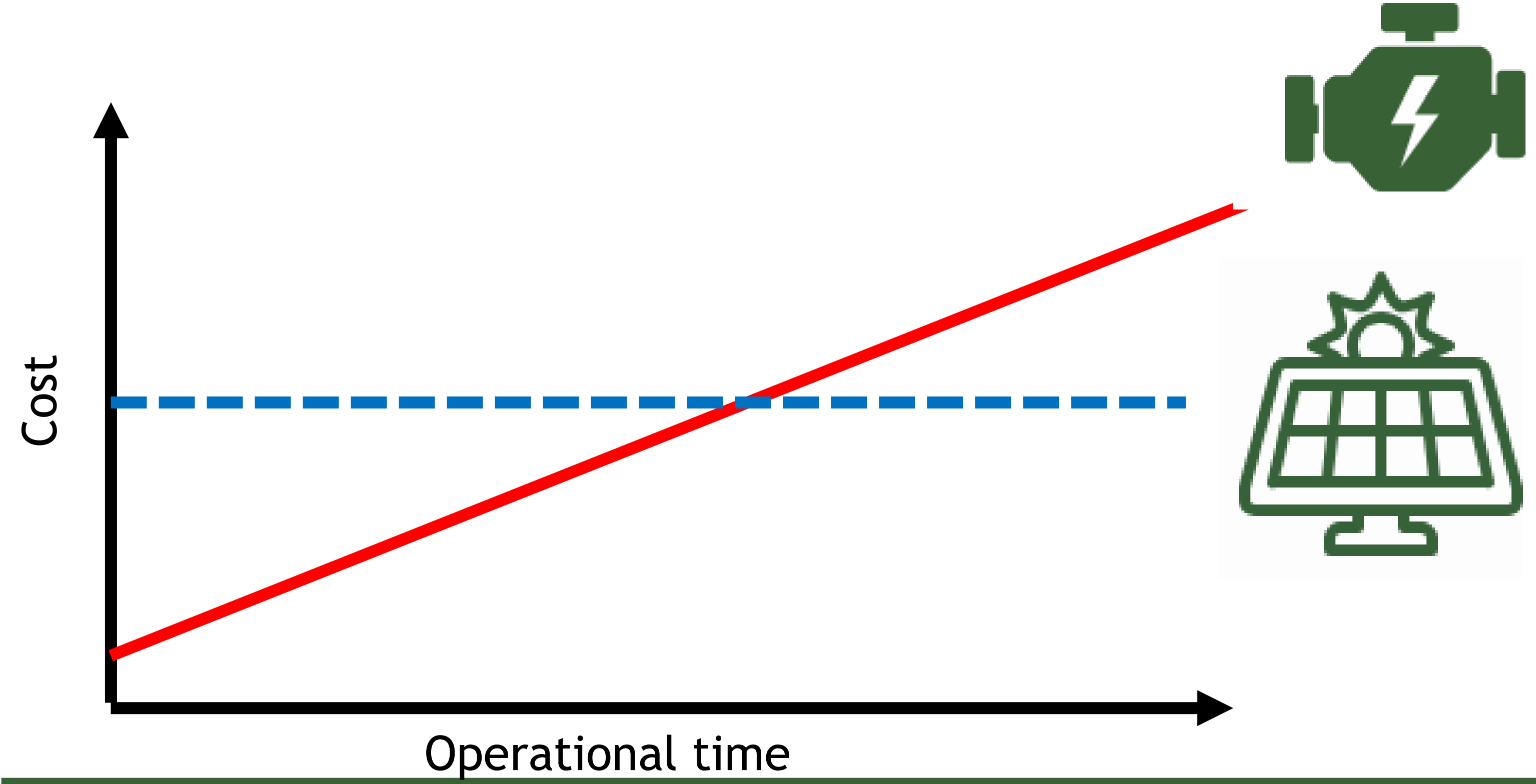
Example Generator Set Architectures







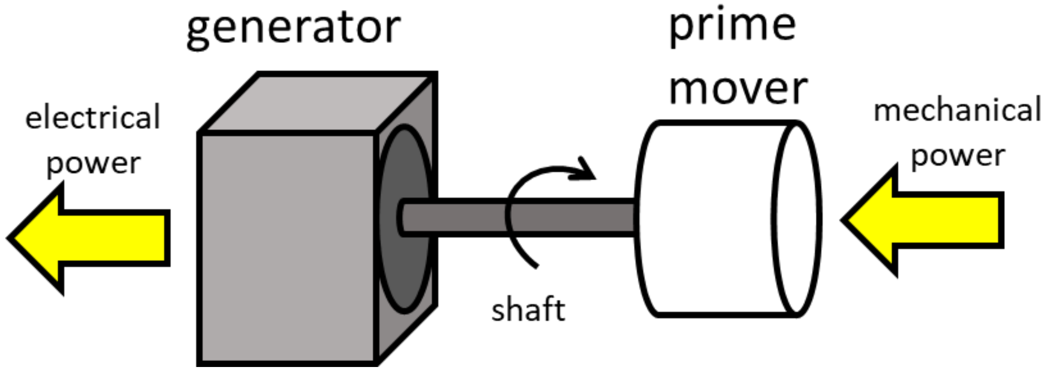
Gen Sets… the big picture



Gen sets make economic sense when the operational time is limited (for example as backup) or when high reliability is needed

Electrical Generators

- Electrical generators convert mechanical power to electrical power
- Off-grid system prime mover powered by internal combustion engine (ICE), wind turbine, hydro turbine
- We consider "synchronous" generators
  - induction generators sometimes used

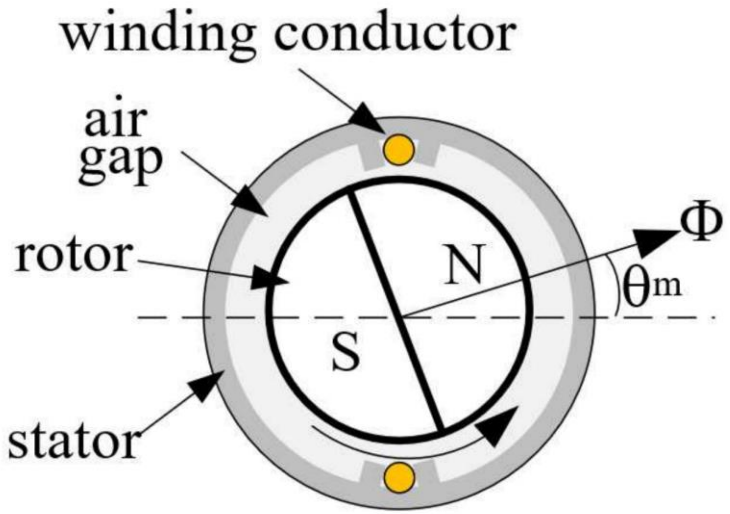


motors are generators operated in "reverse"

Principles of Operation

- Faraday's Law and Lenz's Law: changing magnetic flux induces voltage in coil
- Synchronous generators: magnetic flux provided by magnet (or electromagnet) in rotating shaft (rotor) and coils (armature windings) are stationary (in the stator)
  - as rotor rotates, the coils "see" sinusoidally varying flux
  - sinusoidal voltage is induced
- Rotor shaft is mechanically coupled to the prime mover

Principles of Operation



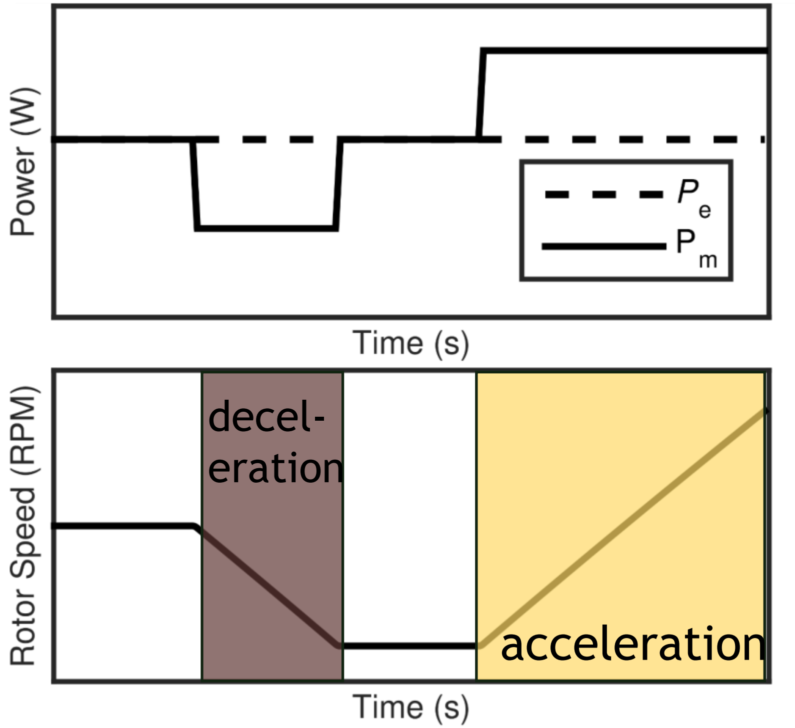
cross section of two-pole synchronous generator with one stator coil

flux ϕ leaves from rotor's north pole

Electrical Generator Basic Concepts

1. The electrical load (P_e) on the generator must be equally matched by the mechanical power (P_m) provided by prime mover (assuming the generator is electrically and mechanically lossless); otherwise, the rotating shaft will speed up or slow down

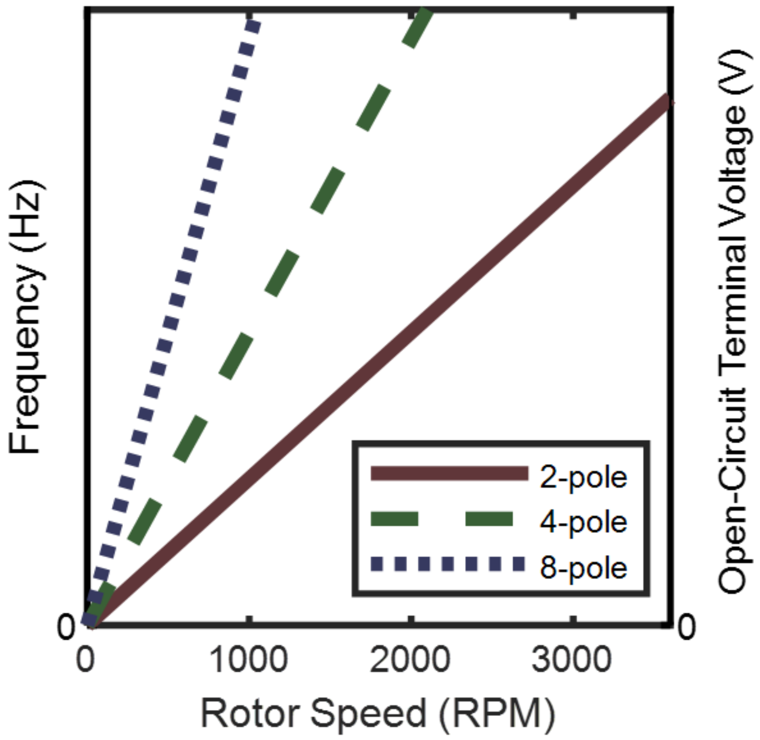
This is a consequence of the law of conservation of energy



Electrical Generator Basic Concepts

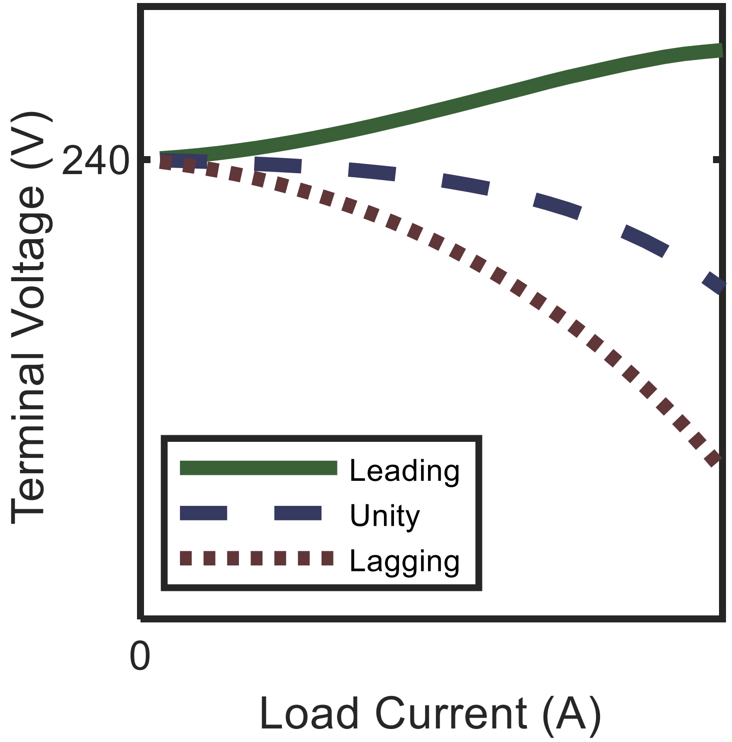
2. The frequency and magnitude of the voltage produced are proportional to:
    - rotational speed of the rotor
    - magnitude of the flux linking the coils
    - number of poles

This is a consequence of Lenz's Law



Electrical Generator Basic Concepts

3. The voltage that appears at the generator's terminals depends on the magnitude and power factor of the load



Induced Voltage

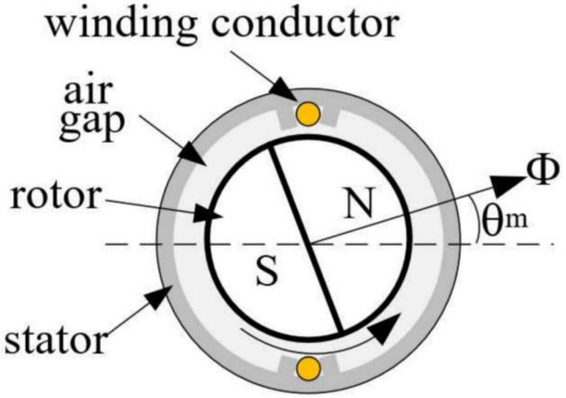
- Flux linking a winding with multiple turns

$$\phi_{\mathrm{w}} = n_{\mathrm{turns}} \Phi \cos(\theta_{\mathrm{m}})$$

- Assuming the rotor spins at a uniform speed

$$\theta_{\mathrm{m}} = \omega_{\mathrm{m}} t$$

- Induced voltage with no-load

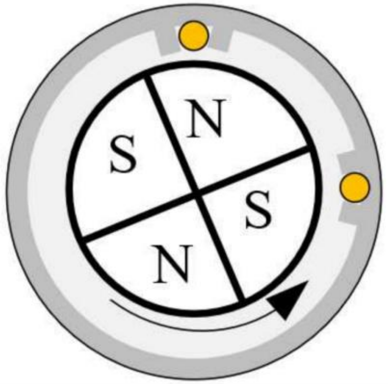


$$e(t) = -\frac{\mathrm{d}\phi_{w}}{\mathrm{d}t} = n_{\mathrm{turns}} \Phi \frac{\mathrm{d}\theta_{\mathrm{m}}}{\mathrm{d}t} \sin(\theta_{\mathrm{m}}) = n_{\mathrm{turns}} \Phi \omega_{\mathrm{m}} \sin\left(\theta_{\mathrm{m}}\right) = n_{\mathrm{turns}} \Phi \omega_{\mathrm{m}} \sin\left(\omega_{\mathrm{m}} t\right)$$

$$\frac{\mathrm{d}\theta_{\mathrm{m}}}{\mathrm{d}t} = \omega_{\mathrm{m}}$$

Induced Voltage: Multipole Case

- Generators often have multiple "poles"
- Coil sees two North-South transitions for each mechanical revolution
- Induced voltage becomes



$$e(t) = n_{\mathrm{turns}} \Phi \omega_{\mathrm{m}} \frac{p}{2} \sin\left(\frac{p}{2}\omega_{\mathrm{m}} t\right)$$

p: number of poles (not power)

Increasing number of poles increases frequency and magnitude of induced voltage for a given rotational speed

Output Voltage Frequency

- Conversion between hertz and revolution per minute (RPM)

$$N = f \times 60$$

- Relationship between mechanical speed (N_m) and frequency of output voltage (f_e) is

$$f_e = \frac{f_m p}{2} = \frac{N_m p}{120}$$

Exercise

What is the fastest speed a generator can rotate at and produce 60 Hz voltage?

A. 60 RPM
B. 600 RPM
C. 1800 RPM
D. 3600 RPM

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A. 60 RPM

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C. 1800 RPM

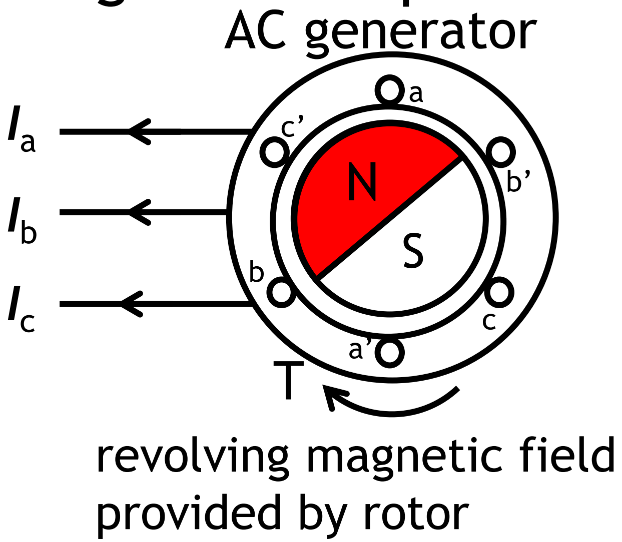
D. 3600 RPM

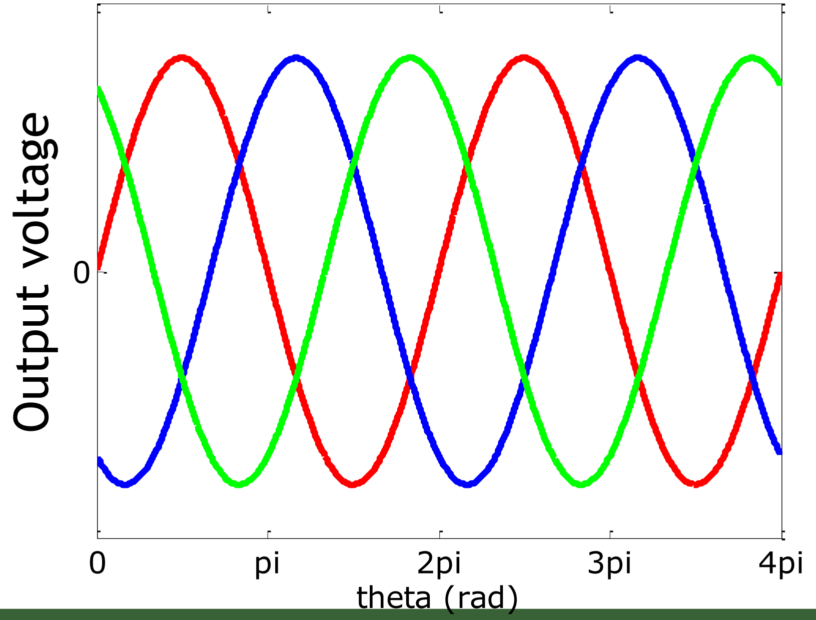
$$f_e = \frac{N_m p}{120}$$

$$60 = \frac{3600 \times 2}{120}$$

Three-Phase Generators

- Most generators produce 3-phase AC
- a, b, c phase windings displaced physically by 120°
- Induced voltages out of phase by 120°



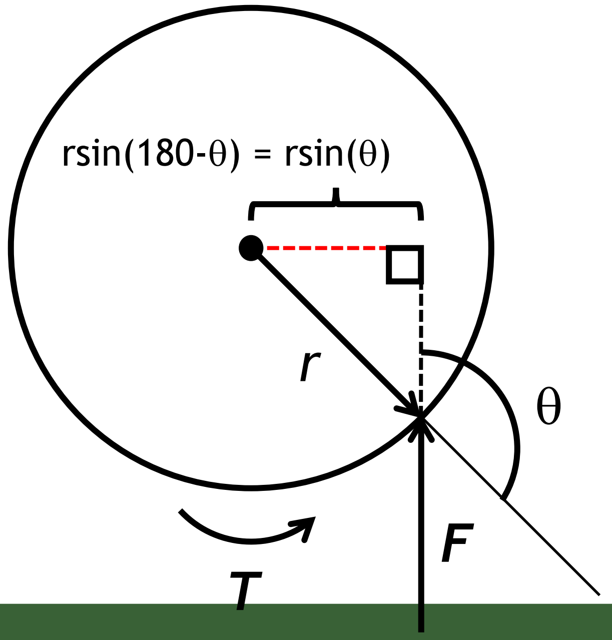


Speed, Torque, and Power

- Generator rotational speed affects the torque and power requirements from the prime mover
  mechanical power = speed x torque
- Increasing the number of poles for slower rotation to achieve a desired electrical frequency increases the required torque from the prime mover
  - larger generator shaft required

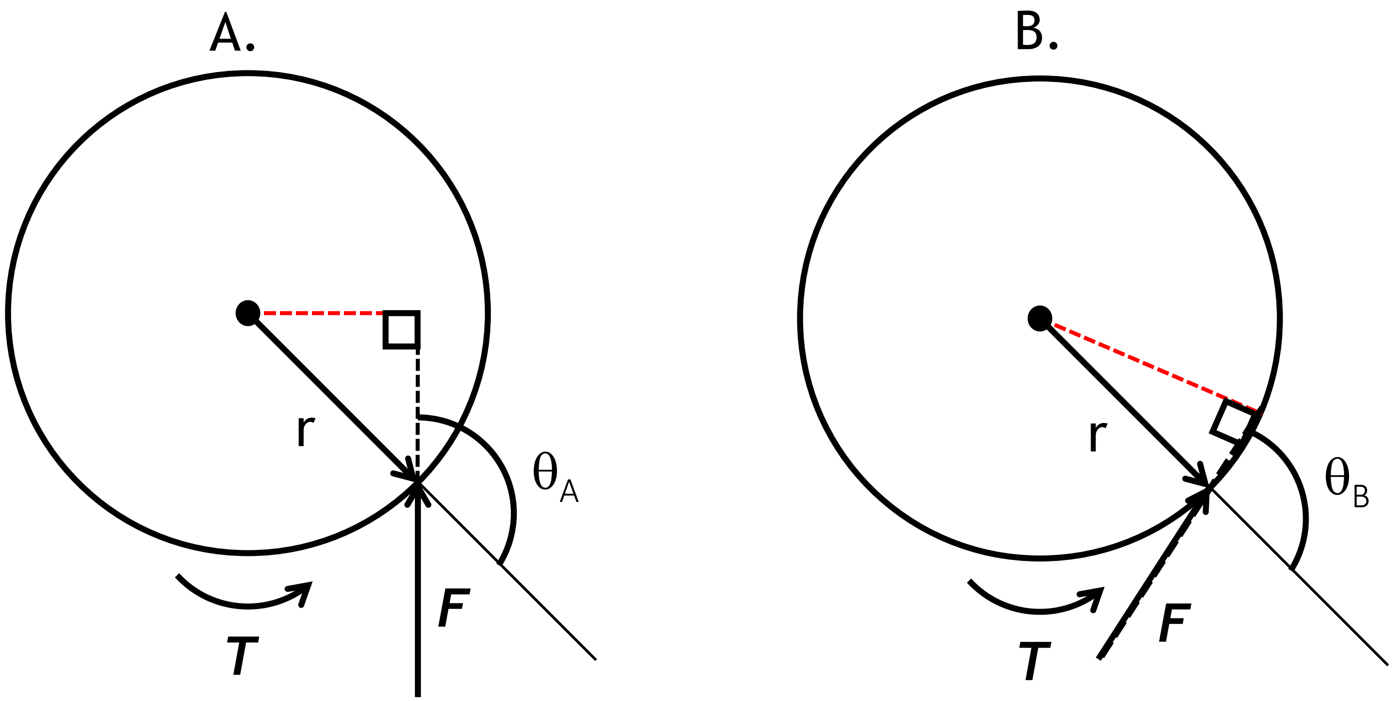
Torque

- Torque: tangential force times radial distance at which it is applied measured from axis of rotation
- $\boldsymbol{T} = \boldsymbol{F}r\sin(\theta)$ (in Nm)



Exercise

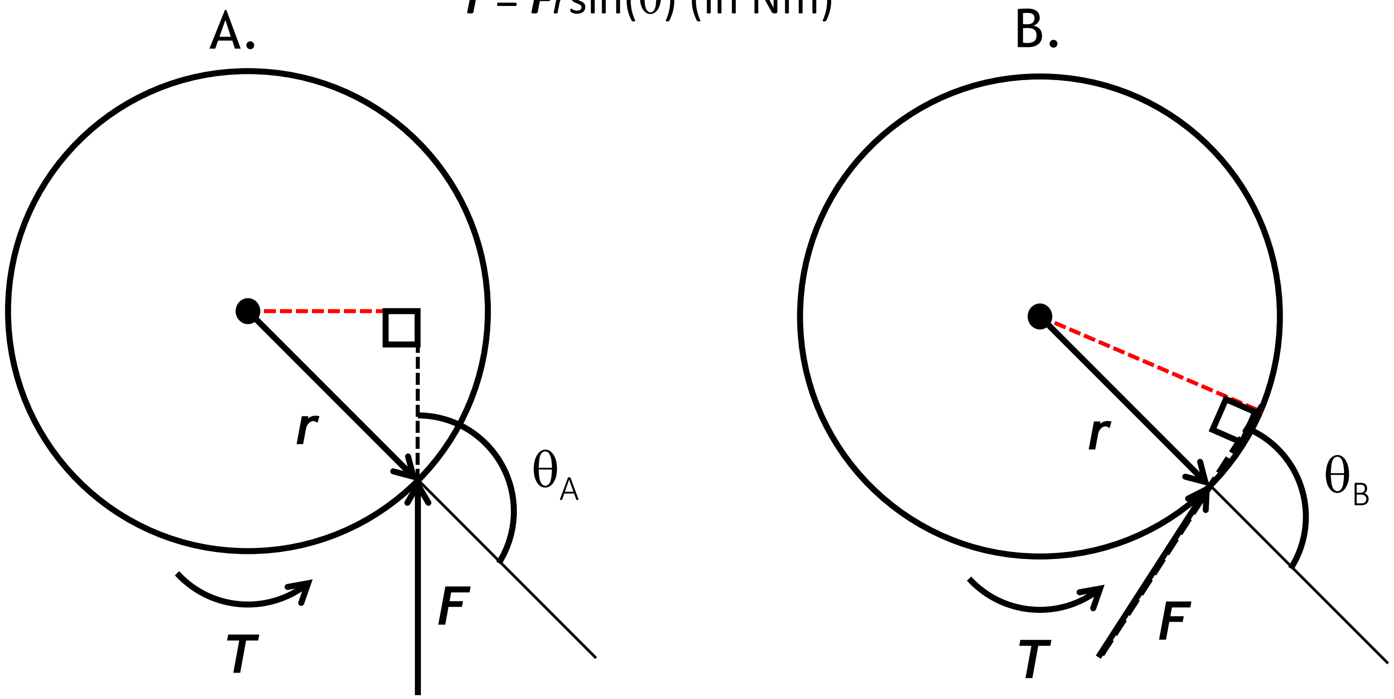
Which experiences greater torque?



Exercise

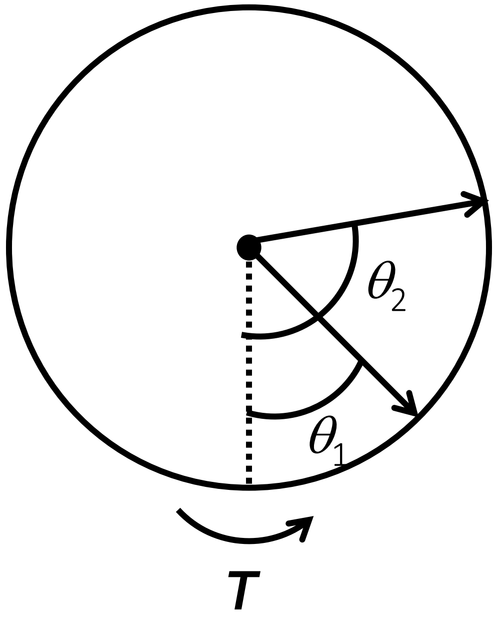
B. experiences greater torque

$\boldsymbol{T} = \boldsymbol{F}r\sin(\theta)$ (in Nm)



Work

- Torque through an angle is work
- For constant torque: $\boldsymbol{W} = \boldsymbol{T}(\theta_2 - \theta_1)$ (joules)
  - θ_1: starting angle (radians)
  - θ_2: ending angle (radians)



Power

Power is rate of work

$$P = \frac{\mathrm{d}W}{\mathrm{dt}} = T\frac{\mathrm{d}\theta}{\mathrm{dt}} = T\omega_{\mathrm{m}} \text{ (watts)}$$

$$T = \frac{P}{\omega_{\mathrm{m}}}$$

angular velocity (rad/sec)

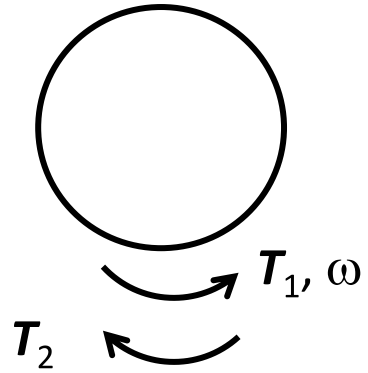
Rotational Dynamics

A shaft experiencing torque will accelerate according to:

$$\alpha_m J = \frac{d\omega_m}{dt} J = T_{net} = T_1 - T_2$$

where

- α: angular acceleration (rad/s^2)
- J: mass moment of inertia (kgm^2)



If $T_1 = T_2$: speed unchanged
If $T_1 < T_2$: slows down
If $T_1 > T_2$: speeds up

Rotational Dynamics

- Generator shaft experience two torques
  - mechanical torque provided by the prime mover
  - electomagnetic torque caused by the interaction of the rotor's magnetic field and that produced by the current in the stator
- Torques are in opposite directions (otherwise the torque would only increase, violating conservation of energy)

Rotational Dynamics

Acceleration/deceleration of rotor depends on the net torque

Net Torque	Condition	Result
$T_{\mathrm{net}} > 0$	$T_{\mathrm{m}} > T_{\mathrm{e}}$, $P_{\mathrm{m}} > P_{\mathrm{e}}$	Rotor accelerates
$T_{\mathrm{net}} = 0$	$T_{\mathrm{m}} = T_{\mathrm{e}}$, $P_{\mathrm{m}} = P_{\mathrm{e}}$	Rotor speed constant
$T_{\mathrm{net}} < 0$	$T_{\mathrm{m}} < T_{\mathrm{e}}$, $P_{\mathrm{m}} < P_{\mathrm{e}}$	Rotor decelerates

Speed Control

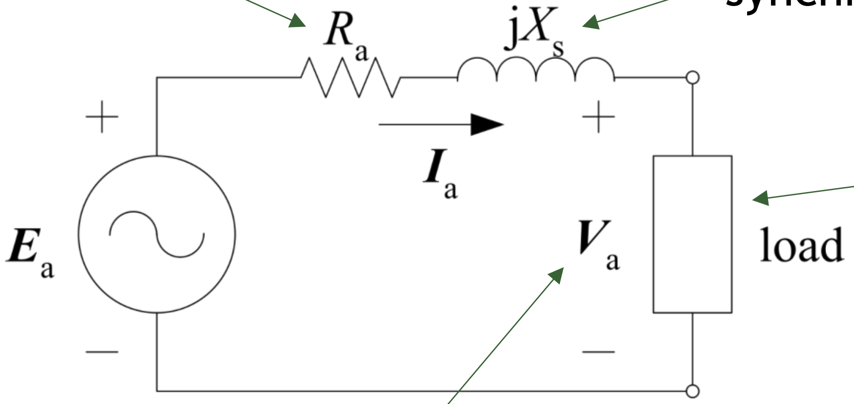
- Rotational speed affects voltage output of generator
- Important to regulate rotational speed
  - WECS and some MHP cannot do this and therefore cannot “form” the AC bus (see Chap. 4)
- Net torque must be controlled
  - mechanical power to prime mover can be controlled by governors (gen sets) and valves (some MHP)

Circuit Model

Equivalent circuit of a single phase of a synchronous generator

winding resistance

synchronous reactance



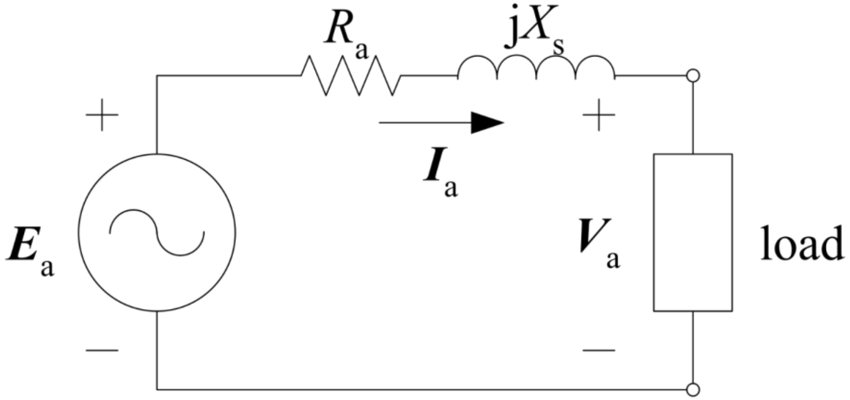
external load

induced voltage,
depends on rotational speed,
flux, machine parameters

terminal voltage

Circuit Model

Equivalent circuit of a single phase of a synchronous generator



$$\boldsymbol{V}_a = \boldsymbol{E}_a - \boldsymbol{I}_a \left(R_a + jX_s\right)$$

Example 6.3

Consider a stand-alone off-grid system consisting of a load and single-phase generator coupled to an AC bus. The bus voltage is nominally 230 V. The generator's resistance is 0.75 Ω and synchronous reactance is 7.5 Ω. Compute the terminal voltage if the induced voltage is $\boldsymbol{E}_a = 230\angle 0^\circ$ V, and the armature current is $\boldsymbol{I}_a = 25.0\angle -70^\circ$ A. Compare this to the open-circuit voltage.

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$$\begin{aligned} \boldsymbol{V}_a &= \boldsymbol{E}_a - \boldsymbol{I}_a\left(R_a + jX_s\right) \\ &= 230\angle 0^\circ - 25.0\angle -70^\circ\left(0.75 + j7.5\right) = 66.40\angle -44.46^\circ\,\mathrm{V} \end{aligned}$$

The terminal voltage has dropped considerably

Excitation

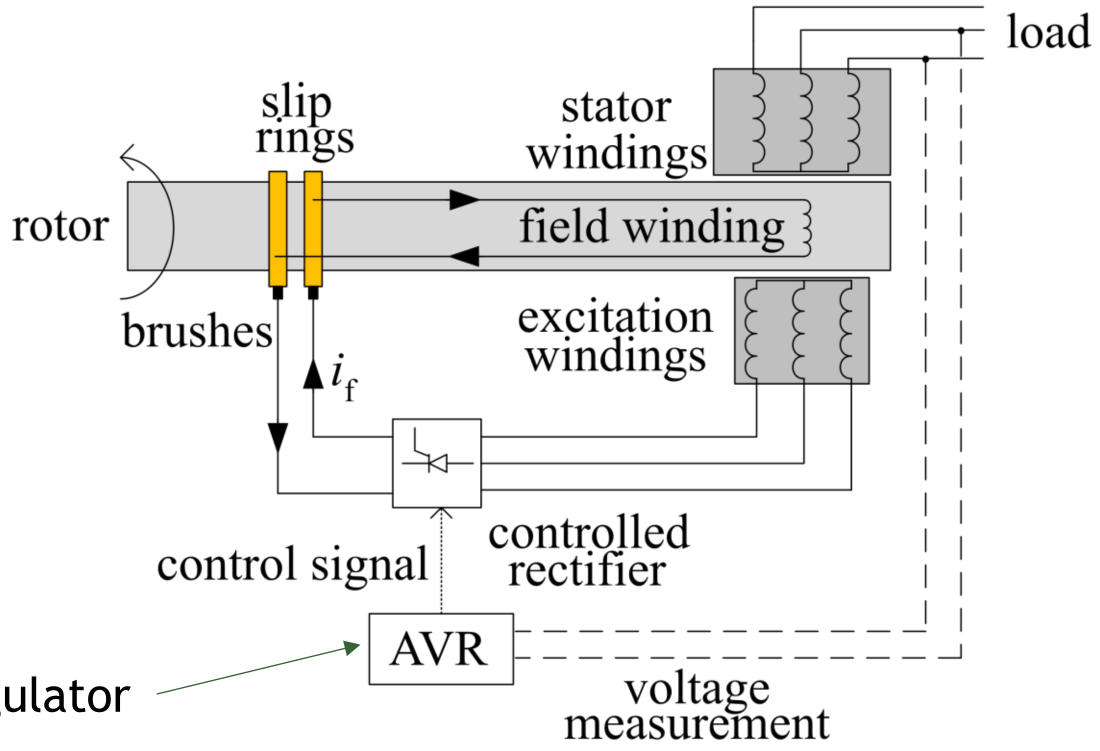
- Terminal voltage ($\boldsymbol{V}_a$) varies with load current and power factor
  - desired to be able to regulate terminal voltage near its nominal value (e.g. 230 V)
- Terminal voltage can controlled via a generator's excitation system

Excitation

Basic idea:

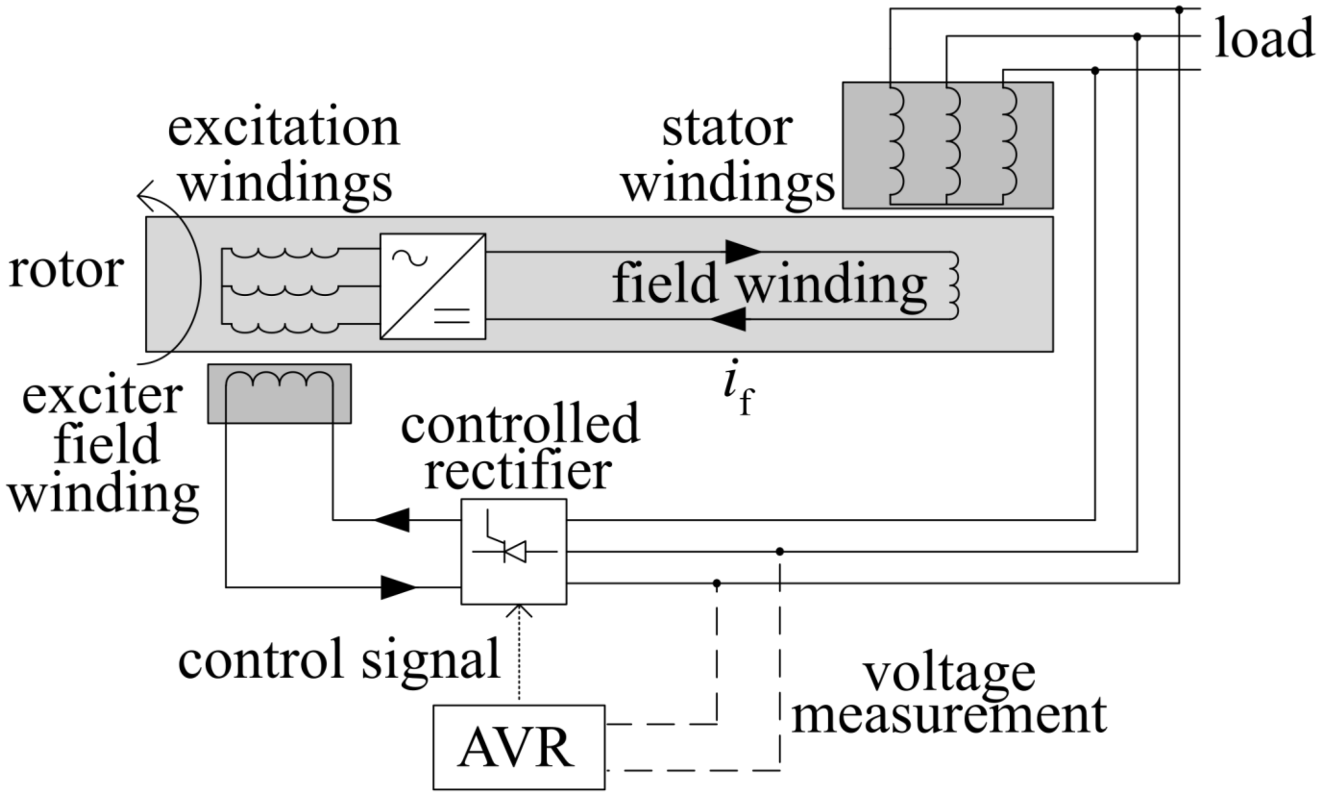
- utilize electromagnets in rotor to generate flux (instead of permanent magnet)
- measure generator terminal voltage
- control current to electromagnet to increase or decrease flux (and hence, induced voltage) to achieve targeted voltage

Static Excitation



Automatic Voltage Regulator

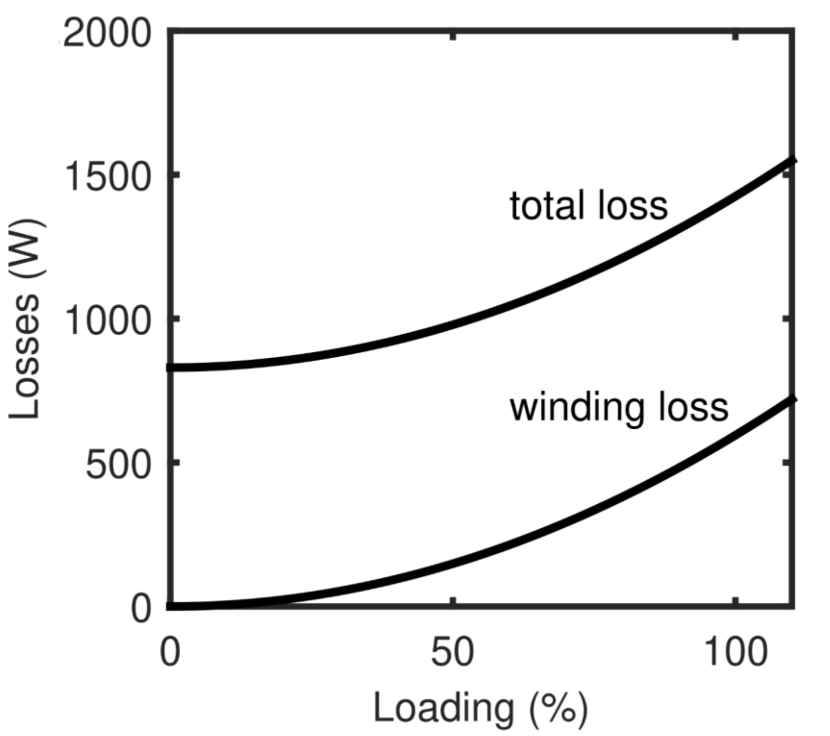
Brushless Excitation

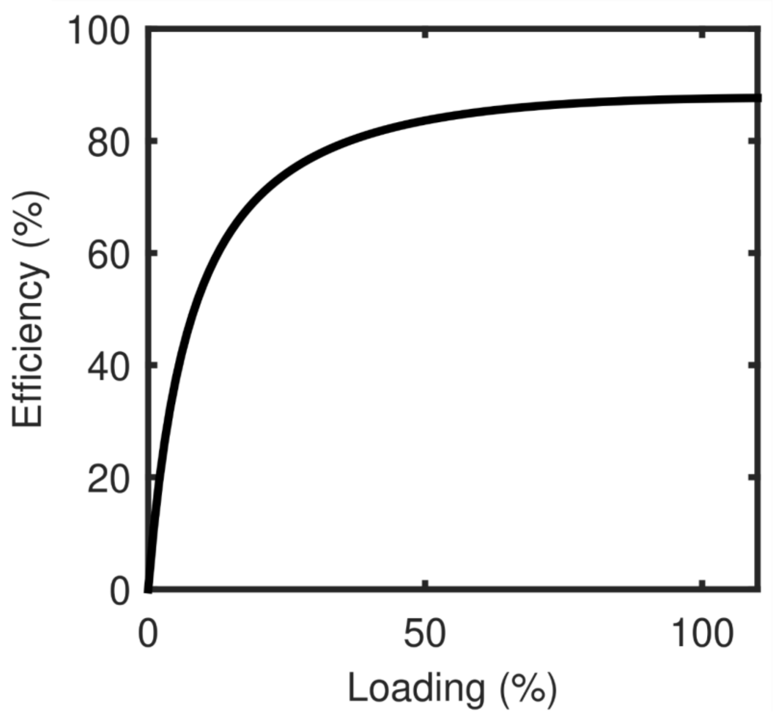


Generator Efficiency

- Synchronous generator efficiency typically 90%
- Loss categories
  - mechanical: friction and windage (aerodynamic drag); increase with rotational speed
  - magnetic: hysteresis and eddy current loss in stator and rotor
  - winding (Copper): I^2R losses in windings in stator, rotor, and field; increases with loading

Losses





generators are most efficient when load at/near rated power

Generator Sets (Gen Sets)

- Very common off-grid energy conversion system
  - 9% of total electricity in Sub Saharan Africa (SSA) produced by gen sets
  - US$50 billion on gen set fuel per year
- Low capital cost, high operating cost
- Reciprocating Internal Combustion Engine (ICE) coupled to synchronous generator
- Fueled by fossil fuel or biomass (syngas or biogas)

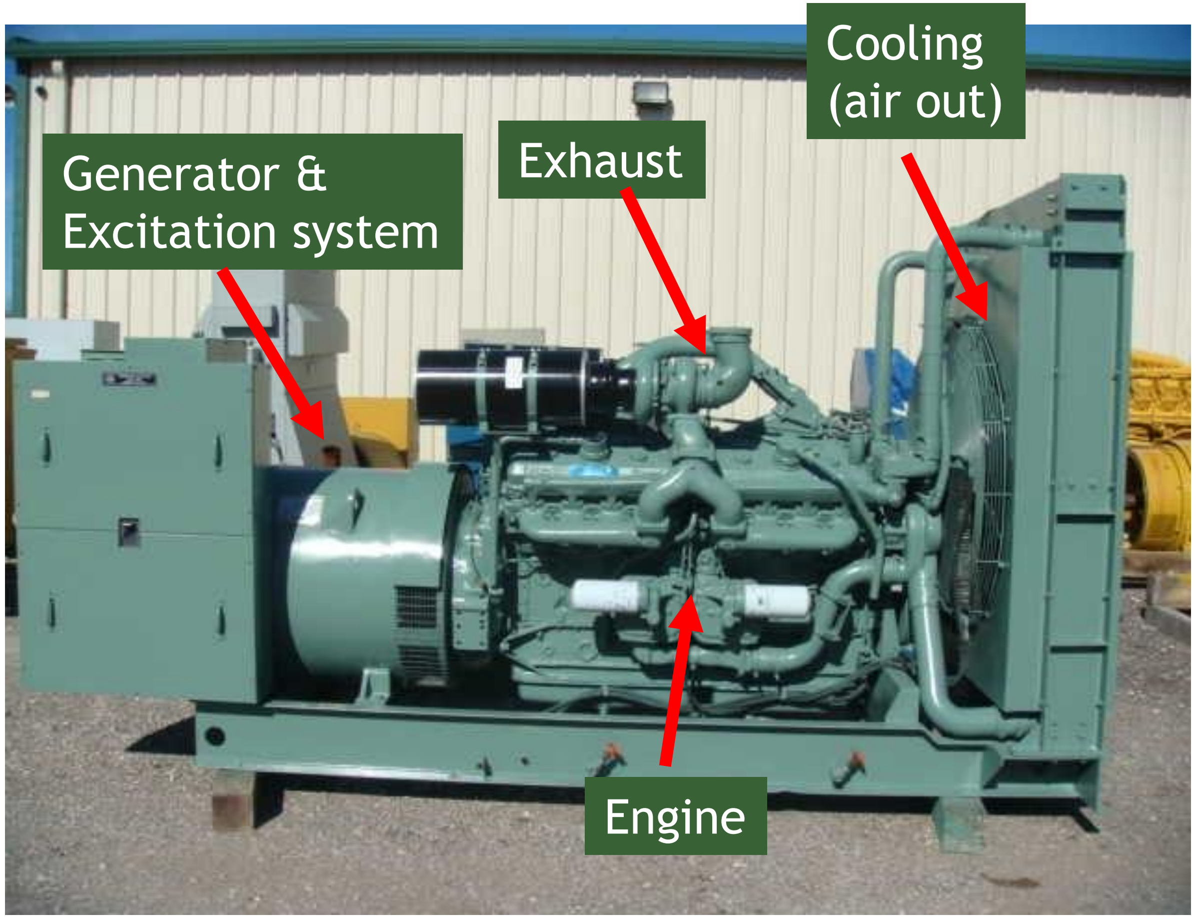
(*courtesy P. Dauenhauer*)

(*courtesy Sigora Haiti*)

Gen Sets Components

Main components:

- fuel tank (not shown)
- fuel and air supply system
- engine
- cooling & exhaust system
- generator & excitation system



source: https://www.powergenenterprises.com/detroit-diesel-generator

https://www.youtube.com/watch?v=3tVyXXvvzYA

Gen Sets

Available in wide range of capacities

- several hundred watts to a few megawatts

portable Gen Set

(*courtesy Sigora Haiti*)

larger capacity gen sets are usually pad-mounted and placed in protective and acoustic damping enclosures

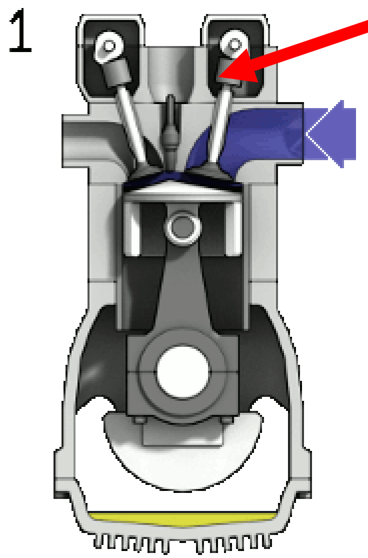
Internal Combustion Engines

- Two types: Spark Ignition (SI) and Compression Ignition (CI)
- Both rely on combustion of a fuel to drive a rotating crankshaft
- Crankshaft is connected to generator shaft, causing it to rotate

(courtesy KiloWatts for Humanity)

Spark Ignition Combustion Engines

Fuel is usually gasoline (petrol)



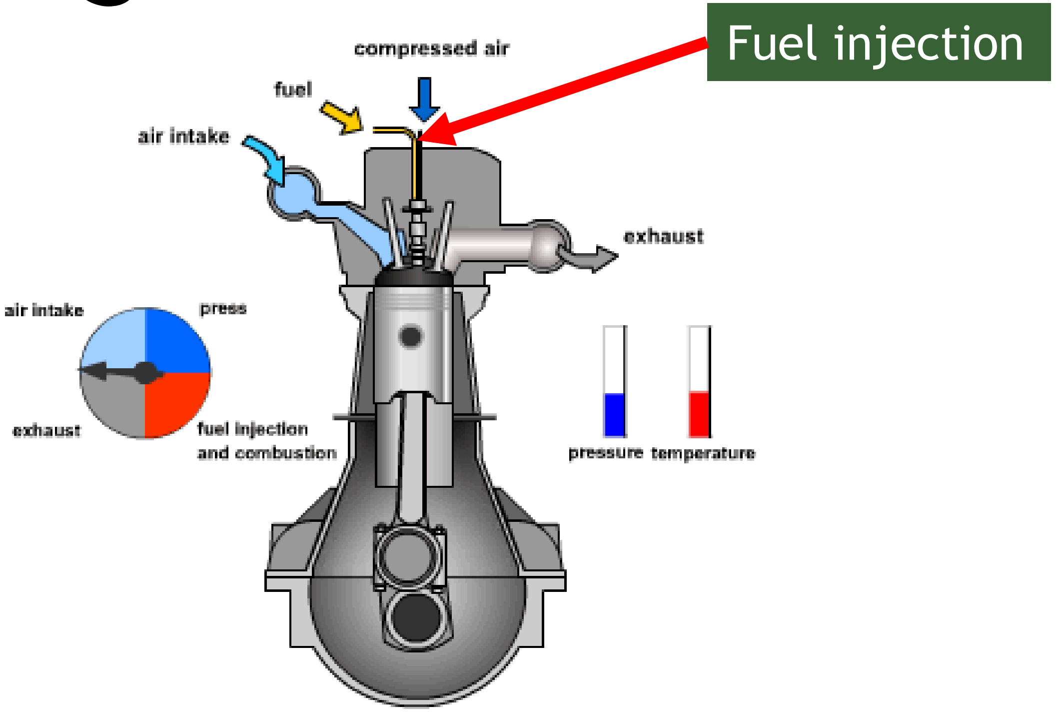
Spark Plug

Fuel and air are pre-mixed prior to injection

source: Zephyris—own work, CC BY-SA 3.0

Compression Ignition Combustion Engines

Fuel is usually diesel



source: https://takemebeyondthehorizon.files.wordpress.com/2009/04/diesel21.gif?w=500

Operational Speed

Designed operational speed of a gen set is a result of speed, torque, cost, and efficiency trade-offs

- smaller-capacity gen sets (<10 kW): usually SI coupled to two pole-generators and operate at 3600 RPM (60 Hz AC) or 3000 RPM (50 Hz AC)
- larger-capacity gen sets: usually CI coupled to four-pole generators operating at 1800 RPM (60 Hz AC) or 1500 RPM (50 Hz AC)

Spark Ignition Versus Compression Ignition

Remember, what is true for diesel vs gasoline for vehicles is not necessarily true for gen sets

Compression Ignition offers:

- higher reliability: 20,000 to 30,000 hours of operation before major overhaul (2-3 times longer than SI)
  - fewer parts, lower speed operation and self-lubrication
- decreased fuel consumption: greater efficiency (1/4 to 1/2 more efficient) from higher compression ratios; diesel has greater energy density than petrol (gasoline)
- robustness: ruggedly built to withstand high compression ratios, less sensitive to the quality of the fuel
- lower maintenance: lower speed operation, lower operating temperature, no spark plugs or carburetor
- safety: diesel fuel is less flammable than gasoline

Spark Ignition Versus Compression Ignition

- Compression Ignition engines are heavier, louder, vibrate more, are more expensive (up front), and emit more un-combusted hydrocarbons
- Diesel fuel can “gel” at low temperatures, but degrades slower than gasoline
- Diesel fuel might be less available and more expensive than gasoline

Gen Set Selection

	Spark Ignition (gasoline)	Compression Ignition (diesel)
Back-Up Application	✓	
Continuous Use Application		✓
Fuel Storage (volume, safety)		✓
Lifespan		✓
Noise	✓	
Physical Size (smaller)	✓	
Portability	✓	
Safety (of fuel)		✓

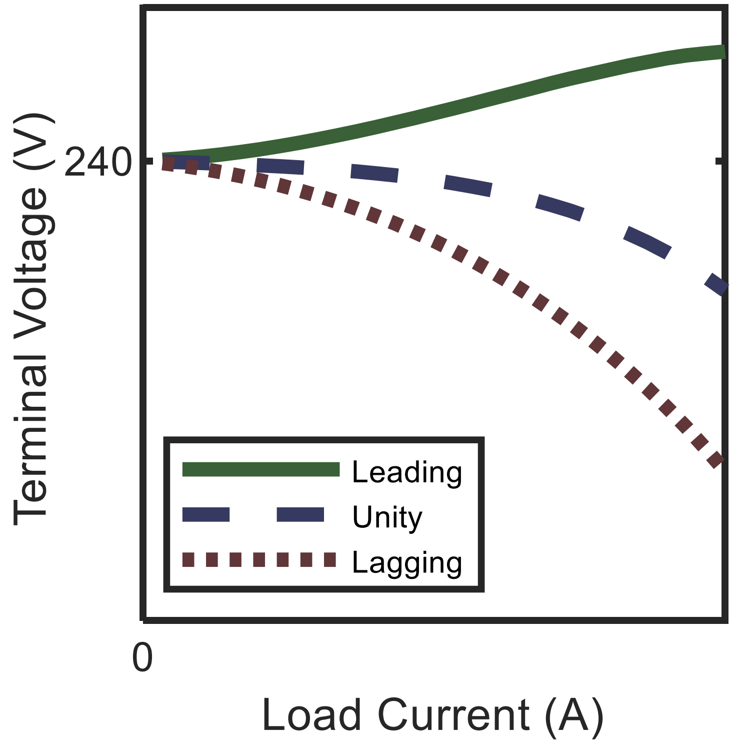
these are general characteristics only

Frequency Regulation of Gen Sets

- Gen Sets are designed to operate at a (nearly) constant speed so that the frequency of the AC voltage is (nearly) constant
  - some generators have a “droop”—frequency somewhat decreases with load (see Chap. 14)
- Governor increases mechanical power to crankshaft if speed decreases, and decreases power if speed increases
  - SI: adjust amount of air-fuel mixture (throttling)
  - CI: adjust amount of injected fuel (fuel metering)

Excitation

- Recall that terminal voltage (AC bus) should be regulated
  - Automatic Voltage Regulators (AVR)
- Low quality gen sets may not have an AVR and thus have poor voltage regulation
- Larger capacity/higher quality: brushless or static exciters and external batteries
- Smaller capacity: rely on residual magnetism on start-up and may require “field flashing” if gen set has been idle for prolonged period



Fuel Consumption

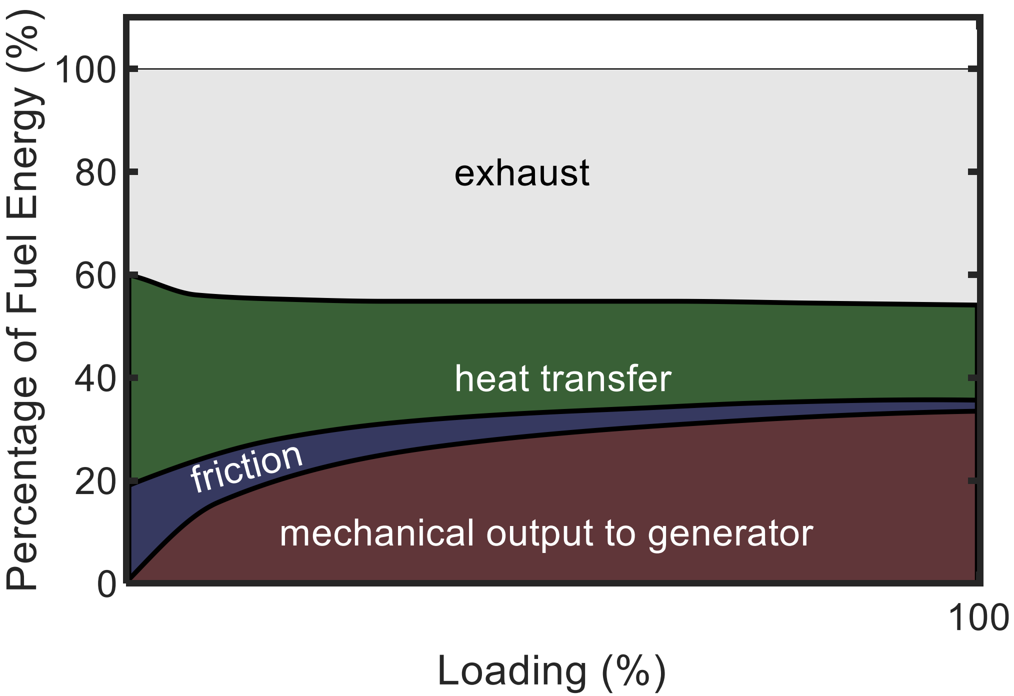
- Fuel costs for gen sets are high
- Prices can fluctuate and consistent supply is not guaranteed
- Energy density
  - Diesel: ~37 to 39 MJ/l
  - Gasoline: ~31 to 36 MJ/l

Country	Diesel Price (US$/liter)
Angola	0.22
Botswana	1.08
India	1.04
S. Africa	1.25
Mali	1.20
Burundi	1.33
Zambia	1.16
Zimbabwe	1.59

source: https://www.globalpetrolprices.com/diesel_prices/

Engine Losses

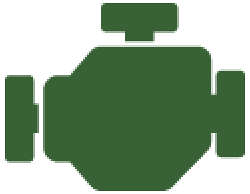
- Friction: from pistons, bearings, valve train, pumps other moving parts
- Heat transfer: heat from combustion that is rejected to the cooling system
- Exhaust: heat in the gases that are emitted from the engine



Efficiency increases with loading

Gen Set Efficiency

ICE Efficiency Generator Efficiency

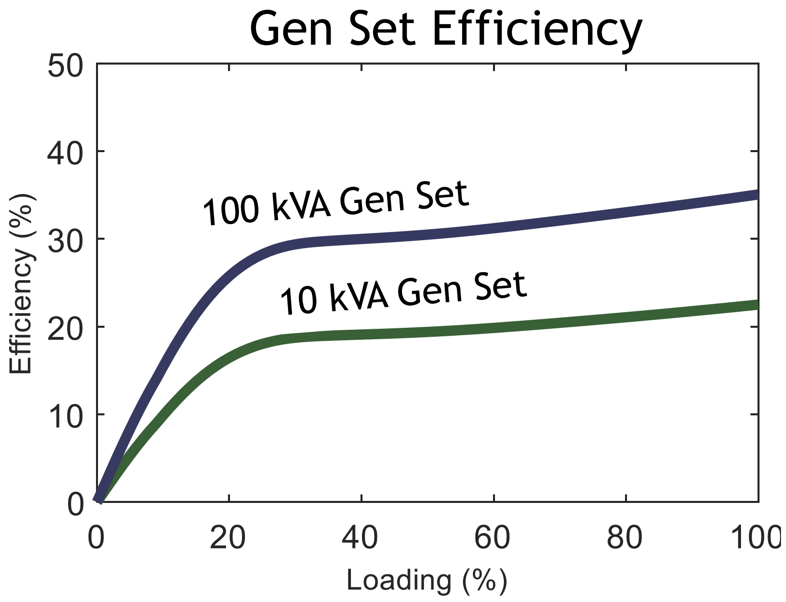
Gen Set Efficiency =  X 

$$\eta_{\text{genset}}\left(P_e\right) = \eta_{\text{ICE}}\left(P_e\right) \times \eta_{\text{gen}}\left(P_{\text{e}}\right)$$

Gen Set Efficiency depends on electrical power output (P_{e})

Gen Set Efficiency

- Gen set efficiency increases with loading and capacity (rated power)
- Maximum efficiency usually between 20% and 40%



Loading: percentage of gen set's rated power being produced by the gen set

Fuel Consumption

Example Gen Set Fuel Consumption

Capacity (kW)	25% (liter/hr)	50% (liter/hr)	75% (liter/hr)	100% (liter/hr)
10	1.3	2.5	3.5	4.3
50	4.9	8.7	12.5	16.4
100	8.3	15.9	22.3	27.6
500	39.7	73.8	89.7	118.1

Gen Set Efficiency

Example Gen Set Fuel Efficiency

Capacity (kW)	Loading (%)			
	25 (%)	50 (%)	75 (%)	100 (%)
10	18	19	20	22
50	24	27	28	29
100	29	30	32	34
500	30	32	39	40

efficiency increases with loading and capacity

Exercise

Compute the efficiency of the 10 kW gen set if loaded at 50%. Assume the energy density of diesel fuel is 39 MJ/liter

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10	1.3	2.5	3.5	4.3
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100	8.3	15.9	22.3	27.6
500	39.7	73.8	89.7	118.1

Exercise

Compute the efficiency of the 10 kW gen set if loaded at 50%. Assume the energy density of diesel fuel is 39 MJ/liter

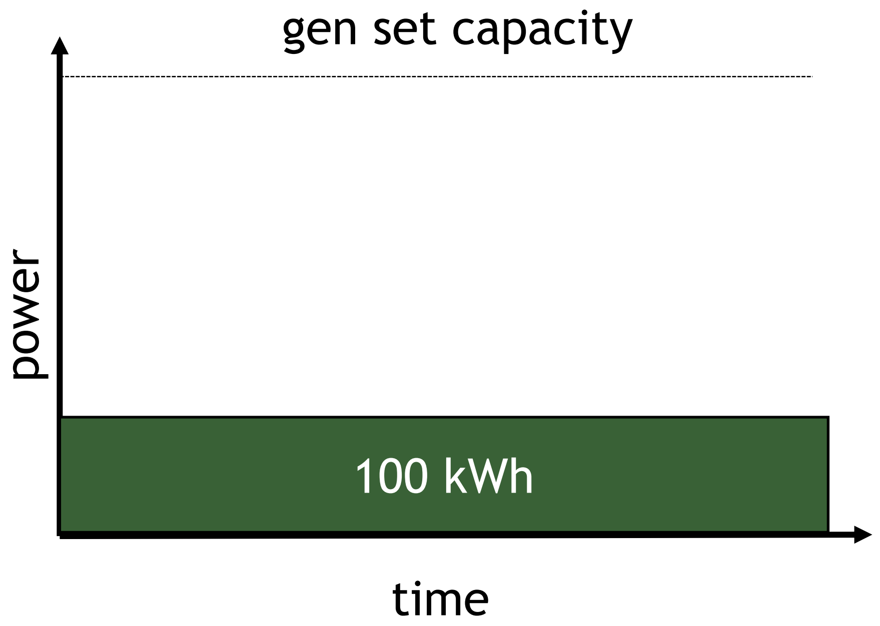
$$E_{\text{out}} = 5 \text{ kW} \times 1 \text{ h} = 5 \text{ kWh}$$

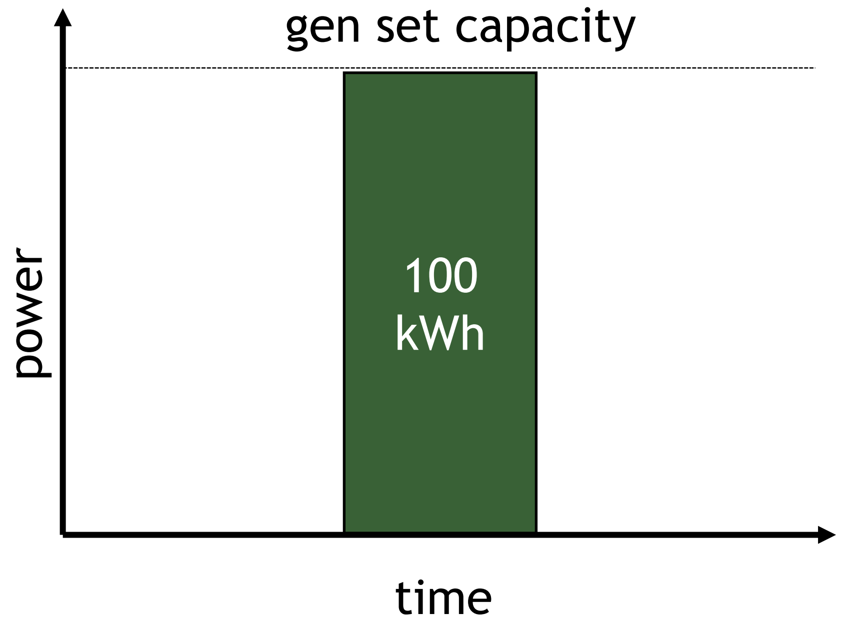
$$E_{\text{in}} = 2.5 \text{ liter} \times 39 \text{ MJ/liter} = 97.5 \text{ MJ} = 97.5 \text{ MJ} \times \frac{1 \text{ kWh}}{3.6 \text{ MJ}} = 27.1 \text{ kWh}$$

$$\eta_{\text{genset}} = \frac{E_{\text{out}}}{E_{in}} = 18.5\%$$

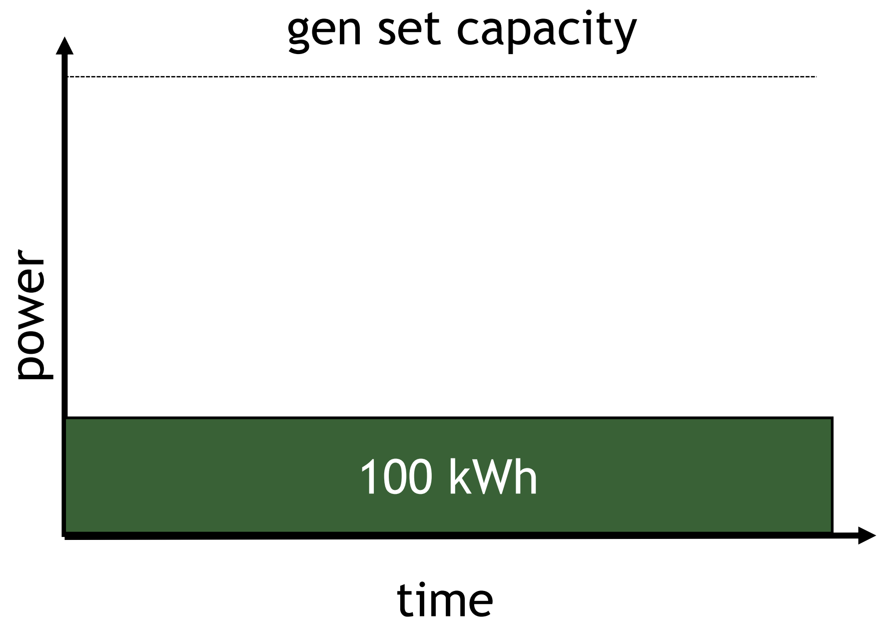
Capacity (kW)	25% (l/hr)	50% (l/hr)	75% (l/hr)	100% (l/hr)
10	1.3	2.5	3.5	4.3

Which is a more efficient strategy to supply 100 kWh of energy?

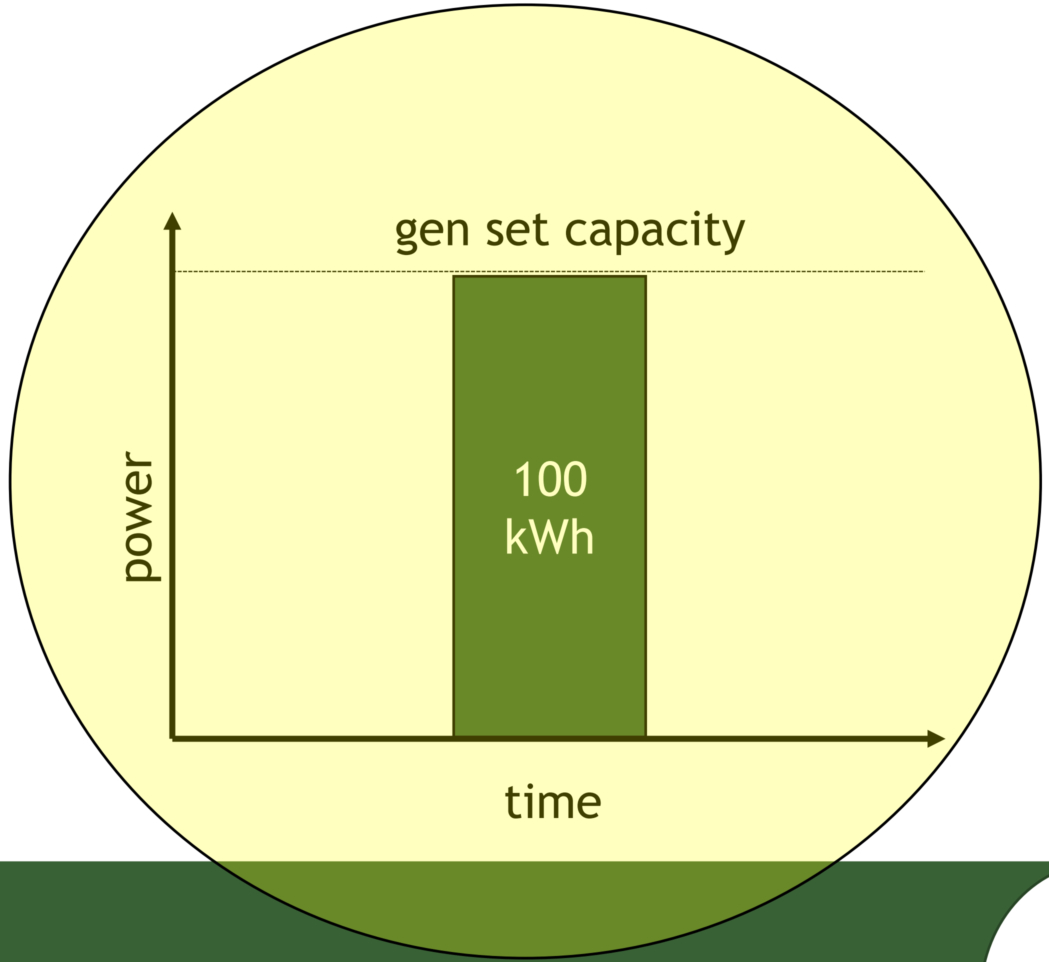




Gen Set Loading

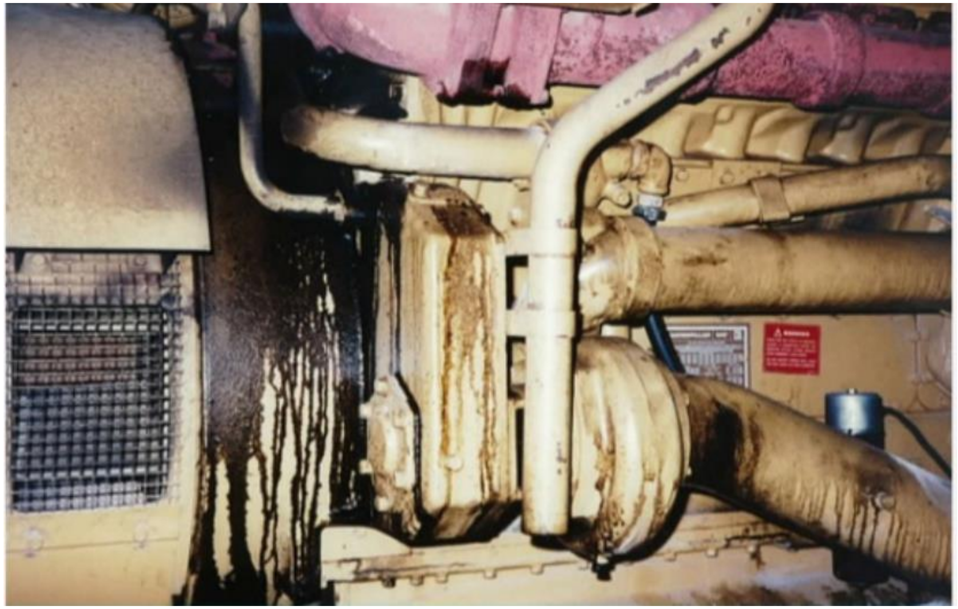


more efficient loading strategy



Wet Stacking

- When diesel gen sets operate at low loading some of the fuel is not combusted
- Oily substance can accumulate in the exhaust system and cause engine failure
- Avoid operating diesel gen sets at below 30 to 50% for prolonged periods of time



source: D. Maalouf, Edarat Group

Exercise

Estimate the daily and annual cost of supplying the village of Mwase. Assume a 5 kW diesel gen set is used whose average consumption is 0.7 liters per hour. The cost of diesel fuel is US$1.4/liter.

Exercise

Estimate the daily and annual cost of supplying the village of Mwase. Assume a 5 kW diesel gen set is used whose average consumption is 0.7 liters per hour. The cost of diesel fuel is US$1.4/liter.

Cost per day: 24 x 0.7 x 1.4 = US$23.5

Cost per year: 365 x 24 x 0.7 x 1.4 = US$8584.8

The upfront cost of the gen set is likely less than US$4,000, which is quickly passed by the fuel costs

Emissions

Emissions are a major environmental consideration of gen sets

- carbon dioxide
- carbon monoxide
- nitric oxides NO_x
- sulfur oxides SO_x
- particulates

Emission Factors

- Emission factors:
  - simple way of estimating emissions from gen set
  - relates emissions to volume of fuel consumed

$$quantity\ of\ emission = EF \times v_{\mathrm{fuel}}$$

Typical Emission Factors of Gen Sets (in U.S.)

Fuel	CO_2	CO	NO_x	SO_x	Particulates
Diesel	2.5	0.015	0.068	0.004	0.005
Petrol (Gasoline)	2.4	0.015	0.025	0.001	<0.001

units in kg/liter

Emission factors can range widely depending on compliance to emission standards

Example 6.7

A large 100kW diesel gen set provides backup power to a mini-grid. The hourly fuel consumption of a gen set is modeled as

$$fuel\,consumption\,per\,hour = 3\ \text{liters} + \left(0.24\text{liters/kW} \times P_{\text{gen}}\right)$$

The gen set is expected to operate for 1.5 hours each night at a loading of 75%. Compute the daily carbon dioxide and NO_x emissions from the gen set.

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A large 100kW diesel gen set provides backup power to a mini-grid. The hourly fuel consumption of a gen set is modeled as

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$$\textit{fuel consumption} = 3 + \left(0.24 \times P_{\text{gen}}\right) = 3 + \left(0.24 \times 75\right) = 21 \text{ liters/h}$$

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After 1.5 hours of generation:

$$v_{\text{fuel}} = 1.5 \times 21 = 31.5 \text{ liters}$$

Example 6.7

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The gen set is expected to operate for 1.5 hours each night at a loading of 75%. Compute the daily carbon dioxide and NO_x emissions from the gen set.

Resulting emissions:

$$CO_2\ emission = EF \times v_{\text{fuel}} = 2.5 \times 31.5 = 78.75\ \text{kg}$$

$$NO_x\ emission = EF \times v_{\text{fuel}} = 0.068 \times 31.5 = 2.14\ \text{kg}$$

Economic Considerations

- Capital cost: lowest of all generation sources (US$100-US$400/kW); few balance of systems components needed
- Fuel cost: main disadvantage of gen sets, typically US$1-2/liter
- Operation and maintenance: high operation and maintenance requirements (changing filters, refueling, parts replacement)
- Energy cost: can be highest of all generation sources, often US$0.40 to US$0.90/kWh for large mini-grids

Environmental Considerations

- Emissions: least environmentally friendly generation source, emitting carbon dioxide, carbon monoxide, nitric oxide, sulfur oxides, and particulates
- Noise: gen sets can be noisy if not placed in an acoustic damping enclosure
- Land: considerations for fuel storage and spill remediation needed

Social Considerations

- Community benefit: gen sets are widely available and come in small and large capacities, potentially benefitting a wide range of users
- Community burden: negative consequences are highly localized (emissions, noise, spillage)
- Health and safety: emissions can cause respiratory and cardiovascular illness; potential fire risk from fuel
- Other: fuel shortages, price volatility, and planning and logistics can make reliable operation challenging

Summary

- Synchronous generators produce voltage by time-varying flux passing through coils
- Several factors affect output voltage: rotational speed, number of poles, load
- Gen sets are ICE coupled to generators
  - Low capital costs, high fuel cost
- Efficient loading of gen sets is important consideration
- Emissions can be estimated using emission factors