Distributed Generation, Reactive Power & Grid Stability

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Abstract

Distributed generation systems including residential Photovoltaic system inverters have the capability of supplying a substantial portion of the local electric power demand, but the supply can be of an inconsistent and transient nature. This can create interesting power system stability problems especially if traditional generation capacity cannot be ramped up and down at rates comparable to photovoltaic generation output. IEEE1547a-2014 adopted to help mitigate system stability issues. IEEE1547-2018 is a further revision, requiring features of inverters that, when implemented, help mitigate stability issues. Features of robust power systems reviewed, and some inverter design details are investigated.

Outline

• Questions I'd like to (try to) answer	1 min
• Definitions & Terms	2 min
• Distributed Generation penetration	3 min
• Features of robust electric distribution system:	
• Reserve capacity	2 min
• Rotating Inertia	2 min
• Harmonics	2 min
• Voltage regulation	1 min
• Reactive power capability	3 min
• Traditional electric generation & distribution system	1 min
• Transmission & distribution losses	1 min

Outline cont'd

• PV Generation system (Net Metered)	2 min
• Storage systems mention	tbd
• Pumped Hydro	
• Battery Based	
• Inverter design	
• Requirements	3 min
• An example (my) inverter (SMA H5)	3 min
• An IEEE1547-2018 compliant topology	tbd
• Quiz questions	3 min
• References	1 min

Questions I'd like to answer
(or at least consider…)

"How much distributed generation capacity do we presently have connected?"

"How much intermittent distributed generation can be added to our local grid before we get stability/power quality issues that will affect customers?"

"If done wrong, what effects will customers see?"

…Line voltage fluctuations, brown-outs, outages...

"what are elements of a robust power system?"

"What can be done to correctly integrate distributed generation?"

And perhaps
"What is the best way to incentivize the adoption of intermittent, unreliable, renewable energy resources so that the utility companies can run profitably while ensuring stable, reliable electric energy delivery?"

…Let's try to keep this based on science & economics…

Definitions & Terms

From IEEE 1541 section 3.1

1. Area Electric Power System (Area EPS): An EPS that serves Local EPSs
2. Available active power: Active power that a DER can deliver to the Area EPS subject to the availability of the DER’s primary source of energy.
3. Distributed Energy Resource (DER): A source of electric power that is not directly connected to a bulk power transmission system. DER includes both generators and energy storage technologies capable of exporting active power to an EPS.
4. electric power system (EPS): Facilities that deliver electric power to a load.
5. island: A condition in which a portion of an Area EPS is energized solely by one or more Local EPSs through the associated PCCs
6. (Local EPS): An EPS contained entirely within a single premises or group of premises.
7. Power factor correction (PFC): As applied to electronic power supplies, the alignment of the load current with the supply voltage, both waveshape and phase.
8. Point of Common Connection PCC: The point of connection between the Area EPS and the Local EPS

How much is connected now?

- A search for "RG&E distributed generation" turns up:

[PDF] Staff Whitepaper on Future Community Distributed Generation ...
https://www.nyserda.ny.gov/-/.../Staff-Whitepaper-Future-Community-Distributed-Ge... ▾
Jul 26, 2018 - Community **Distributed Generation** (CDG) projects in each utility .... For NYSEG, **RG&E**, and National Grid, remaining capacity within each ...

The chart below shows the current status of the authorized Tranches in each utility as of July 15, 2018. … **Development in the service territory of …National Grid has** also **been** somewhat **slower** than in other utility territories, especially considering National Grid's large size. While **development has generally been strong in** the New York State Electric & Gas Corporation **(NYSEG) and** Rochester Gas and Electric Corporation **(RG&E) service territories**, it has slowed as later tranches have been reached. By contrast, the pace of development in Central Hudson and O&R has remained high even as MTC (Market Transition Credit) compensation has declined.

- "follow the money…"

How much is connected now?

- A Tranche is a block of MW of Community Distributed Generation (CDG)
- sized based on a target net incremental annual revenue impact of 2%.

Tranche	ConEd	Orange & Rockland	NYSEG	Central Hudson	National Grid	RG&E
0/1	7.9 of 136 MW	20 of 23 MW CLOSED	62 of 62 MW CLOSED	38.6 of 39 MW CLOSED	90.5 of 140 MW	28 of 28 MW CLOSED
2	0 of 206 MW	12 of 12 MW CLOSED	84 of 84 MW CLOSED	18.3 of 19 MW CLOSED	0 of 157 MW	42 of 42 MW CLOSED
3	0 of 205 MW	34.2 of 12 MW CLOSED	62 of 77 MW	31.4 of 19 MW CLOSED	0 of 177 MW	3 of 41 MW
4	N/A	15.5 of 15 MW CLOSED	0 of 80 MW	21.3 of 20 MW CLOSED	N/A	N/A

How much is it paying?

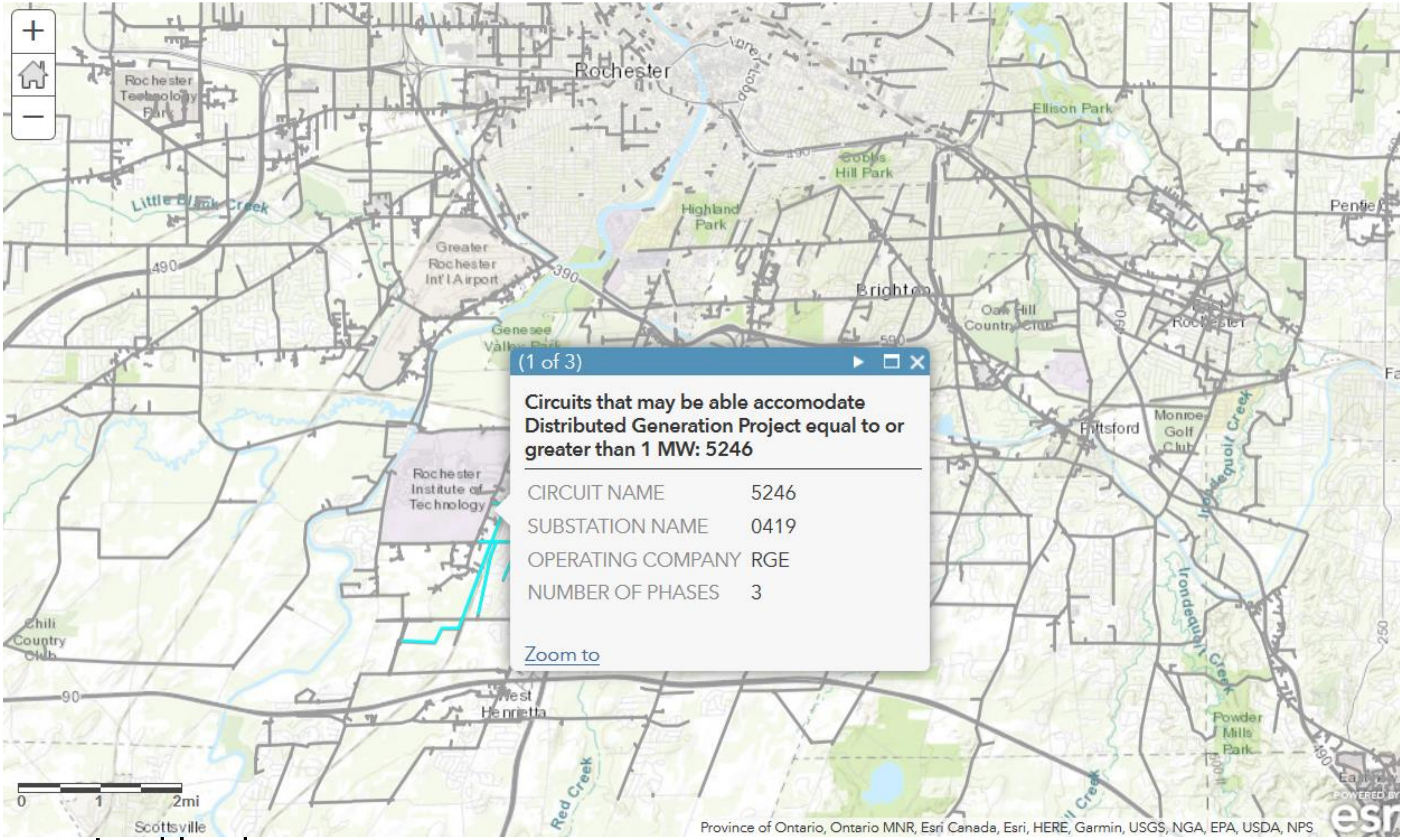
For context, the currently authorized MTCs for SC-1 for each Tranche in each territory are:

Tranche	ConEd	Orange & Rockland	NYSEG	Central Hudson	National Grid	RG&E
0/1	$0.1054	$0.0911	$0.0314	$0.0599	$0.02820	$0.0383
T 2	$0.0949	$0.0821	$0.0259	$0.0524	$0.02290	$0.0327
T 3	$0.0845	$0.0731	$0.0204	$0.0449	$0.01750	$0.0271
T4		$0.0462	$0.0149	$0.0373		

- I was paid $0.0256 / kWh for 244kWh of excess generation on the 2018 annual true-up

➢ Don't over-size your PV Array thinking you'll recoup your investment faster…

How much can be added?



Looking here: https://www.arcgis.com/home/item.html?id=4b90359f4de54b16aec6a3c971efe4dc

Seems like a lot!

A Robust Power System

- Has Reserve Capacity
- Manages Reactive Power
- Limits Harmonics
- Maintains Voltage Regulation
- Maintains synchronous frequency

(at least from the point of view of a Distributed Energy Resource)

Operating Reserve

Definition

The operating reserve is made up of the spinning reserve as well as the non-spinning or supplemental reserve:

- The **spinning reserve** is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system. For most generators, this increase in power output is achieved by increasing the torque applied to the turbine's rotor.[3]
- The **non-spinning reserve** or **supplemental reserve** is the extra generating capacity that is not currently connected to the system but can be brought online after a short delay.

https://en.wikipedia.org/wiki/Operating_reserve

Reactive Power

Definition

P = true power $P = I^2 R$ $P = \frac{E^2}{R}$

*Measured in units of **Watts***

or, E*I*cos(θ) ; θ being the /_E - /_I

Q = reactive power $Q = I^2 X$ $Q = \frac{E^2}{X}$

*Measured in units of **Volt-Amps-Reactive (VAR)***

or, E*I*sin(θ) ; θ being the /_E - /_I

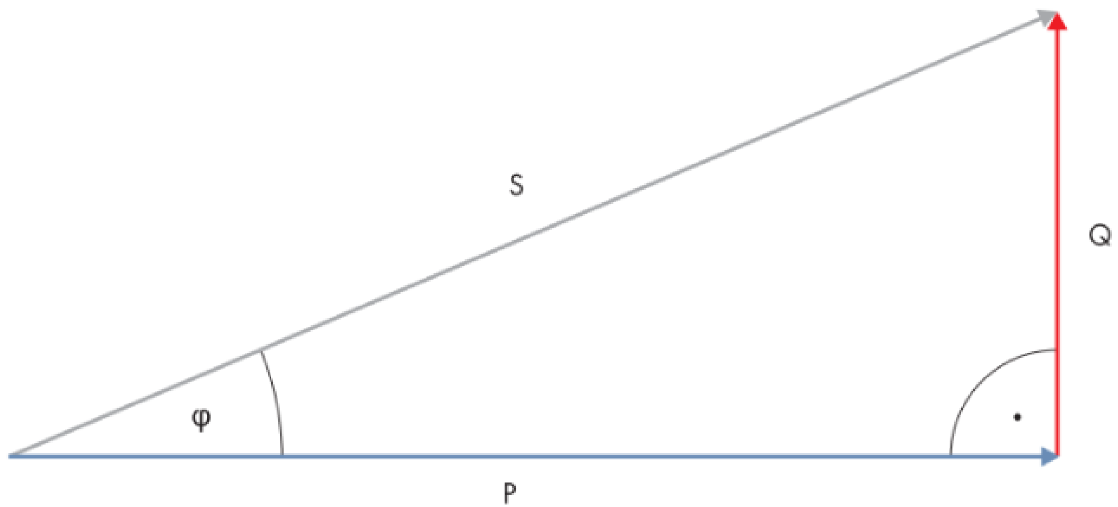
S = apparent power $S = I^2 Z$ $S = \frac{E^2}{Z}$ $S = IE$

*Measured in units of **Volt-Amps (VA)***

From: https://www.allaboutcircuits.com/textbook/alternating-current/chpt-11/true-reactive-and-apparent-power/

Reactive Power

Identification	Symbol	Unit
Apparent power	S	[VA]
Active power	P	[W]
Reactive power	Q	[VAr]
Displacement power factor	$\cos(\varphi)_{leading\ /\ lagging}$	Factor without unit

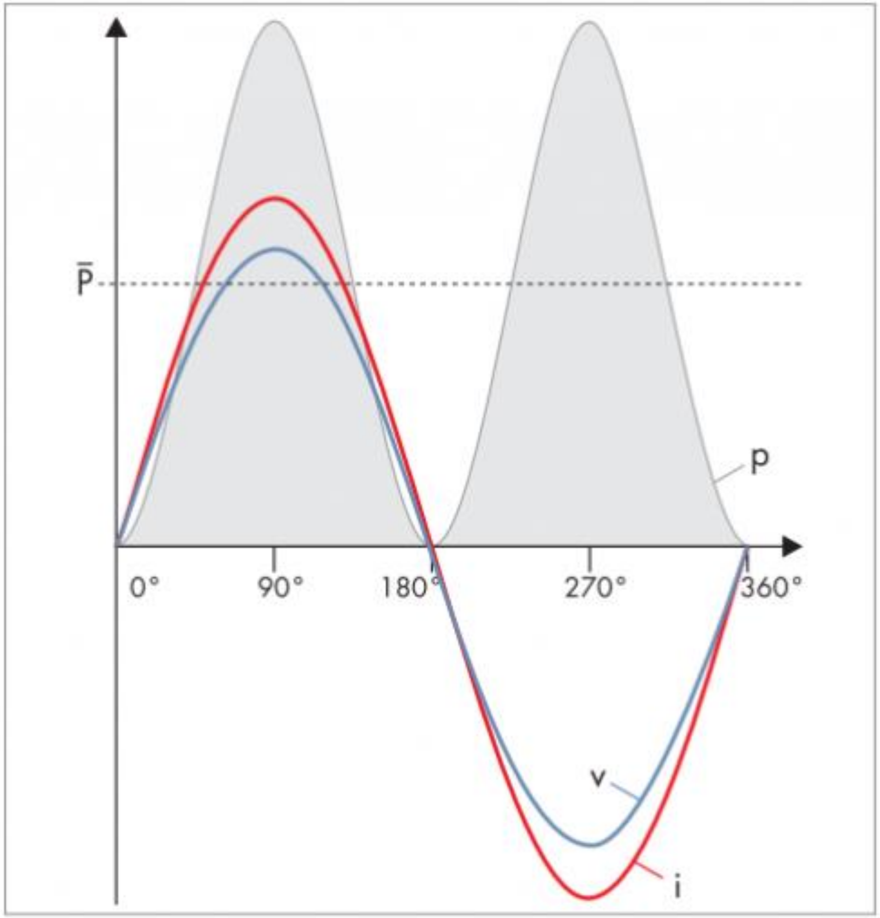


$S^2 = P^2 + Q^2$ (Pythagorean theorem for right-angled triangles)

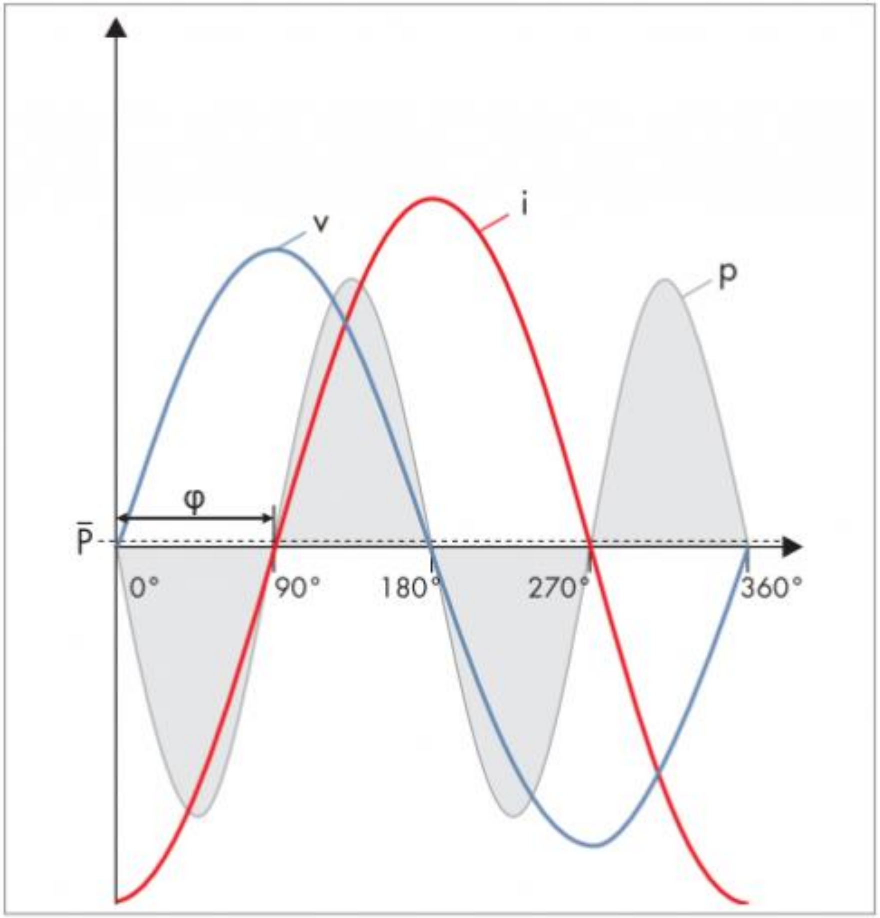
$S = \sqrt{P^2 + Q^2}$ $\quad S = \frac{P}{\cos(\varphi)}$ $\quad P = S \cdot \cos(\varphi)$ $\quad Q = \sqrt{S^2 - P^2}$

From https://www.sma-sunny.com/en/bad-power-factor-a-reason-to-oversize-your-inverter/

Reactive Power



Fluctuating, but always positive power – pure active power results when the current i and the voltage v are in phase



The average value of the power is zero – pure reactive power – in case of a phase shift of 90 degrees between i and v

From https://www.sma-sunny.com/en/bad-power-factor-a-reason-to-oversize-your-inverter/

Reactive Power

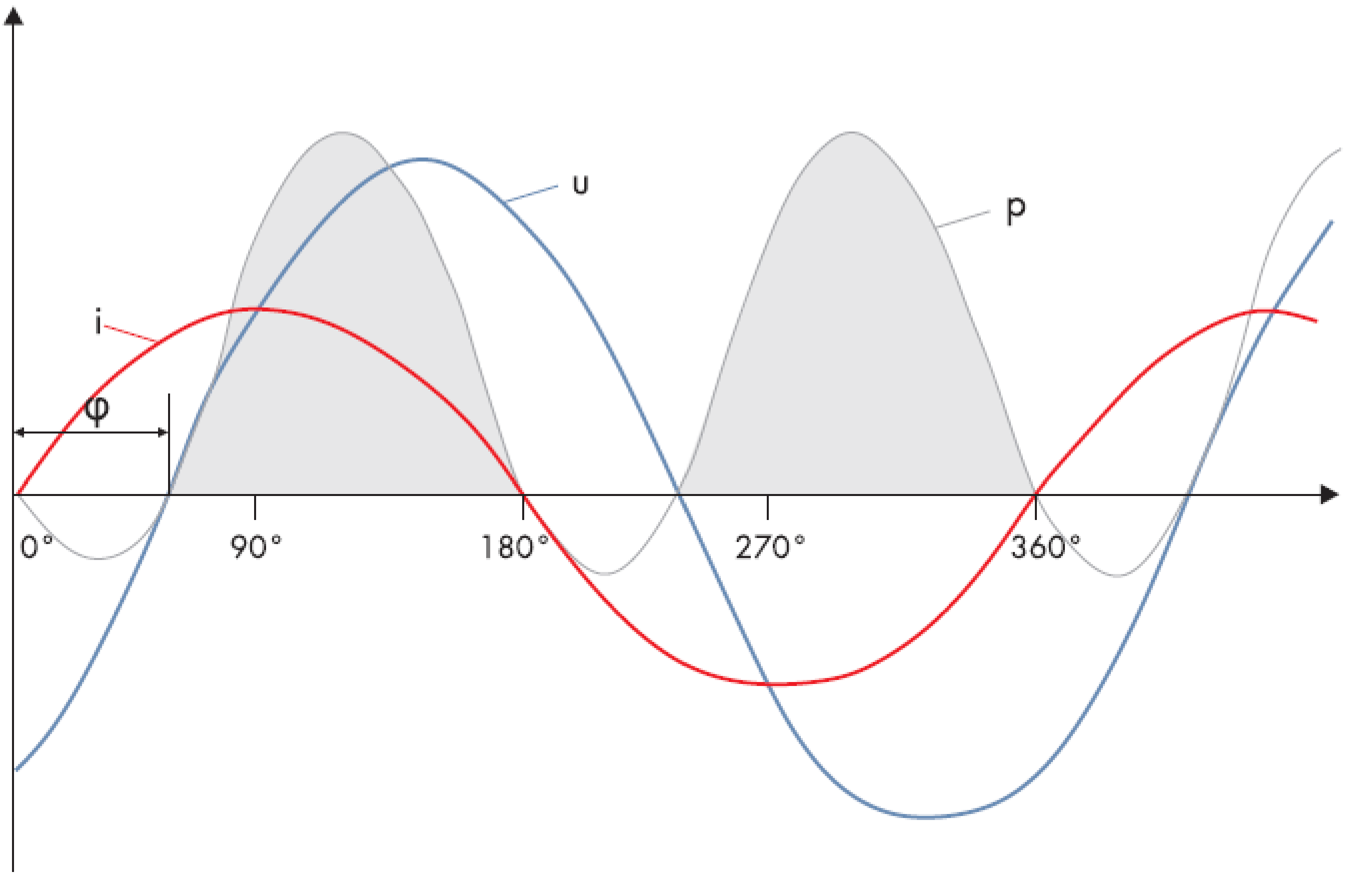


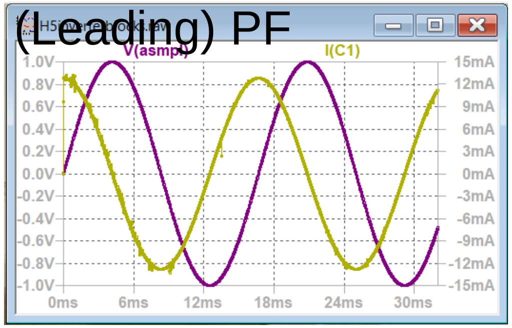
Figure 3: Apparent power: current and voltage are phase-shifted and therefore reduce the active power.

From https://www.sma-america.com/partners/knowledgebase/q-at-night.html

Reactive Power

Leading & Lagging Power Factor (Load sign convention)

Voltage **(E)** **L**eads Current **(I)** – Inductive **(L)** load – negative (Lagging) PF
Current **(I)** leads Voltage **(E)** – **C**apacitive load – Positive (Leading) PF
Memory jogging mnemonic: “**ELI the ICE man**”

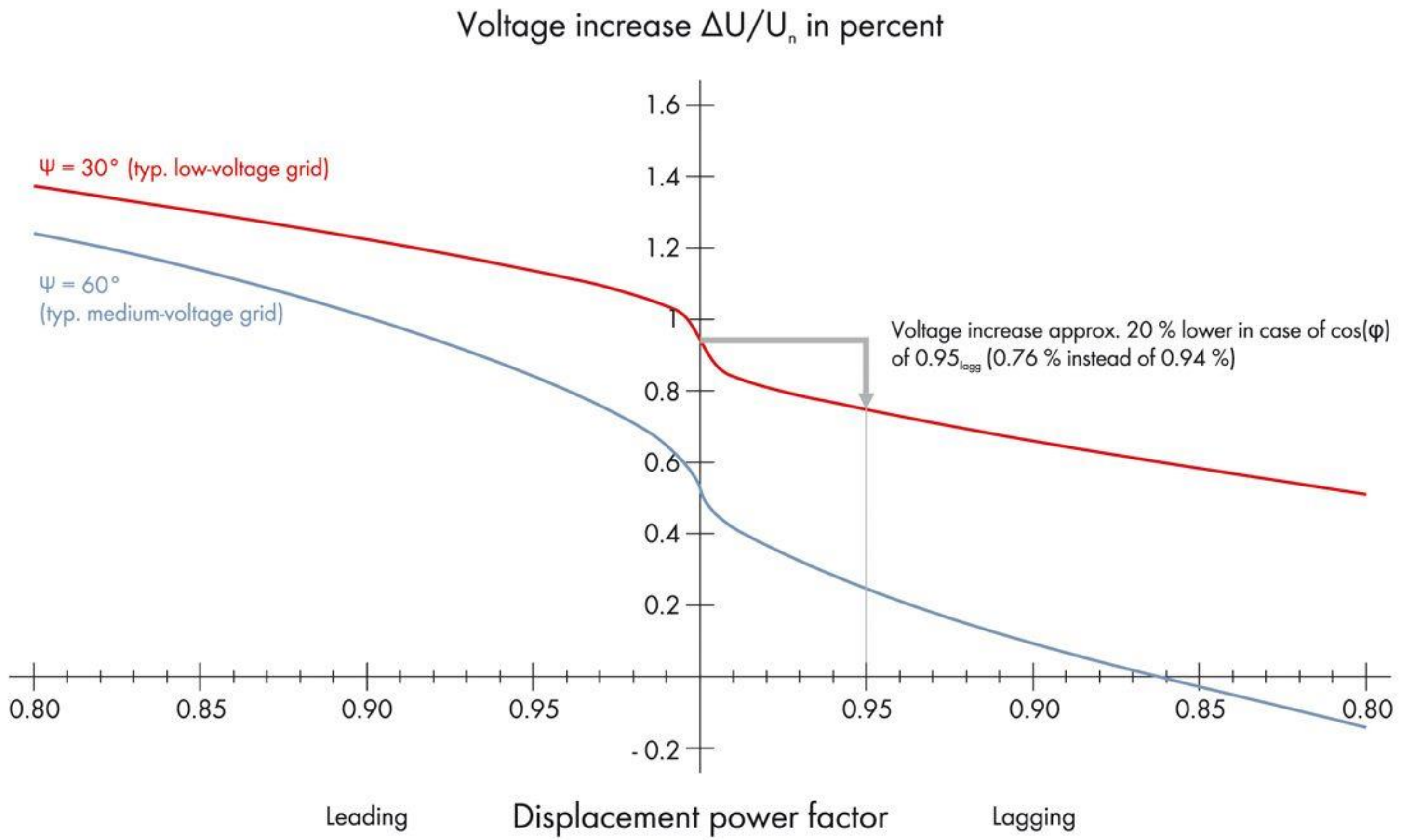


From IEEE1547-2018; **Generator sign convention**:
Where applicable, the stated technical specifications and requirements are given in generator sign convention, which is **opposite** to **load sign convention**.

- In **generator sign convention**, a **DER current lagging voltage** provides/**injects reactive power** to the system (over-excited operation of DER, positive reactive power), and this tends **to increase the applicable voltage** under normal system conditions;
- a **DER current leading voltage** consumes/**absorbs reactive power** from the system (under-excited operation of DER, negative reactive power), and this tends **to decrease of the applicable voltage** under normal system conditions.

Reactive Power

Leading & Lagging Power Factor



(cos(φ), Load sign convention)

From https://www.sma.de/en/partners/knowledgebase/sma-shifts-the-phase.html

Harmonics

load-induced currents in the local EPS

Can be produced by imperfect construction of the inverter current output waveform

DC Injection – Component of an unbalanced AC waveform - a bad thing.

Even harmonics – waveform with frequency components of even integer multiples of the fundamental waveform.

- A component of DC injection
- Practical example: Half-wave rectified AC

Odd harmonics - waveform with frequency components of odd integer multiples of the fundamental waveform

- No DC injection with odd harmonics
- Practical example: Full-wave rectified (Non-PFC) electronic power supplies (loads)

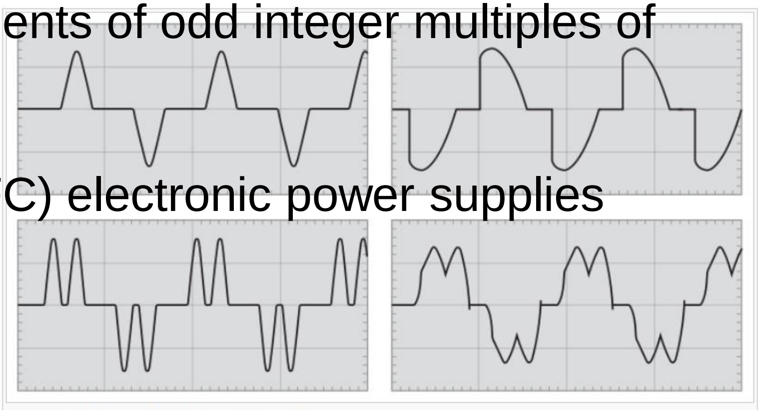
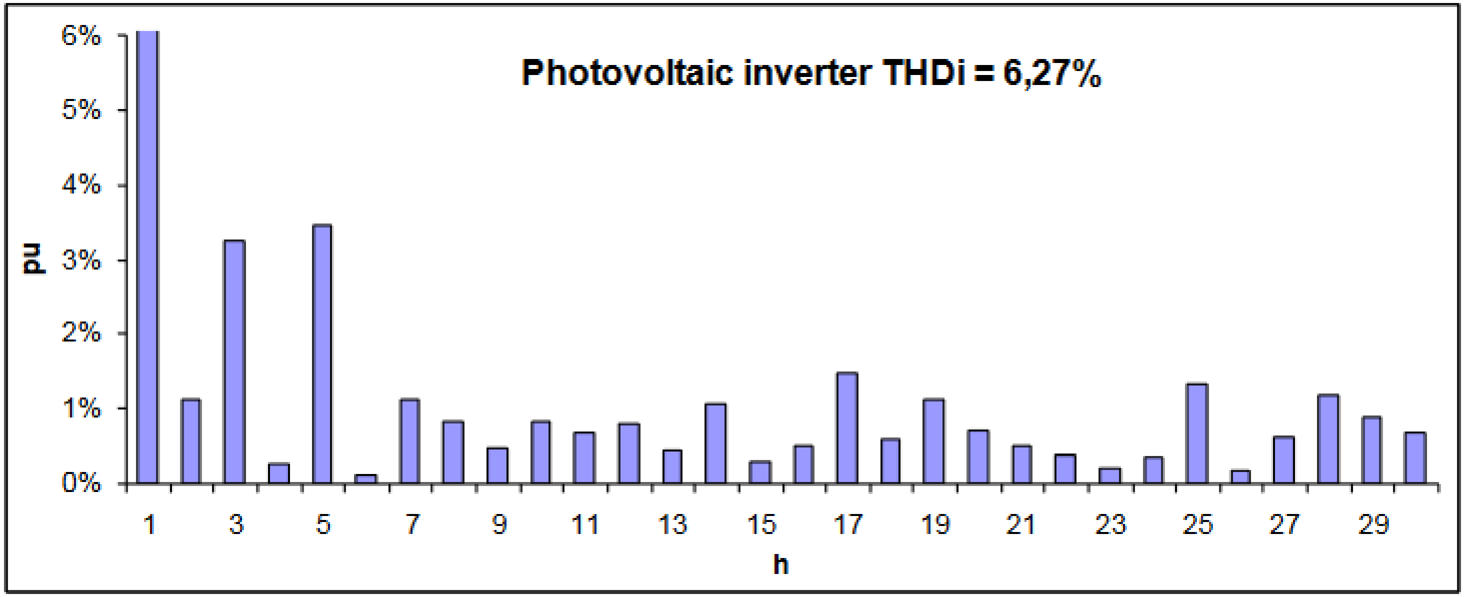


Fig. M1: Examples of distorted current waveforms

From: http://www.electrical-installation.org/enwiki/Definition_of_harmonics

Harmonics

Fourier series composition



From: https://www.comarcond.com/wp-content/uploads/2017/05/Informativa-fotovoltaico_-eng.pdf

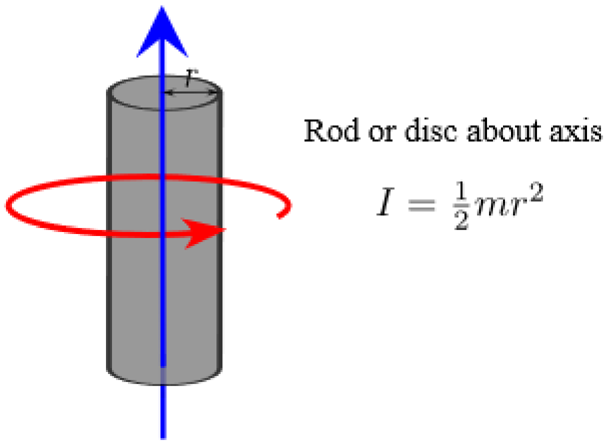
Rotating Inertia

Definition;
Rotational Inertia is a scalar value which tells us how difficult it is to change the rotational velocity of an object around a given rotational axis.

Rotational inertia is needed to find the energy which is stored as rotational kinetic energy in a spinning flywheel.

$$\tau = I\alpha = \mathrm{I} * \mathrm{dw/dt}$$

(show a (Torque*Velocity) power input to a flywheel, with (load torque*velocity) power removed. With net torque = zero, velocity ω remains constant. With load power fluctuations, the input power must match match the load power, else the angular velocity changes as a function of rot'l inertia.



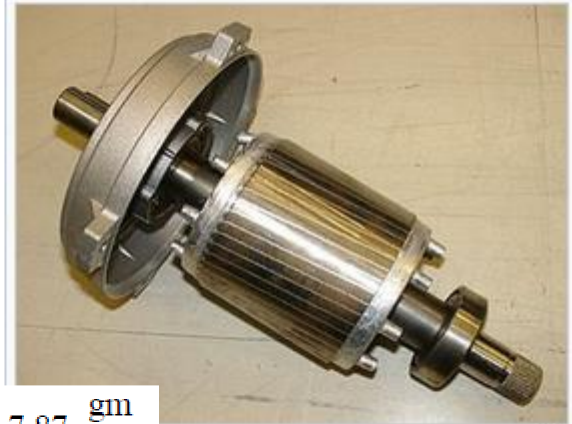
Rotating Inertia

Example, in terms I can relate to:

Electric motor calcs: Baldor FDL3510M 1725RPM 1HP Farm Duty motor

Voltage (Hi):	$Vin := 230 \cdot V$	
Full Load Amps:	$Iin := 6.5 \cdot amp$	
Full Load PF:	$PF := 73\%$	$\varphi = acos(0.73) = 43^o$
Full Load Efficiency	$\eta_{FL} := 67\%$	
Volt - Amps in	$VAin := Vin \cdot Iin$	$VAin = 1.495 \cdot kW$
Power in:	$Pin := Vin \cdot Iin \cdot PF$	$Pin = 1.091 \cdot kW$
FL Power Out:	$Pout := Pin \cdot \eta_{FL}$	$Pout = 0.981 \cdot hp$
FL Torque:	$T_{FL} := \frac{Pout}{1725 \cdot rpm}$	$T_{FL} = 4.048\ J$ $\quad T_{FL} = 4.048 \cdot N \cdot m$
(!) Note: Joule = Watt*sec = Newton*Meter		$T_{FL} = 2.986\ ft \cdot lbf$

Rotating Inertia



Squirrel cage rotor

Example

Rotor Radius: $r_r := 50\text{mm} = 5 \cdot \text{cm}$

Density of Iron: $\rho_{Fe} := 7.87 \frac{\text{gm}}{\text{cm}^3}$

Rotor Length $l_r := 6.5\text{in} = 16.51 \cdot \text{cm}$

Rotor Volume: $v_r := \pi \cdot r_r^2 \cdot l_r = 1297\,\text{cm}^3$ $\quad v_r \cdot \rho_{Fe} = 10.205\,\text{kg}$

Rotor mass (ρ*v): $m_r := \pi \cdot r_r^2 \cdot l_r \cdot \rho_{Fe}$ $\quad m_r = 10.205\,\text{kg}$

Rotor Moment of Inertia: $I_r := \frac{1}{2} \cdot m_r \cdot r_r^2$ $\quad I_r = 0.013\,\text{m}^2 \cdot \text{kg}$

with full load net torque, acceleration: $\alpha := \frac{T_{FL}}{I_r}$ $\quad \alpha = 317.321 \frac{\text{rad}}{\text{s}^2}$

Spinning at synchronous speed 1800rpm: $\omega_s := 1800 \cdot \text{rpm}$ $\quad \omega_s = 188.496 \frac{\text{rad}}{\text{s}}$

as $\alpha = \frac{d}{dt}\omega$ $\quad \Delta T := \frac{\omega_s}{\alpha}$ $\quad \Delta T = 0.594\,\text{s}$

Net Torque applied: $\tau = I \cdot \alpha = I \cdot \frac{d\omega}{dt}$

Quiz Questions

1. “Islanding” as it relates to Distributed Energy Resources is:
   - A. A good feature, because it allows more resilient back-up power during widespread outages.
   - B. To be implemented cautiously, as Local EPS loads may overwhelm Available Active Power
   - C. Both A&B
   - D. NOT ALLOWED, in consideration for safety of line workers.
2. Reactive Power units of measure are:
   - A. Watts
   - B. Volt-Amps
   - C. VARs
   - D. There is no such thing as reactive power
3. Robust power systems include:
   - A. Operating Reserves
   - B. Multiple Sources
   - C. Politicians
   - D. Most of the above

Quiz Answers

1. "Islanding" as it relates to Distributed Energy Resources is:
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2. Reactive Power units of measure are:
   A. Watts (Active Power)
   B. Volt-Amps (Apparent power)
   C. VARs
   D. There is no such thing as reactive power
3. Robust power systems include:
   A. Operating Reserves
   B. Multiple Sources
   C. Progressive Regulatory Policy
   D. Most (or all) of the above

Generation & Distribution System

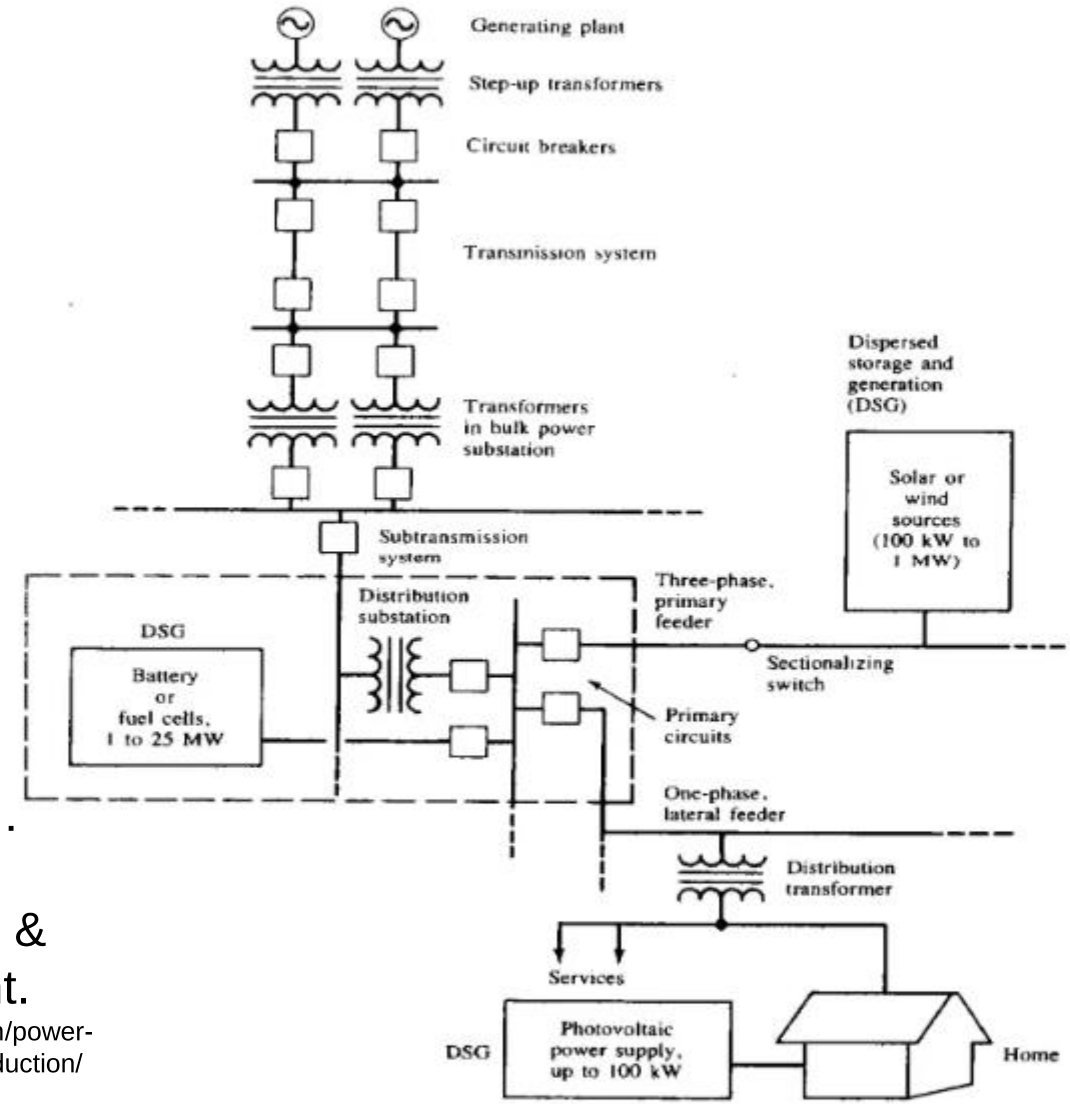
Large Power Generation stations, transmission systems, Subtransmission systems
(Bulk Power Systems)

Distribution substation
(Area EPS)

Lateral feeder
(Local EPS) – fed by one utility source, unless…

DSG – Dispersed Storage & Generation, (DER) present.

From https://www.electricalengineering123.com/power-voltage-distribution-systems-components-introduction/



Single Line diagram of typical electrical power system network

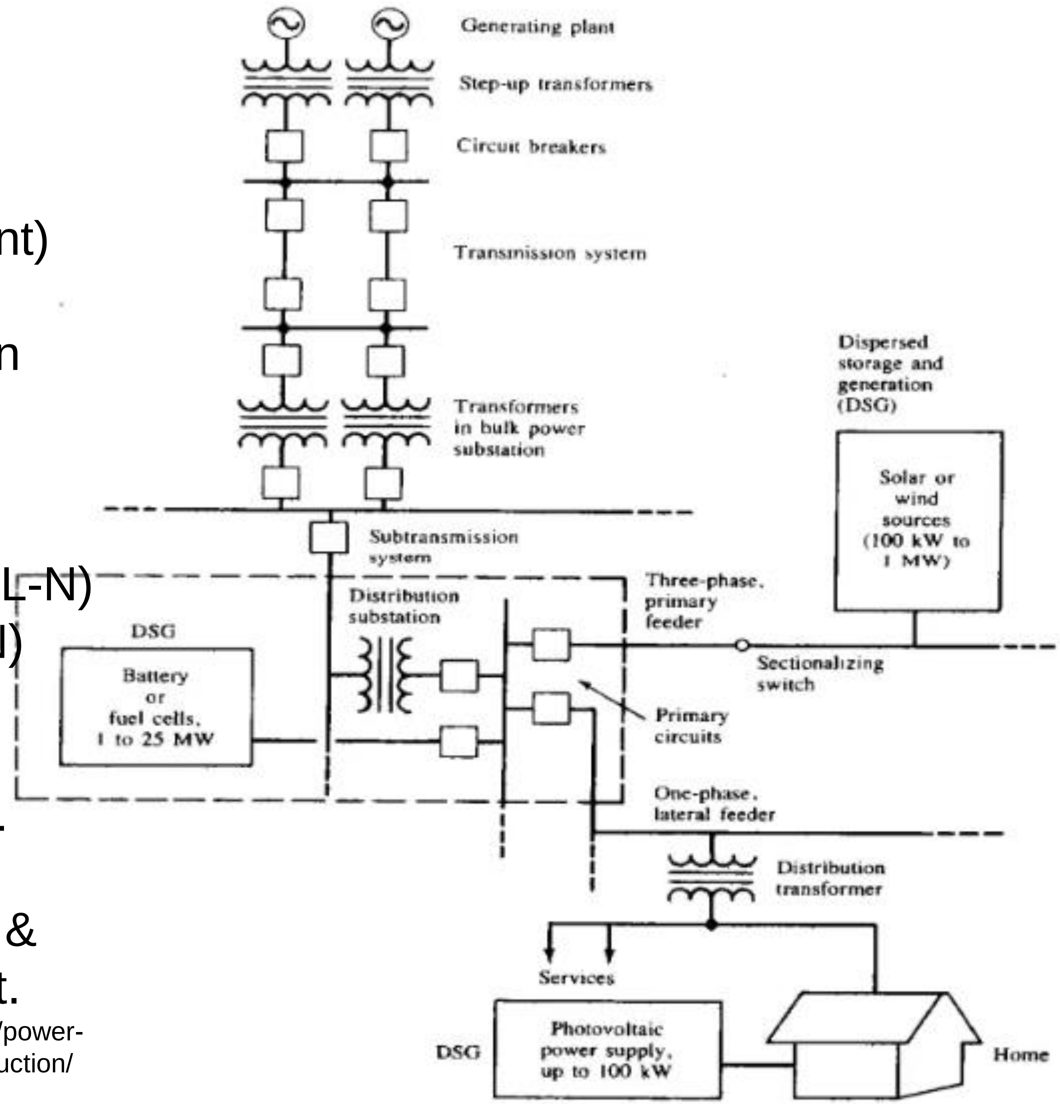
Generation & Distribution System

Transmission losses
(Conductor losses dominant)
High voltage transmission
Medium voltage distribution

Distribution substation
(Area EPS)
RG&E: 4160V L-L (2400V L-N)
Or 12480V L-L (7200V L-N)
Lateral feeder
(Local EPS) – fed by
one utility source, unless…

DSG – Dispersed Storage &
Generation, (DER) present.

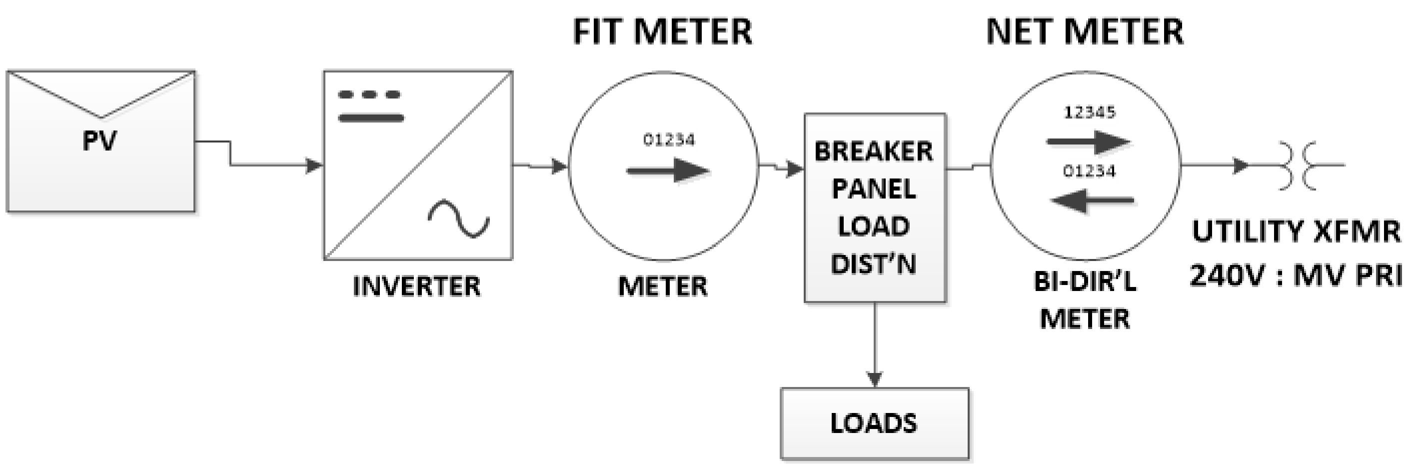
From https://www.electricalengineering123.com/power-voltage-distribution-systems-components-introduction/



Single Line diagram of typical electrical power system network

PV Generation System

Block diagram of Grid-tied PV inverter (Net metered) system



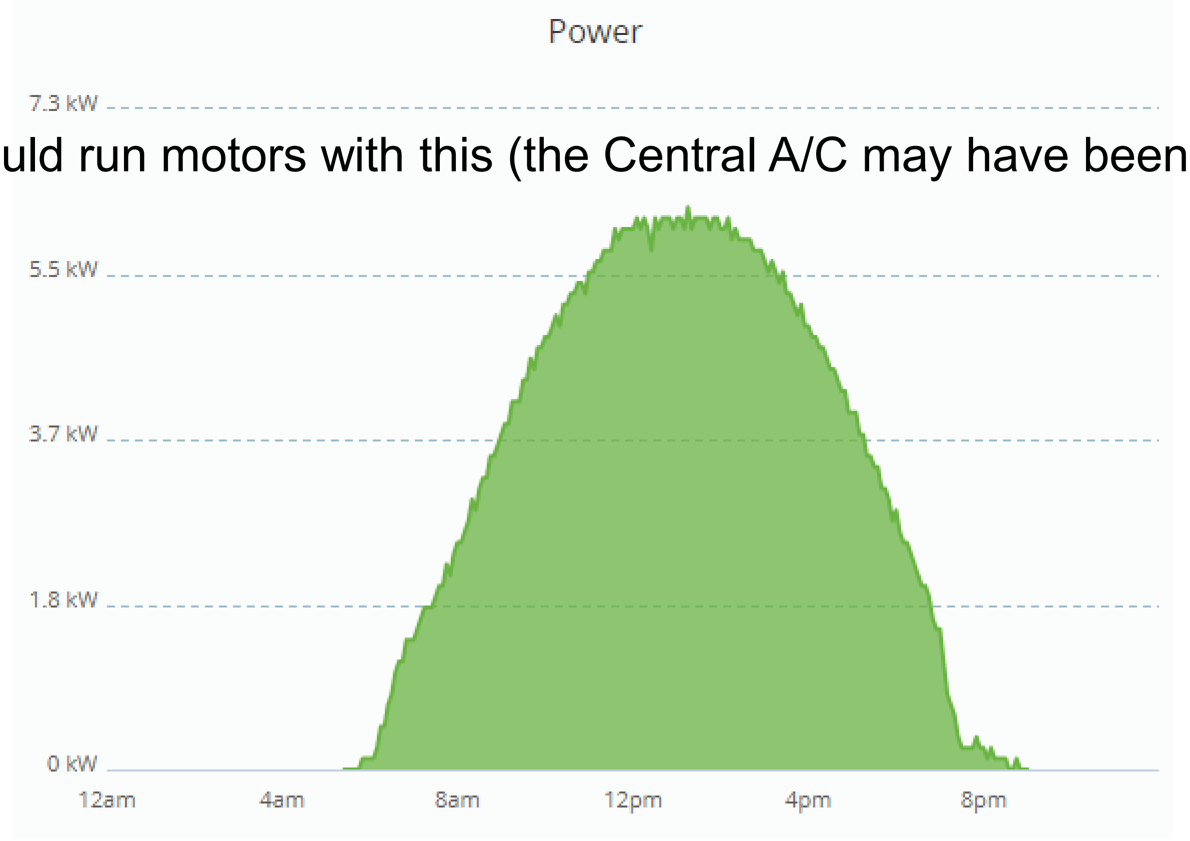
Production = FIT Meter (kWhr meter reading)
Excess Generation (meter reading) = (Production-Consumption)kW*(hr)
Utility Delivered (kWhr meter reading)

Consumption = Production + Utility Delivered – Excess Generation (kWh)

PV Generation System Typical Performance

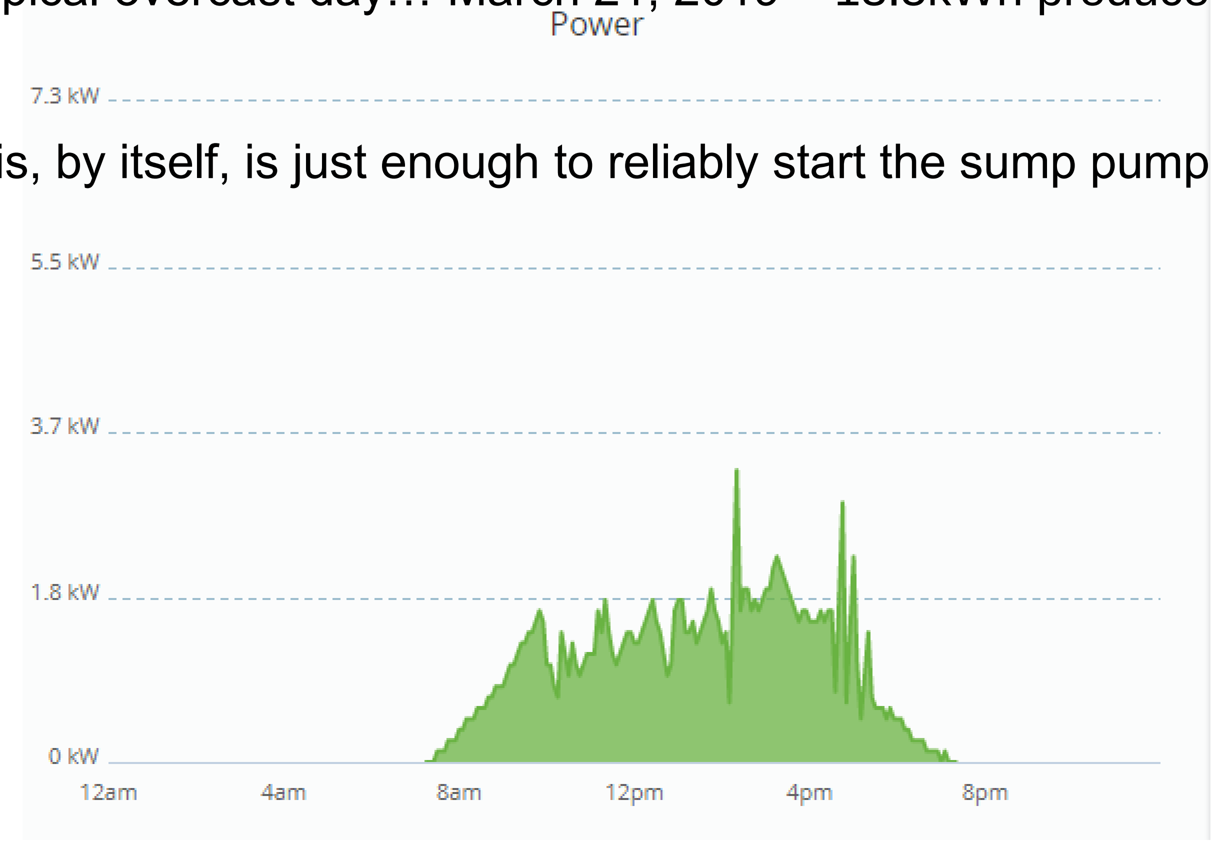
A Great Day for Solar… June 14, 2018 - 55.1kWh produced

You could run motors with this (the Central A/C may have been)…



PV Generation System Typical Performance

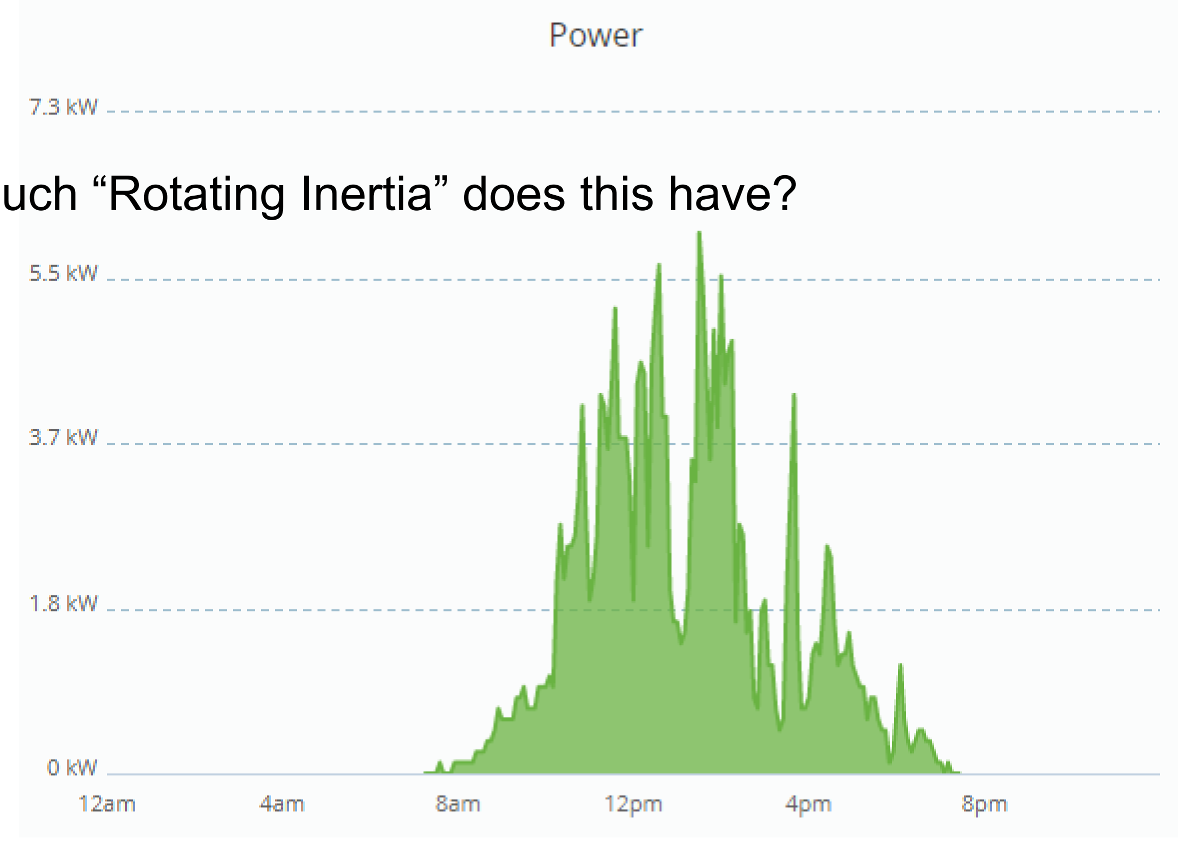
A typical overcast day… March 21, 2019 – 13.5kWh produced



(This, by itself, is just enough to reliably start the sump pump motor… I tried it!)

PV Generation System Typical Performance

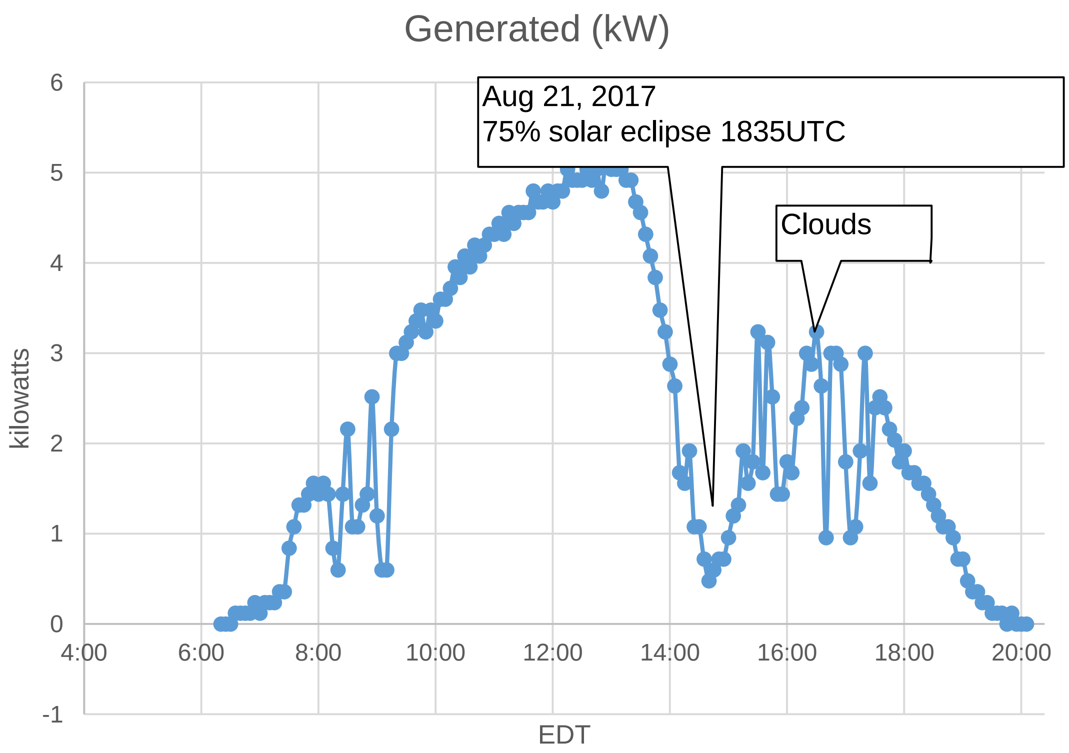
A bad day for the power company… March 18, 2019 – 21.2kWh produced
-with rapid fluctuations due to passing clouds



How much "Rotating Inertia" does this have?

PV Generation System Typical Performance

Or an occasional solar eclipse… Aug 21, 2017 – 31.8kWh produced
-with some more rapid fluctuations due to passing clouds



Inverter Requirements

From IEEE1547-2018

Table 3—Minimum measurement and calculation accuracy requirements for manufacturers[a]

Time frame	Steady-state measurements			Transient measurements		
Parameter	**Minimum measurement accuracy**	**Measure-ment window**	**Range**	**Minimum measurement accuracy**	**Measure-ment window**	**Range**
Voltage, RMS	(± 1% V_{nom})	10 cycles	0.5 p.u. to 1.2 p.u.	(± 2% V_{nom})	5 cycles	0.5 p.u. to 1.2 p.u.
Frequency[b]	10 mHz	60 cycles	50 Hz to 66 Hz	100 mHz	5 cycles	50 Hz to 66 Hz
Active Power	(± 5% S_{rated})	10 cycles	0.2 p.u. < P < 1.0 p.u.	Not required	N/A	N/A
Reactive Power	(± 5% S_{rated})	10 cycles	0.2 p.u. < Q < 1.0 p.u.	Not required	N/A	N/A
Time	1% of measured duration	N/A	5 s to 600 s	2 cycles	N/A	100 ms < 5 s

[a]Measurement accuracy requirements specified in this table are applicable for voltage THD < 2.5% and individual voltage harmonics <1.5%.

Inverter Requirements

From IEEE1547-2018

Table 4—Enter service criteria for DER of Category I, Category II, and Category III

Enter service criteria		Default settings	Ranges of allowable settings
Permit service		Enabled	Enabled/Disabled
Applicable voltage within range	Minimum value	≥ 0.917 p.u.[a]	0.88 p.u. to 0.95 p.u.
	Maximum value	≤ 1.05 p.u.	1.05 p.u. to 1.06 p.u.
Frequency within range	Minimum value	≥ 59.5 Hz	59.0 Hz to 59.9 Hz
	Maximum value	≤ 60.1 Hz	60.1 Hz to 61.0 Hz

[a] This corresponds to the Range B of ANSI C84.1, Table 1, column for service voltage of 120−600 V.

Table 5—Synchronization parameter limits for synchronous interconnection to an EPS…

(requirements easily met for a PV Inverter)

Inverter Requirements

From IEEE1547-2018

Table 6—Voltage and reactive/active power control function requirements for DER normal operating performance categories

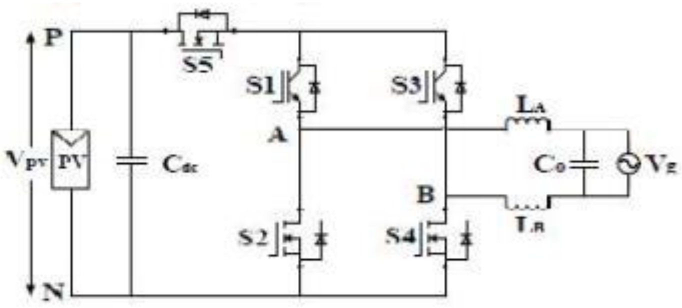
DER category	Category A	Category B
Voltage regulation by reactive power control		
Constant power factor mode	Mandatory	Mandatory
Voltage—reactive power mode[a]	Mandatory	Mandatory
Active power—reactive power mode[b]	Not required	Mandatory
Constant reactive power mode	Mandatory	Mandatory
Voltage and active power control		
Voltage—active power (volt-watt) mode	Not required	Mandatory

[a]Voltage-reactive power mode may also be commonly referred to as ‚volt-var' mode.
[b]Active power-reactive power mode may be commonly referred to as ‚watt-var' mode.
Refer to Annex B for definitions of Category A and Category B.

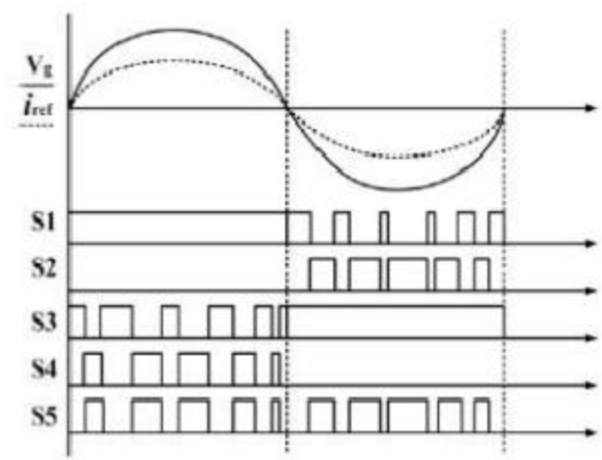
Inverter Design

SMA SB-6000TL-US No longer available

H5 topology – US7411802
Complies with UL1741
and IEEE1547-2003
Non-compliant with IEEE1547-2018
Unity Power Factor only (PF=1.0)



(a)



(b)

Inverter Design

H5 topology

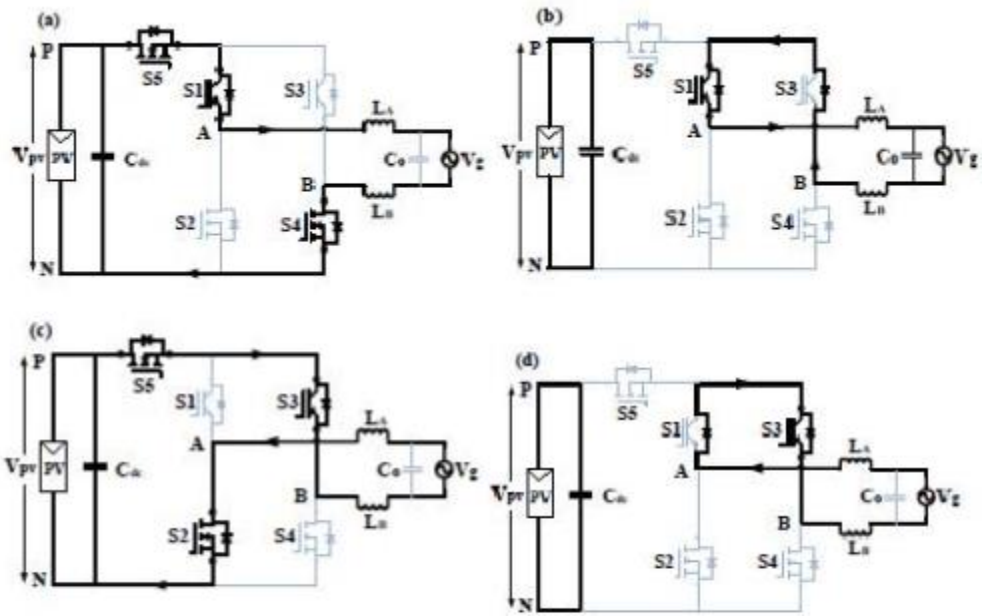
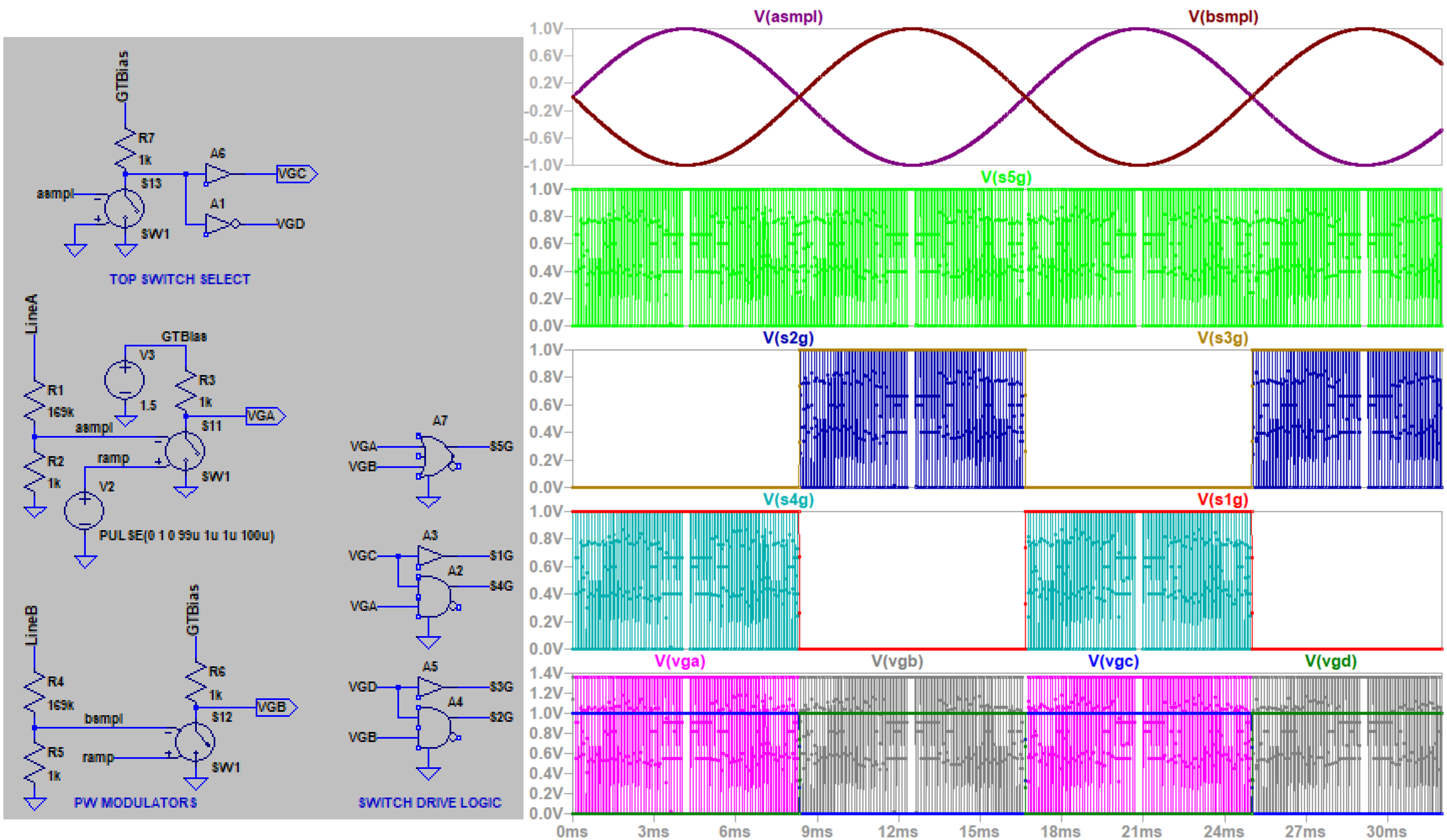


Fig.1. Operation modes of H5 topology. (a) Active mode in the positive half period. (b) Freewheeling mode in the positive half period. (c) Active mode in the negative half period.(d) Freewheeling mode in the negative half period.

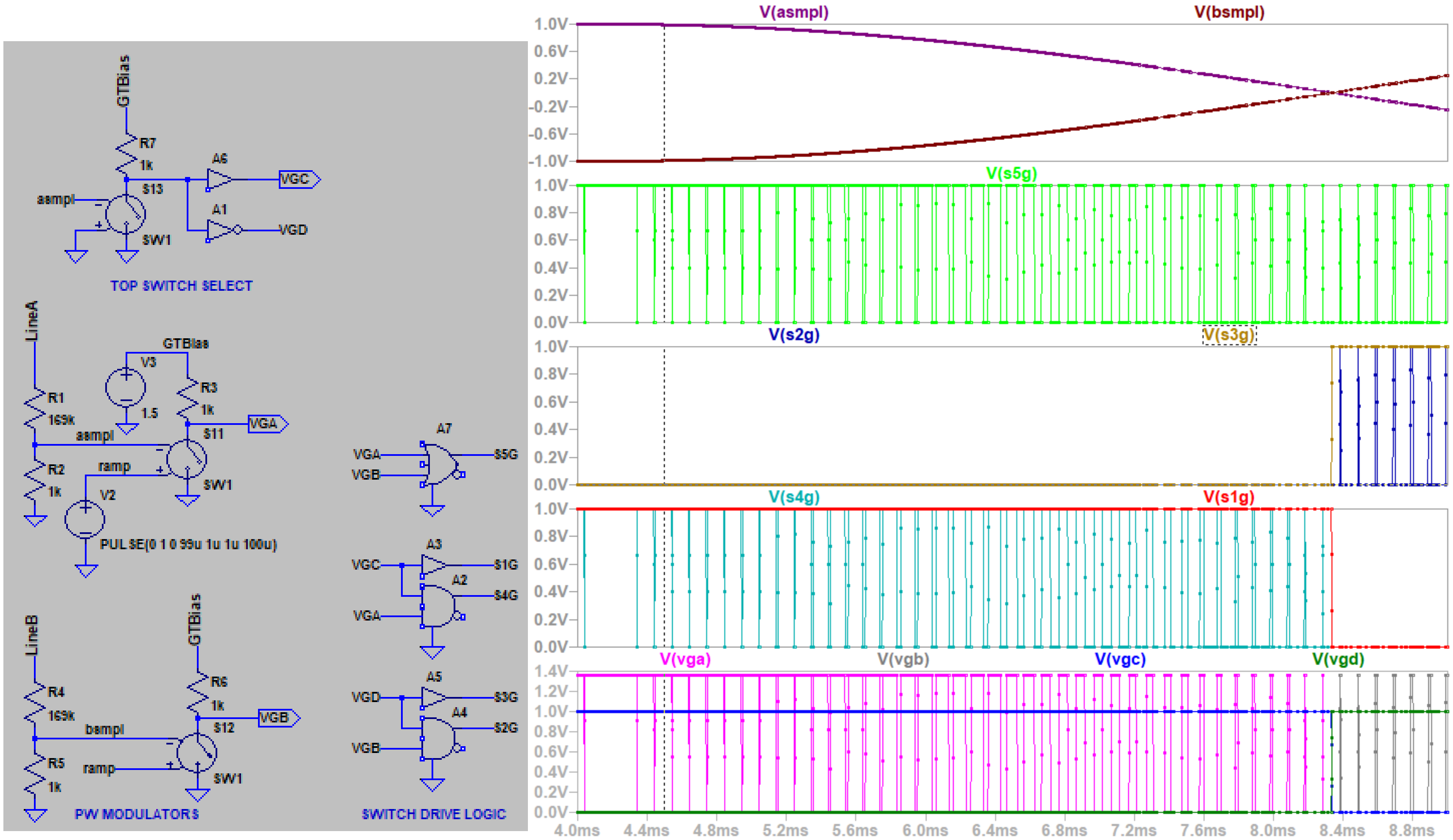
Inverter Design

H5 topology switch drive signals



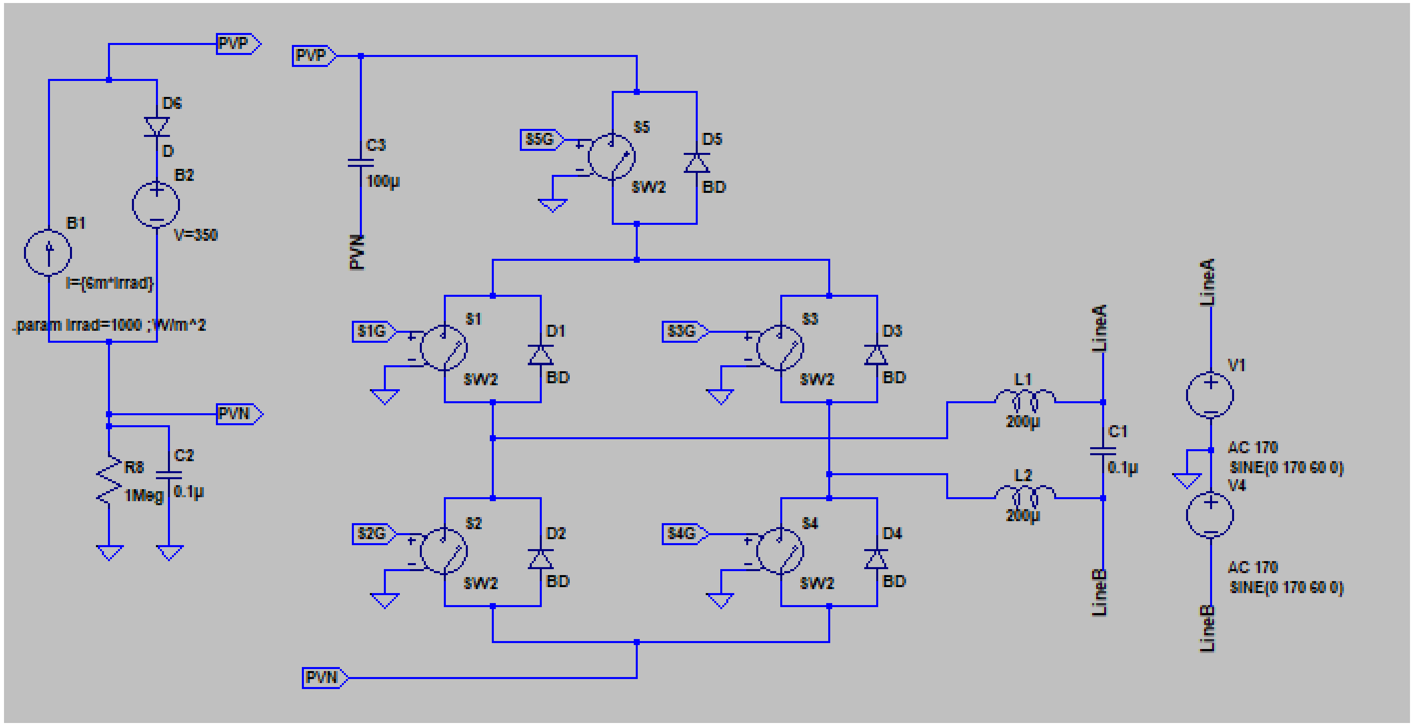
Inverter Design

H5 topology switch drive signals



Inverter Design

H5 topology Power section



Questions I'd like to answer (or at least consider…)

"How much distributed generation capacity do we presently have connected?"

"How much intermittent distributed generation can be added to our local grid before we get stability/power quality issues that will affect customers?"

"If done wrong, what effects will customers see?"

…Line voltage fluctuations, brown-outs, outages...

"what are elements of a robust power system?"

"What can be done to correctly integrate distributed generation?"

And perhaps
"What is the best way to incentivize the adoption of intermittent, unreliable, renewable energy resources so that the utility companies can run profitably while ensuring stable, reliable electric energy delivery?"

…Let's try to keep this based on science & economics…

A parting thought

States that work swiftly to address the new standards will be better equipped to integrate new technologies, optimize the benefits of DER, and improve system power quality.*

* From: https://irecusa.org/2018/07/smart-inverter-update-new-ieee-1547-standards-and-state-implementation-efforts/

Quiz Questions

4. Reactive Power can most simply be added with
    A. Capacitors, which support distribution line voltage
    B. Loading coils, as with telephone phone line compensation
    C. Over-excited generation
    D. Many ways, It’s not a simple problem
5. Rotating Inertia is a property that supports
    A. Line voltage regulation
    B. Synchronous frequency stability
    C. Harmonic suppression
    D. All of the above
6. Distributed Energy Resources support voltage by
    A. Providing local electric energy, reducing supply loading
    B. Always improve supply power factor
    C. May inject reactive power, thereby improving supply Power Factor
    D. A and C

Quiz Answers

4. Reactive Power can most simply be added with
   A. Capacitors, which support distribution line voltage
   B. Loading coils, as with telephone phone line compensation
   C. Over-excited generation
   D. Many ways, It's not a simple problem
5. Rotating Inertia is a property that supports
   A. Line voltage regulation
   B. Synchronous frequency stability
   C. Harmonic suppression
   D. All of the above (?)
6. Distributed Energy Resources support voltage by
   A. Providing local electric energy, reducing supply loading
   B. Always improve supply power factor
   C. May inject reactive power, thereby improving supply Power Factor
   D. A and C

References & Citations

This is a preliminary list of references consulted in preparation. Include only references that make the “final cut”

1. Single-line diagram of typical EPS: https://www.electricalengineering123.com/power-voltage-distribution-systems-components-introduction/
2. https://www.nerc.com/comm/PC/System%20Planning%20Impacts%20from%20Distributed%20Energy%20Re/IEEE%20SCC21_1547_Overview_NERC_SPIDERWG_01072019.pdf
3. https://energyworkshops.sandia.gov/wp-content/uploads/2018/08/6_Vartanian_2018_PE_Workshop.pdf
4. https://www.pjm.com/-/media/committees-groups/subcommittees/sos/20180301/20180301-item-13-der-ride-through.ashx
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   Recommendations for Harmonizing Distributed Generation Interconnection Practices: Technical Review Processes in NY State
6. **From H4, H5 to H6 – Standardization of Full Bridge Single Phase**