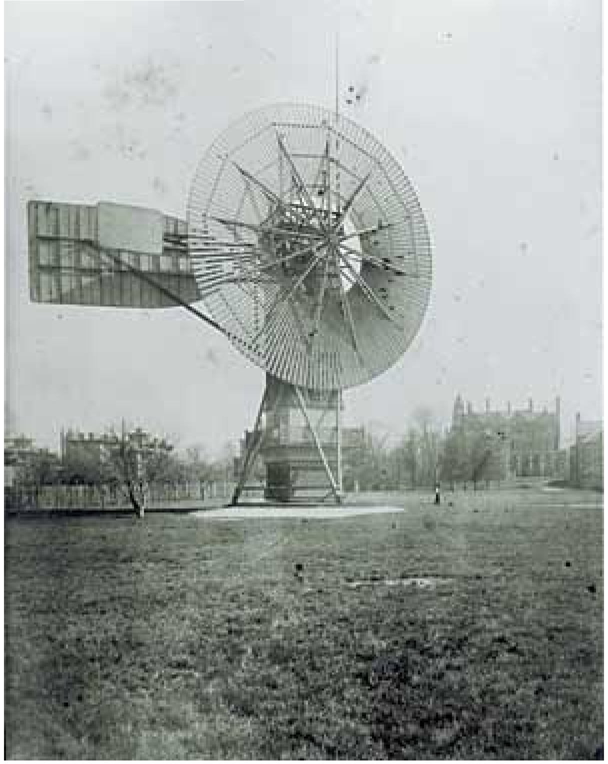
Wind Farm Electrical Systems

History of Wind Power

Pitstone Windmill, believed to be the oldest windmill in the British Isles



The Giant Brush Windmill in Cleveland, Ohio

During the winter of 1887-88 Brush built what is today believed to be the first automatically operating wind turbine for electricity generation.

It was a giant - the World's largest - with a rotor diameter of 17 m (50 ft.) and 144 rotor blades made of cedar wood. Note the person mowing the lawn to the right of the wind turbine.

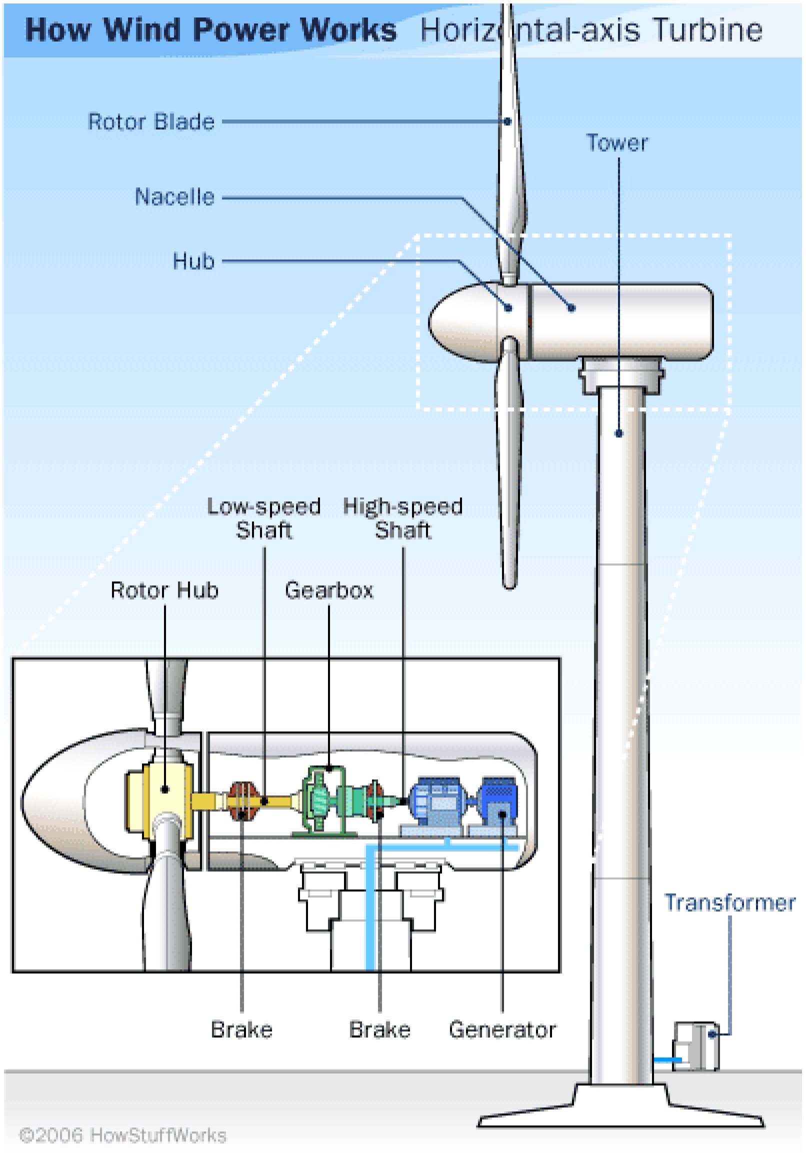
The turbine ran for 20 years and charged the batteries in the cellar of his mansion.

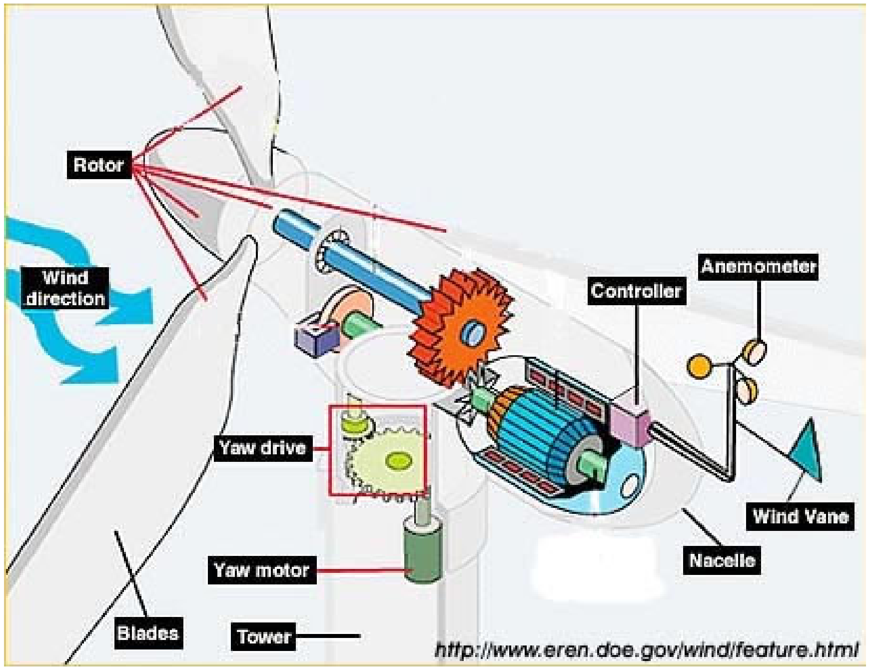
Despite the size of the turbine, the generator was only a 12 kW model.

Grandpa’s Knob

The first large-scale electricity-producing windmill (the world's largest at the time) was installed in 1941 at Grandpa's Knob, on the border of Castleton and West Rutland, VT, to take advantage of New England's strong wind energy regime. The turbine restarted on March 3, 1945 and operated normally until March 26, when the turbine suffered a massive failure. One of the 75-foot blades suddenly snapped off and hurled 700 feet down the mountain. The experiment, still largely considered a success, ended with the turbine being razed in the summer of 1946

Wind Turbine Generator Introduction

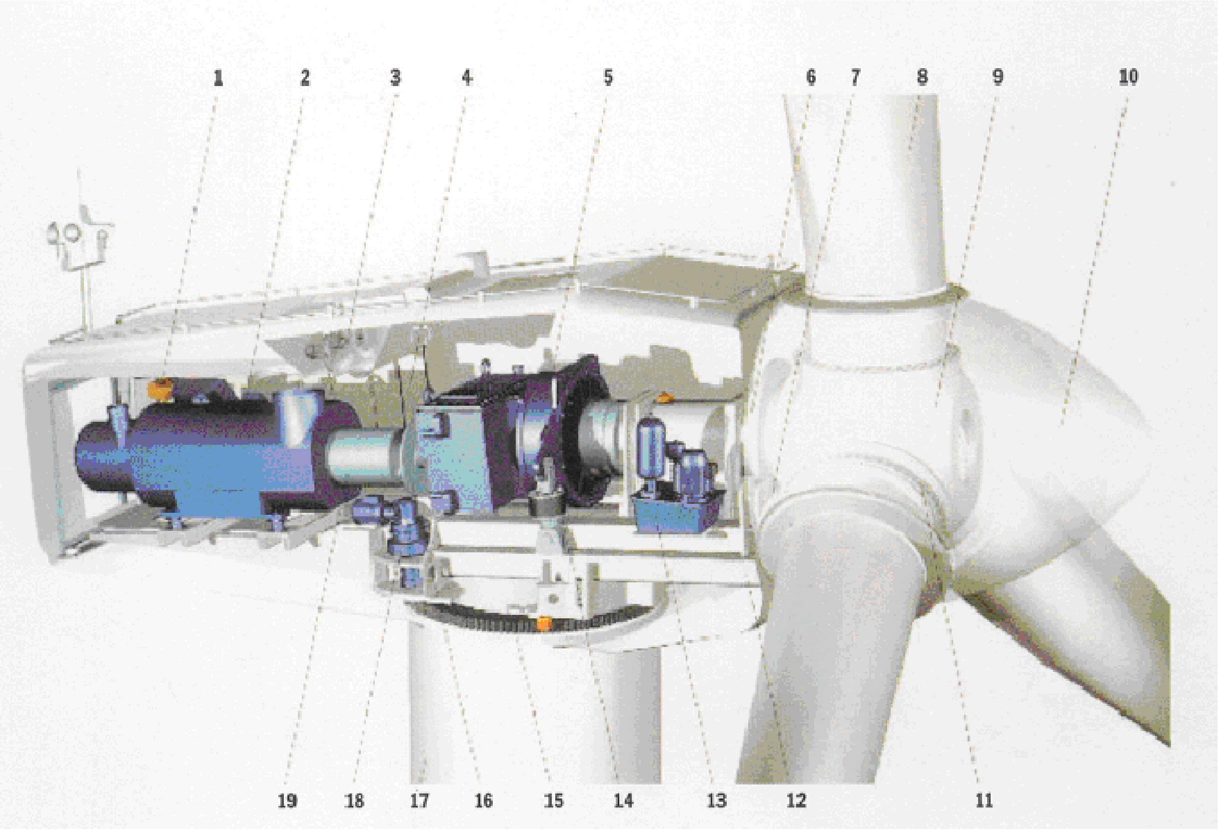




A small anemometer and wind vane on top of the wind turbine electronically tell a controller which way to point the rotor into the wind. Then the "yaw drive" mechanism turns gears to point the rotor into the wind.

Nacelle Design

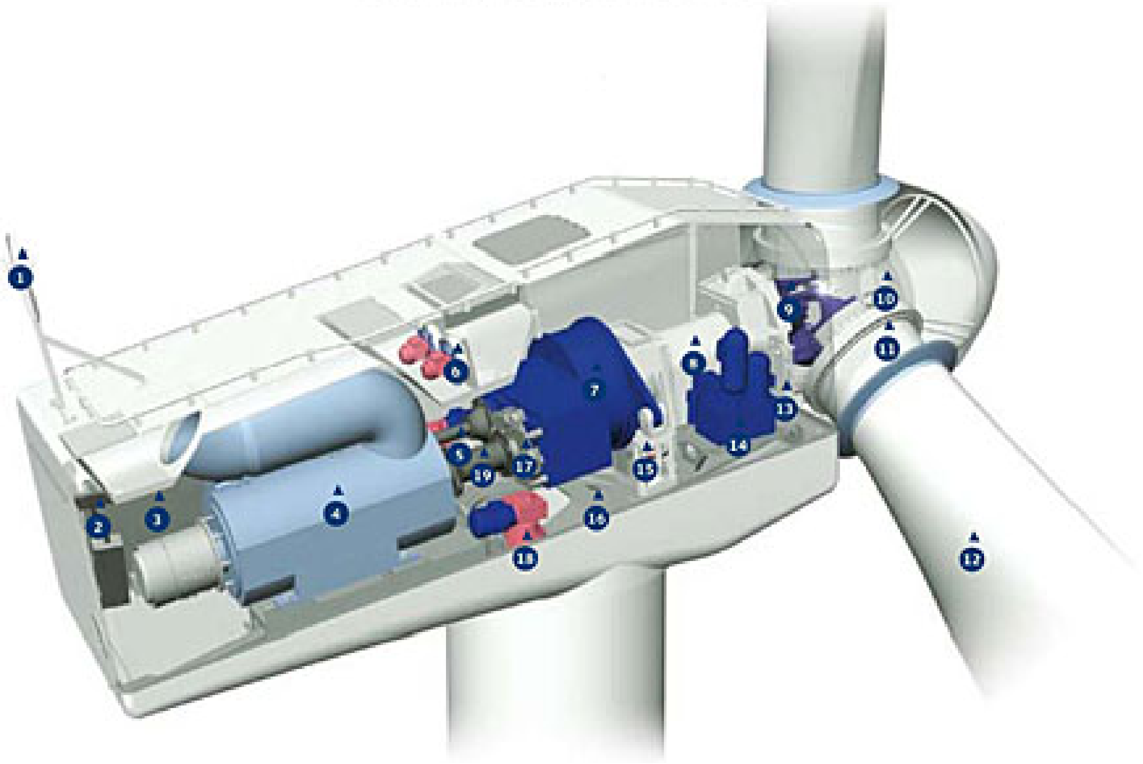
Nacelle Details



1. **Maintenance Hoist.**
2. **Generator: 800 kW, Induction, 4 poles, 690 Volts.**
3. **Cooling system (Air)**
4. **Top Control unit. (PLC)**
5. **Gear box: ratio 71.3**
6. **Main shaft**
7. **Maintenance Rotor Lock System.**
8. **Blade.**
9. **Blade Hub**
10. **Nose cone**
11. **Blade bearing (for pitch control)**
12. **Base Frame**
13. **Hydraulic Unit (disk brakes, gear box)**
14. **Gear frame attachment**
15. **Yaw Ring**
16. **Brake**
17. **Tower (three sections)**
18. **Yaw motor drive: 2.2 kW**
19. **Cardan**
20. **Windvane for yaw control.**
21. **Anemometer for pitch control.**

Nacelle Details

Technical specifications



① Ultrasonic wind sensor

② Service crane

③ VMP-Top controller with converter

④ OptiSpeed* Generator

⑤ Pitch cylinder

⑥ Oil and water coolers

⑦ Gearbox

⑧ Main shaft

⑨ Pitch system

⑩ Blade hub

⑪ Blade bearing

⑫ Blade

⑬ Rotor lock system

⑭ Hydraulic unit

⑮ Torque arm

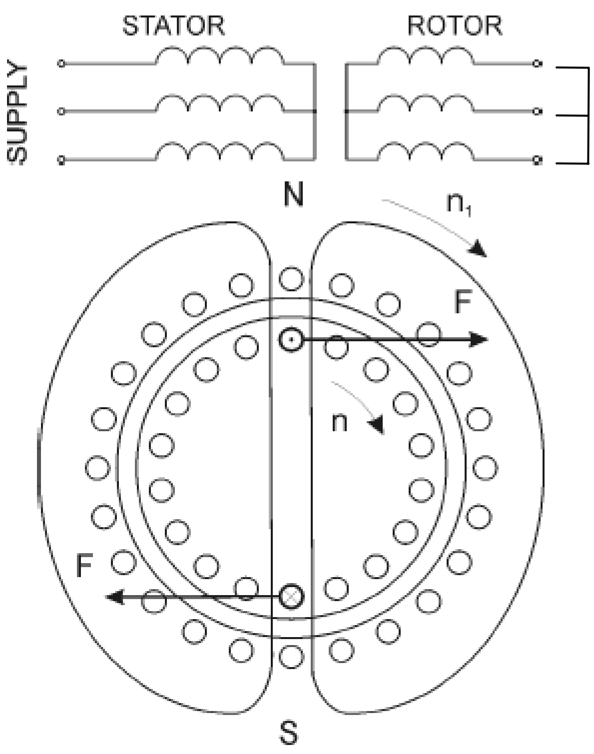
⑯ Machine foundation

⑰ Mechanical disc brake

⑱ Yaw gear

⑲ Composite disc coupling

Induction (Asynchronous) Machine



Slip is the difference of speeds $n_1 - n$ usually expressed in p.u. or %

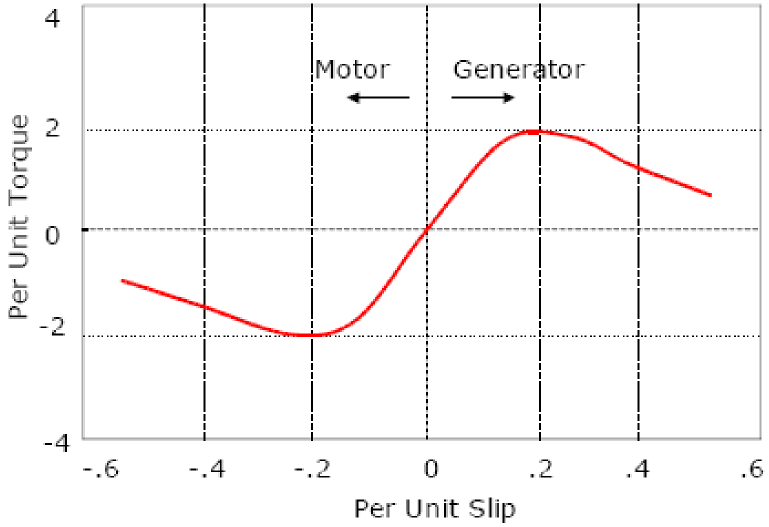
$\boxed{s = \frac{n_1 - n}{n_1}}$ or $s = \frac{n_1 - n}{n_1} 100\%$

$\boxed{n = n_1(1 - s)}$

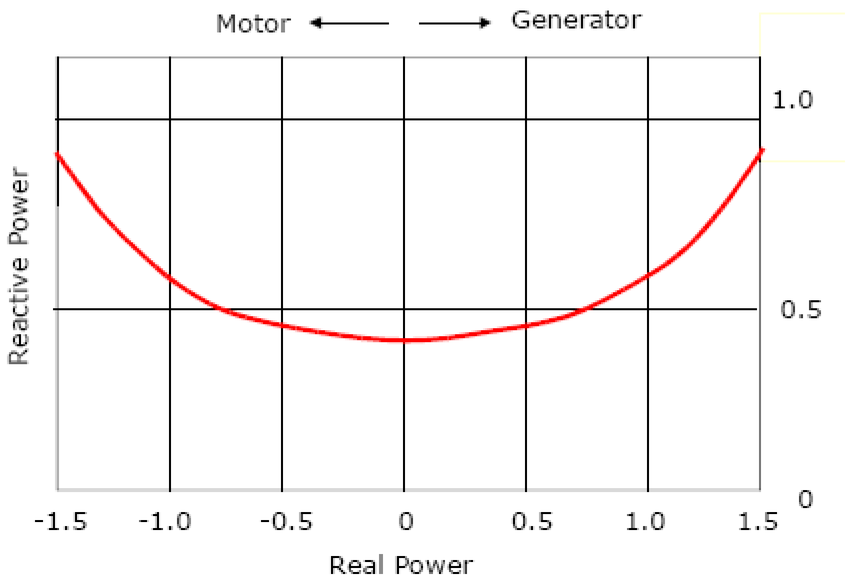
n	…	$-n_1$	0	n_1	$2n_1$	…
s	…	2	1	0	-1	…

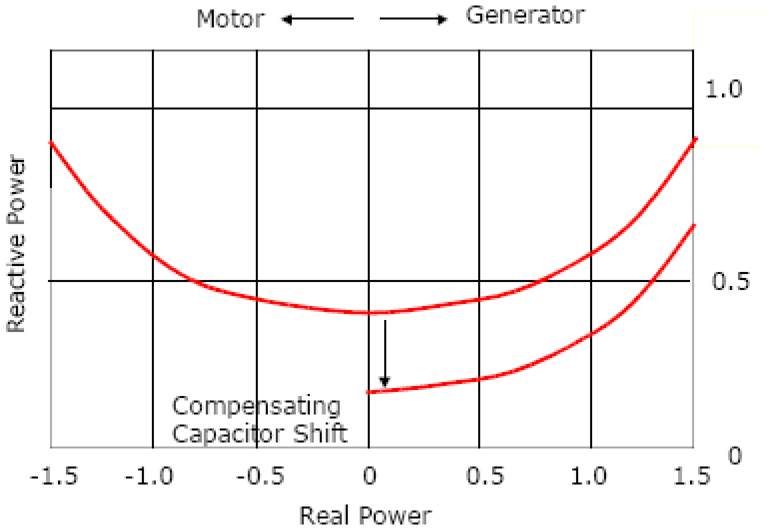
For $n < n_1$ the direction of torque is the same as speed n (of the rotor)
It is driving torque – the machine operates as a motor.

It is quite easy – after determination of rotor emfs & currents – to notice, that for $\boxed{n > n_1}$ the torque produced is opposite to n - therefore it is braking torque. If we want to keep the speed constant at such level, we must drive the machine – the machine operates as a generator (the mechanical energy must be supplied to the machine).

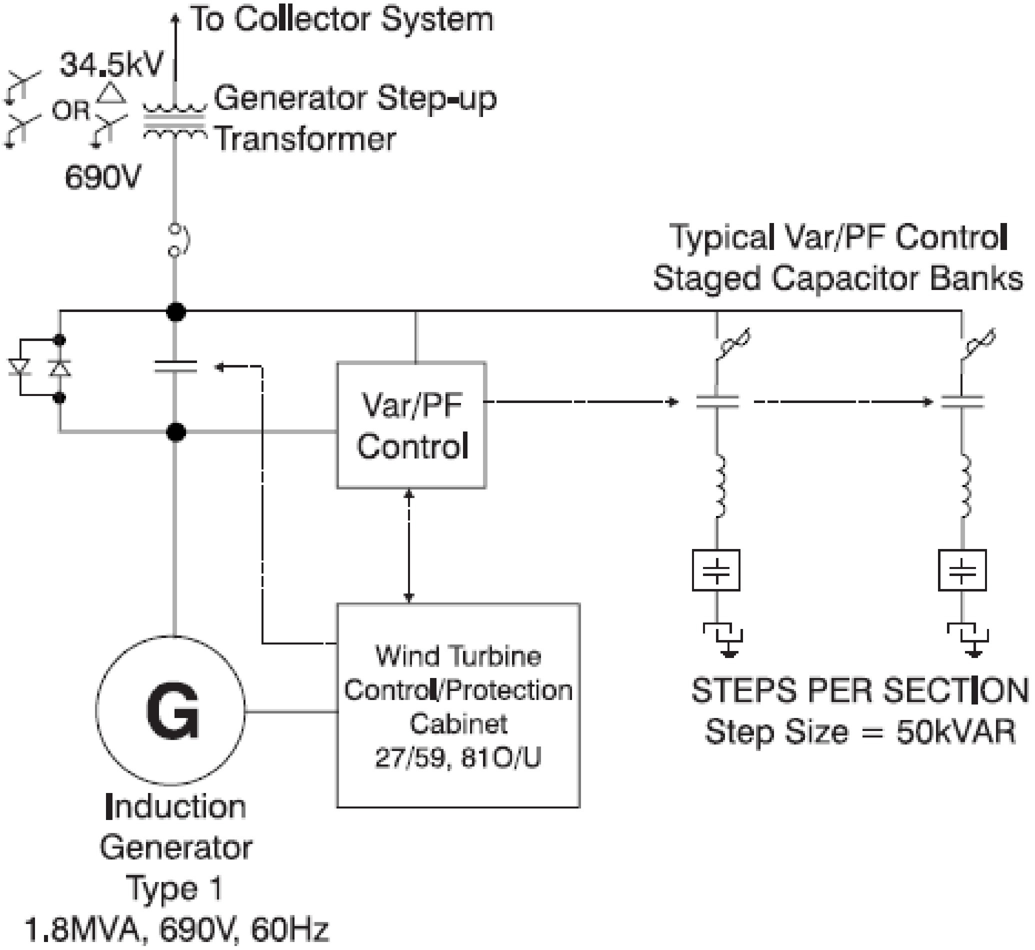


Induction Machine Reactive Power

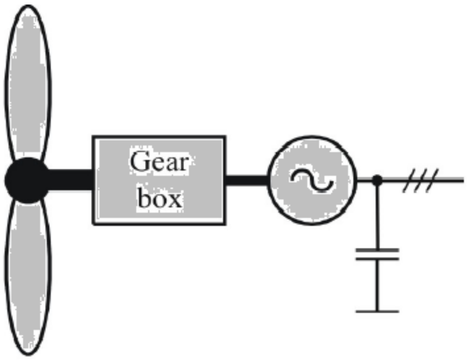


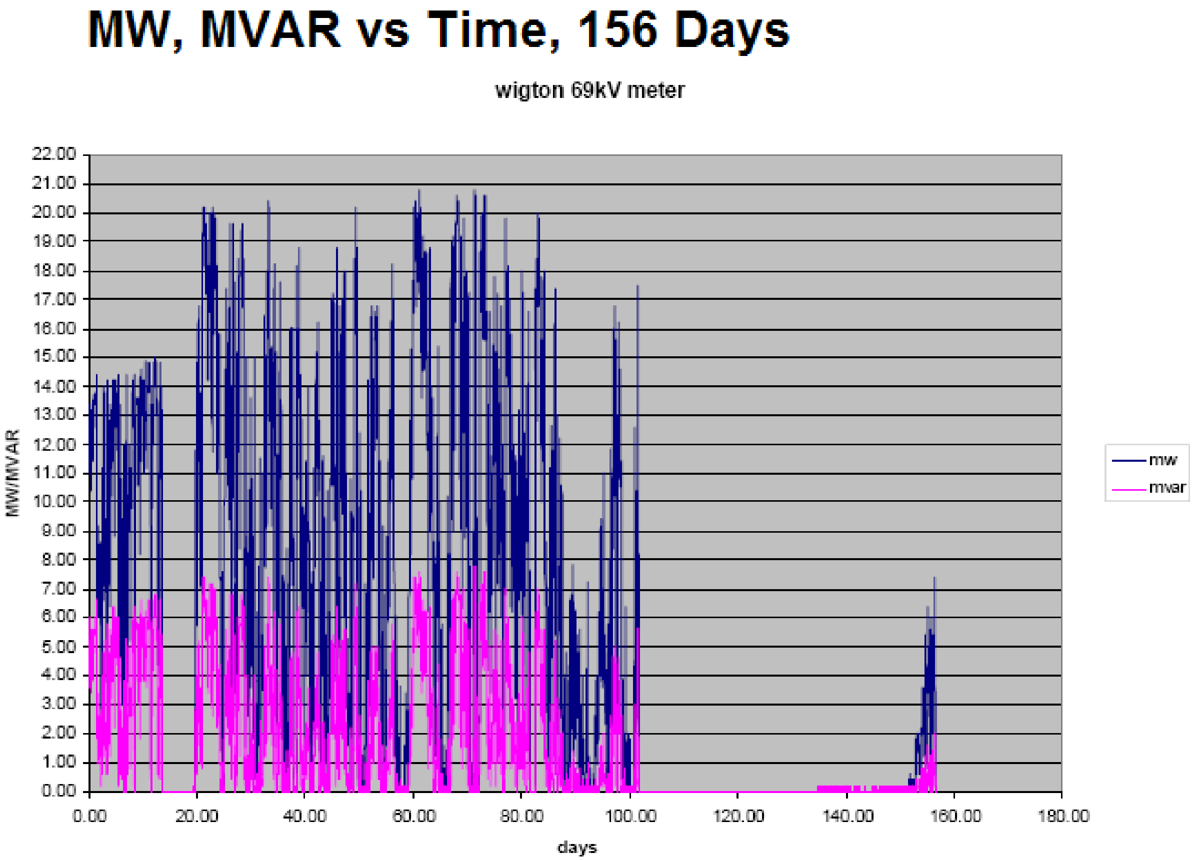


Wind Turbine Induction Generator



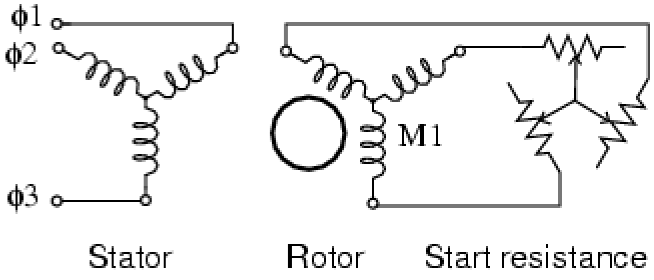
Induction Generator Issues

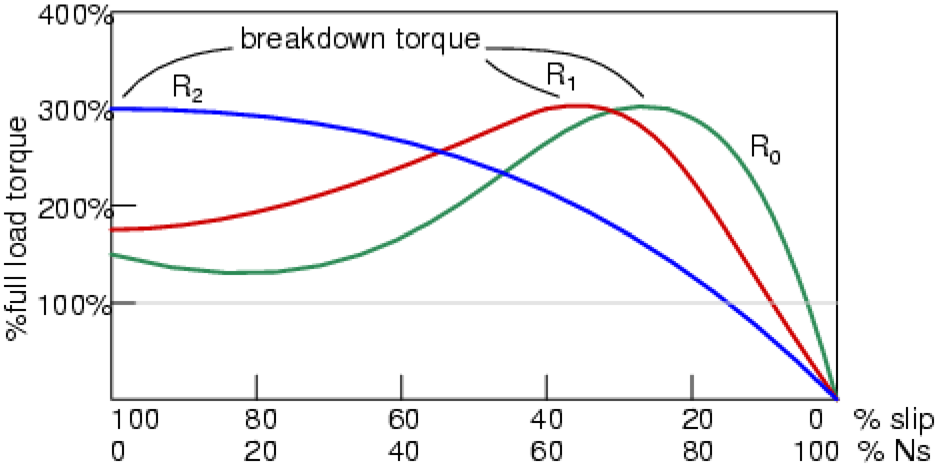


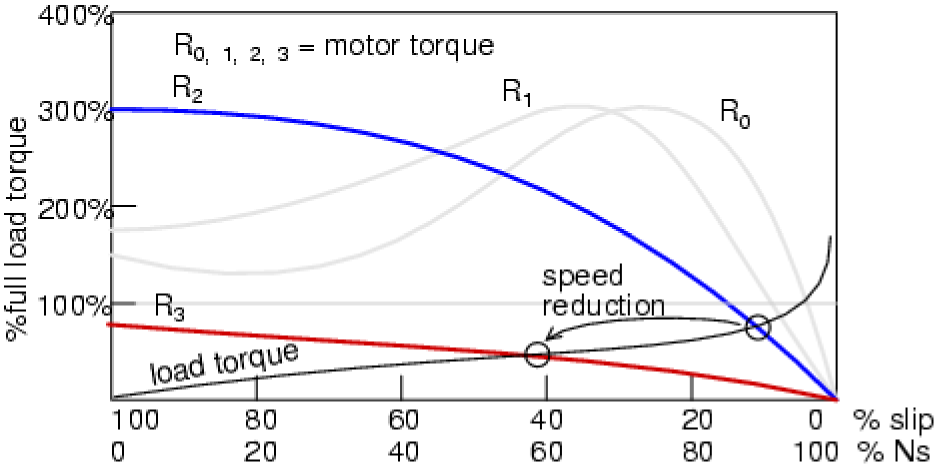


- Capacitors require to provide excitation
- Fixed speed operation only
- Gearbox torque is of concern
- Can’t provide reactive or voltage control
- Uncompensated wind farm is a consumer of reactive power (see chart)
- Reactive power compensation is needed to control the voltage

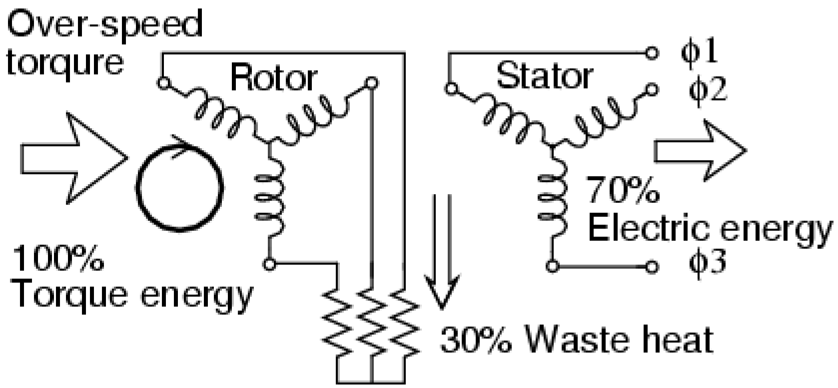
Wound Rotor Induction Machine



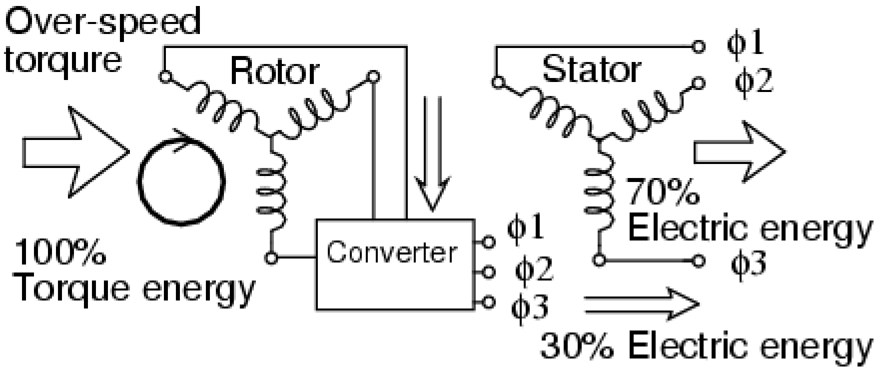




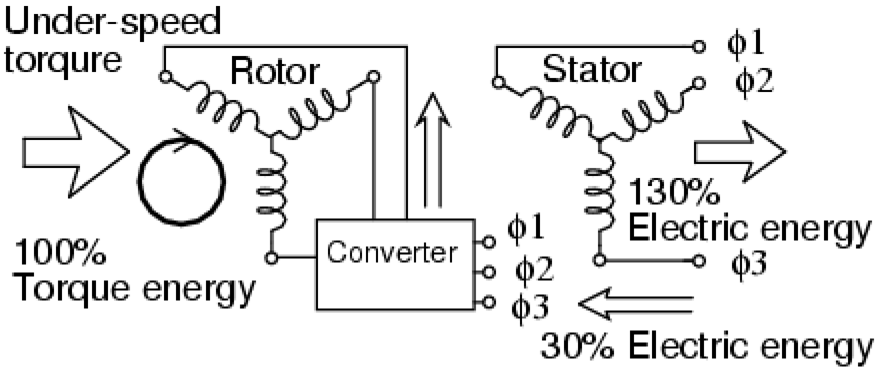
Wound Rotor Induction Generator



Singly Fed Induction Generator
Rotor Energy Dissipated



Doubly Fed Induction Generator Converter
Absorbs Over-speed Rotor Energy & Provides
Output Energy



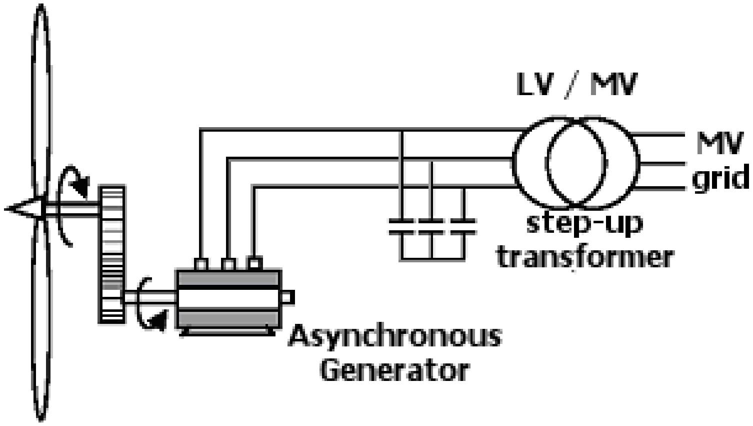
Doubly Fed Induction Generator
Converter Absorbs Energy for Under-speed Rotor
& Provides Output Energy

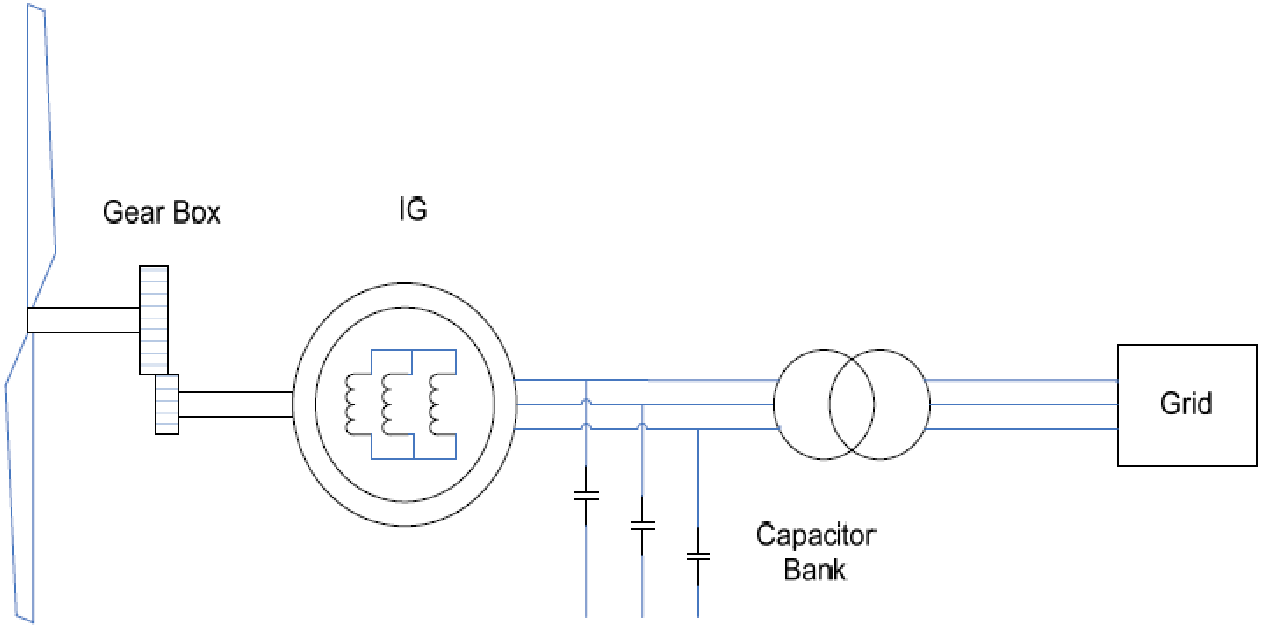
Wind Turbine Generator Constant Speed Systems

Squirrel Cage Induction Generator

- Cheap & Simple

- Torque variations not compensated
- Flicker
- Capacitors to compensate reactive power

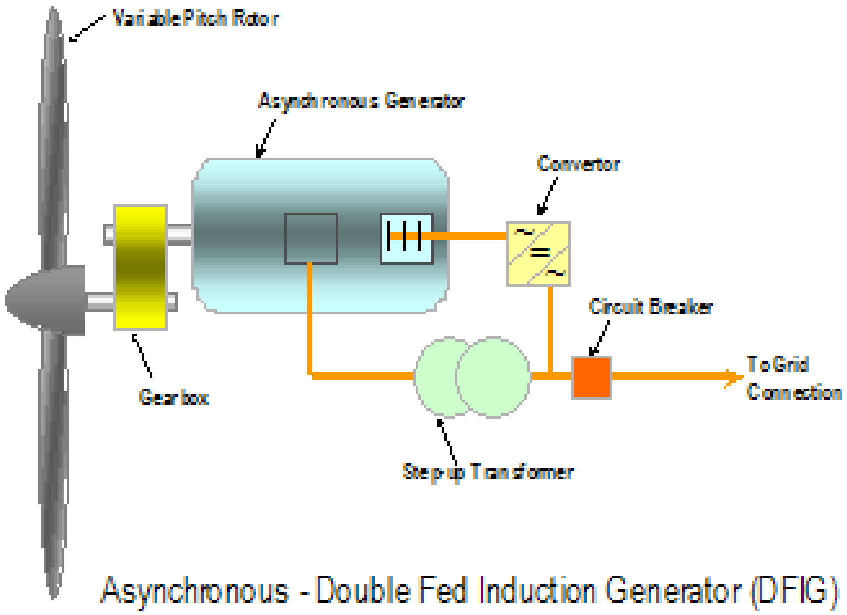




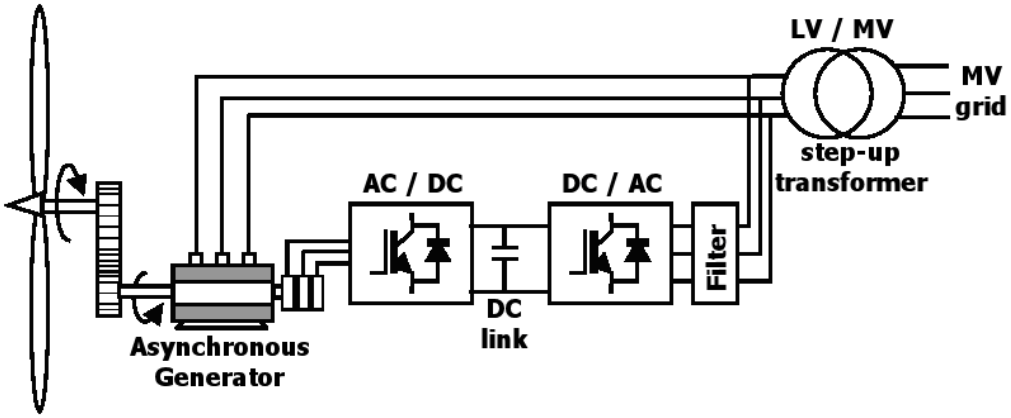
Wind Turbine Generator Variable Speed Systems

Doubly Fed (Wound Rotor) Induction Generator DFIG

- Optimum power control
- Converter size
- Restricted speed variability
- Expensive



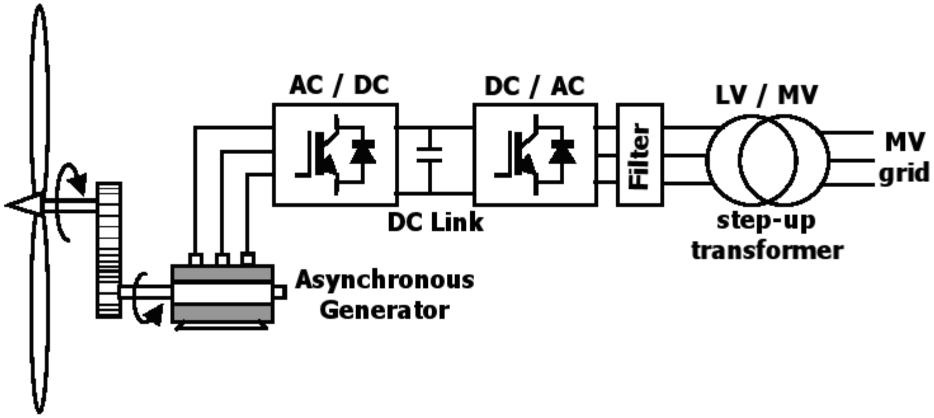
Asynchronous - Double Fed Induction Generator (DFIG)



Wind Turbine Generator Variable Speed Systems

Squirrel Cage Induction Generator

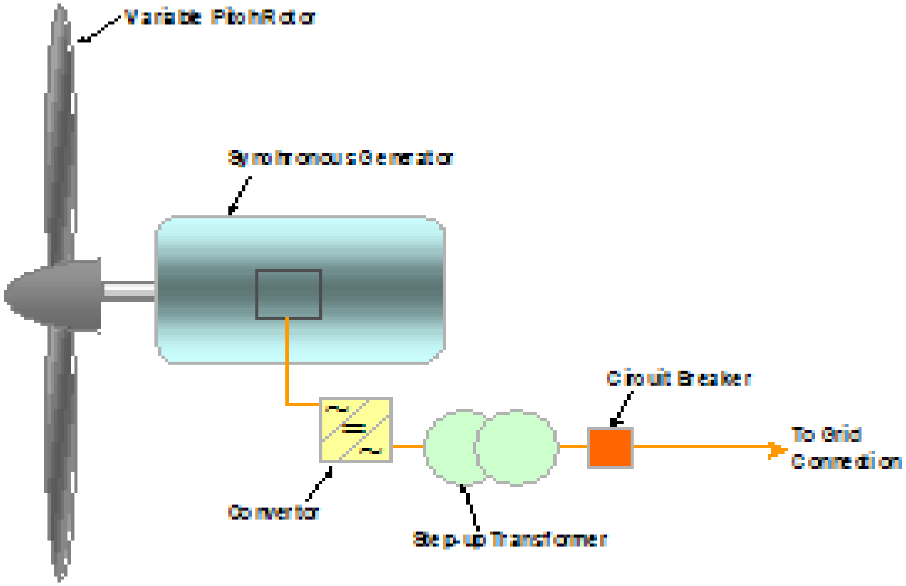
- Optimum power control
- 100% speed variability
- Converter size
- Expensive



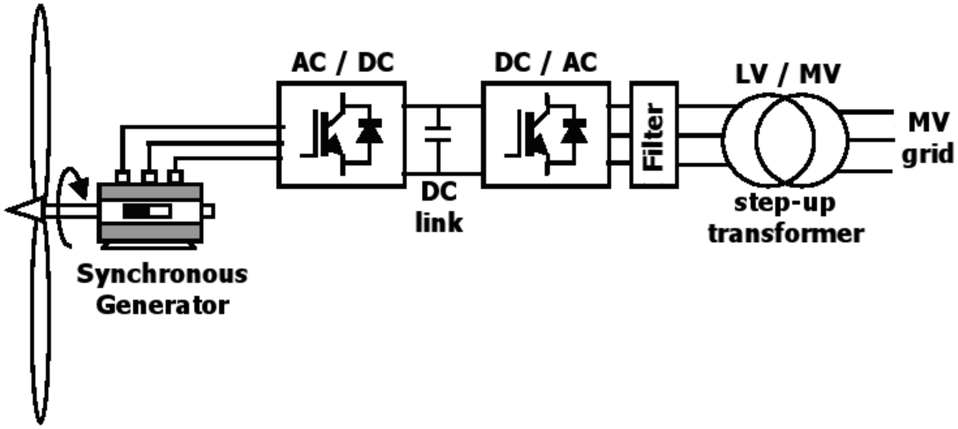
Wind Turbine Generator Variable Speed Systems

Permanent Magnet Synchronous Generator

- Optimum power control
- 100% speed variability
- Without Gearbox
- Converter size
- Generator complexity
- Very expensive



Synchronous - Unsynchronised Generator



WT Generator Comparison

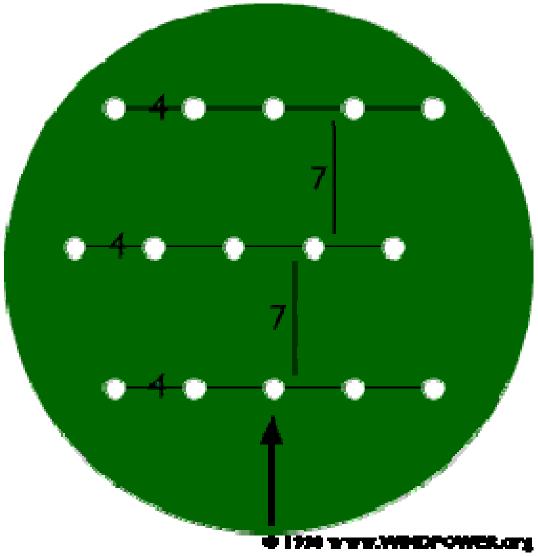
	Constant speed	Variable speed		
	Directly Connected Squirrel Cage Asynchronous Generator	Back to Back Connected Squirrel Cage Asynchronous Generator	Permanent Magnet Synchronous Generator	Wound Rotor Asynchronous Generators
Advantages	Cheap	100% speed variation	100% speed variation	Voltage and Power Factor control
	Robust	Voltage and Power Factor control	Voltage and Power Factor control	Good energy extraction
		High energy extraction	High energy extraction	30 % of Power processed by the converter
			Robust	
			Self-excitation	
Drawbacks	Flicker	100 % of Power processed by the converter	100 % of Power processed by the converter	Limited speed variation
	No Voltage control	Expensive	Generator complexity	Expensive
	No Power Factor control			
	Low energy extraction		Very expensive	

Wind Farms

A wind farm is a collection of wind turbines in the same location. Wind turbines are often grouped together in wind farms because this is the most economical way to create electricity from the wind.

If multiple wind turbines are placed too close to one another, the efficiency of the turbines will be reduced. Each wind turbine extracts some energy from the wind, so directly downwind of a turbine winds will be slower and more turbulent. For this reason, wind turbines in a wind farm are typically placed 3-5 rotor diameters apart perpendicular to the prevailing wind and 5-10 rotor diameters apart parallel to the prevailing wind. Energy loss due to the "Wind Park Effect" may be 2-5%.

The largest wind farm in the world is in Texas. It has 421 wind turbines spread out over 47,000 acres. This wind farm can produce a total of 735.5 Megawatts of electricity.



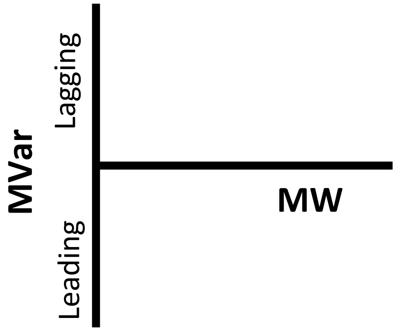
Wind Farm Layout to minimize "Wind Park Effect"

Comparison Wind Farm & Conventional Power Plant

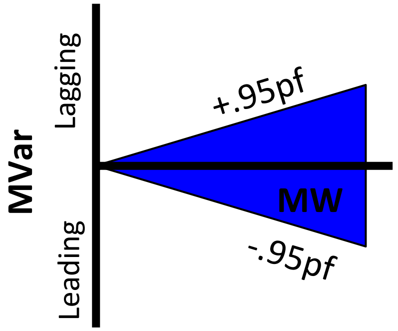
	Wind Farm	**Conventional Power Plant**
Configuration	Multiple small generators	One large generator
Location	Determinate on wind speed	Sited for economics (transmission access)
Control	1st Generation had no voltage ride through	Voltage & Frequency
Reactive Power	Capacitor banks and power electronics	Self generated
Reliability	Output varies with wind	Output predictable

Generator Reactive Capability

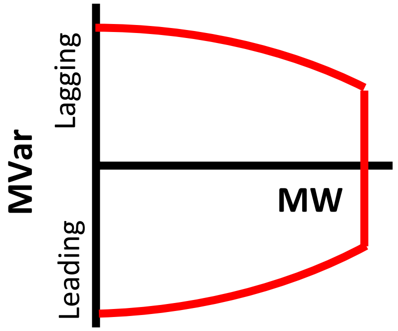
Induction generators – no inherent reactive production capability



Doubly fed induction generators - +/- 0.95 pf



Synchronous Generator – reactive capability



First Generation Wind Turbines

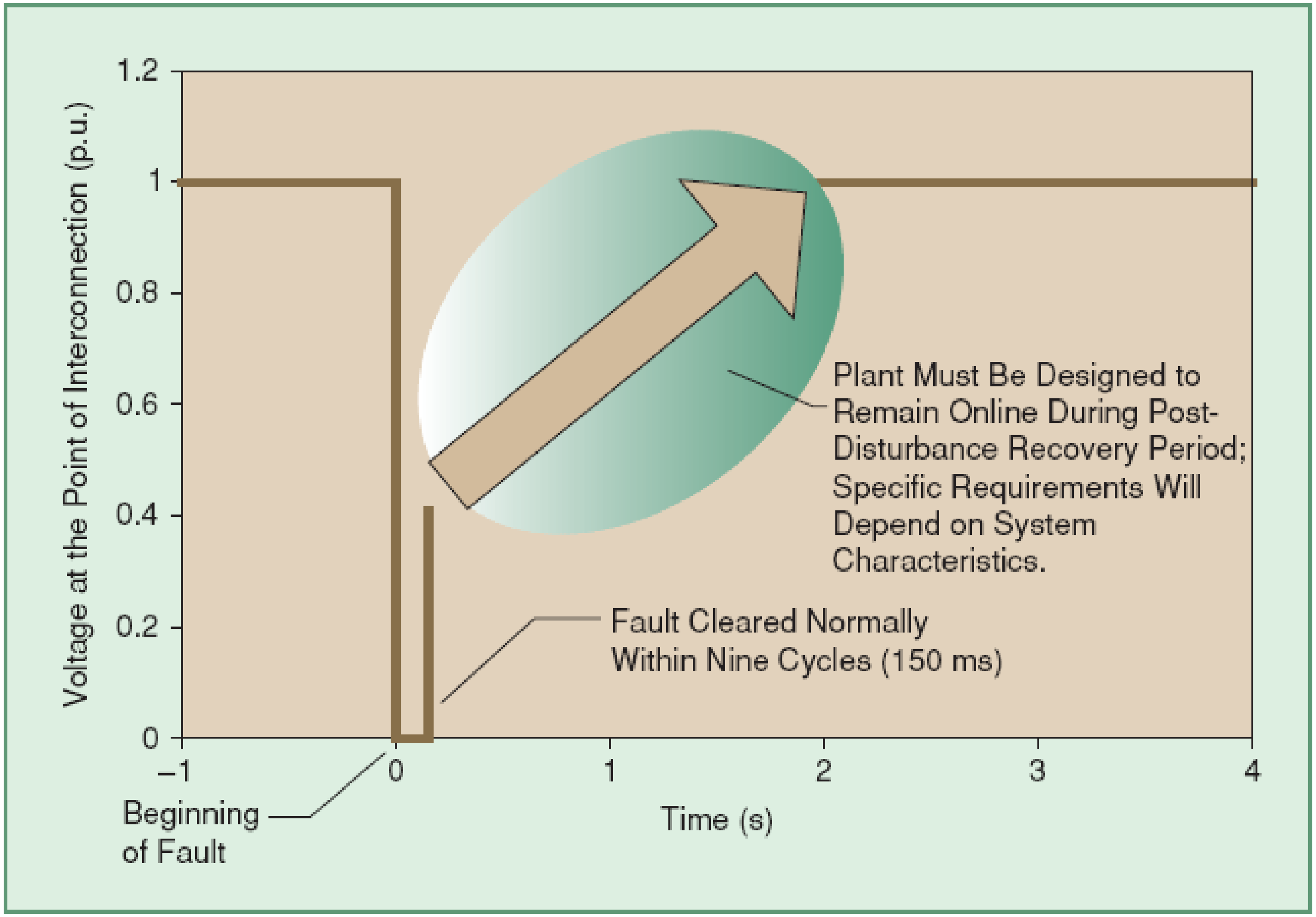
- Small Output (less than 1 MW)
- Fixed Speed Induction Generator
- Required Capacitive Compensation To Operate
- No Low Voltage Ride Through (LVRT); Tripped Off For Low System Voltage
- No Reactive Power Support
- No SCADA Control/Data to System Operator
- Low Penetration Level In Grid

August 2003 Blackout

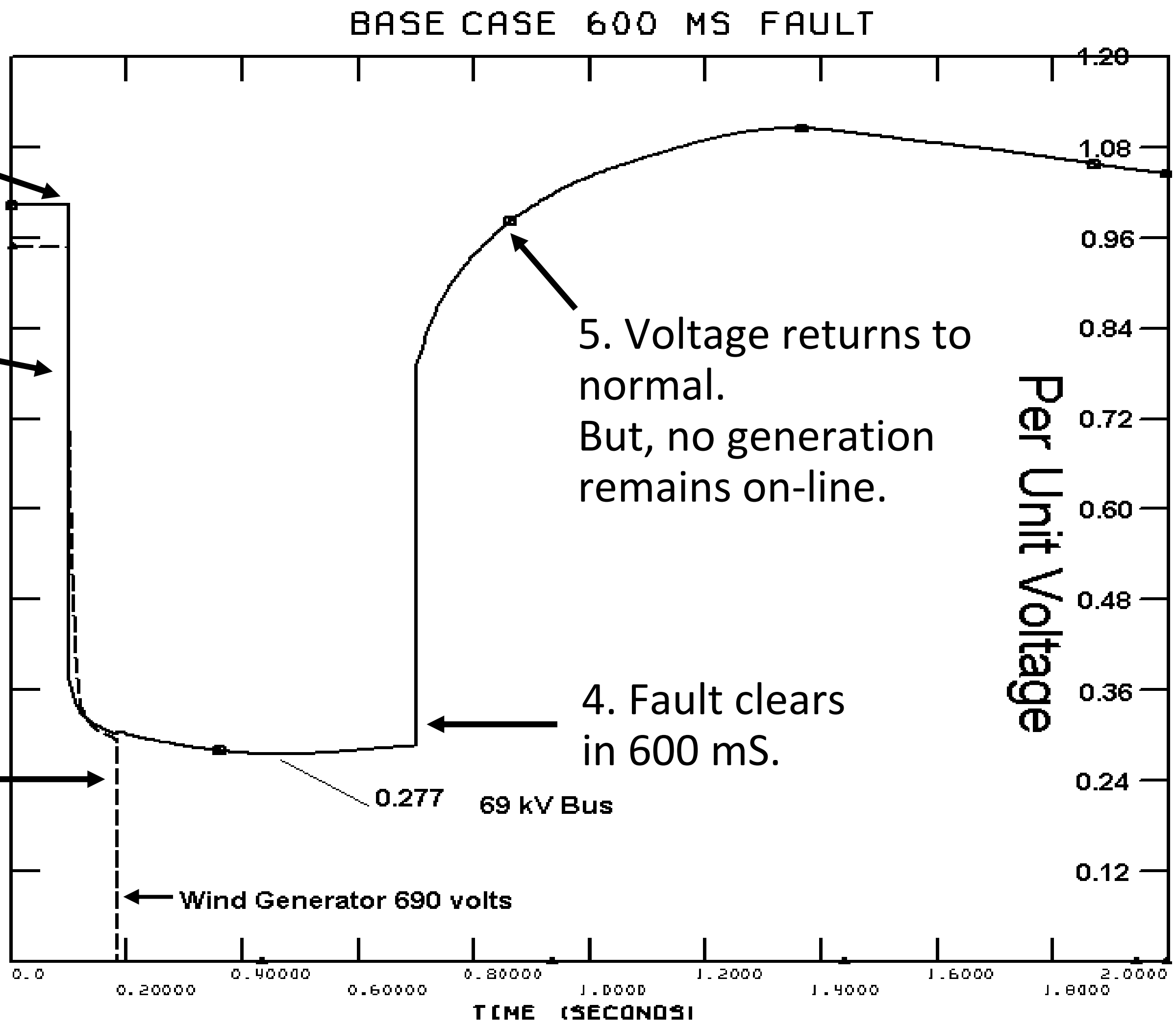
- Higher System Penetration (5-10%)
- No LVRT/Reactive Support Aggravated Situation
- FERC Order No. 661-A, Interconnection for Wind Energy (NERC Member Grid Codes Also)
- Three Common Components To Grid Codes:

1. LVRT Requirements
2. Reactive Power; Provide +/- 0.95 PF and Dynamic Reactive Support If Required
3. Provide Data to Transmission Operator (SCADA)

Low Voltage Ride Through FERC 661A



First Generation WTG – No LVRT



1. Fault on utility transmission grid

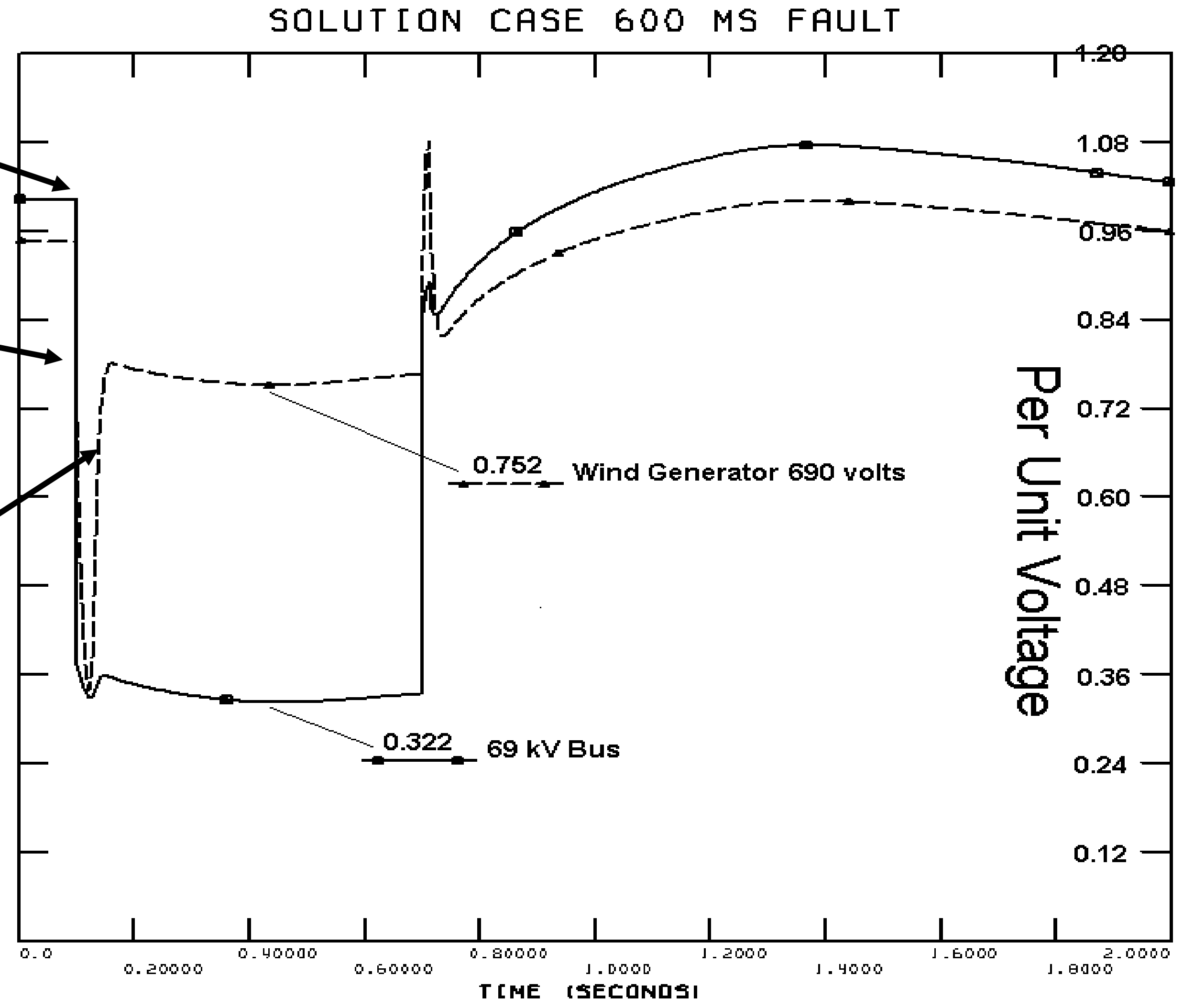
2. Transmission system voltage drops rapidly.

3. Wind generation trips off-line because voltage is below 0.75 pu at generator terminals for 5 cycles.

4. Fault clears in 600 mS.

5. Voltage returns to normal.
But, no generation remains on-line.

WTG with SVC (or enhanced DFIG)



1. Fault on utility transmission grid

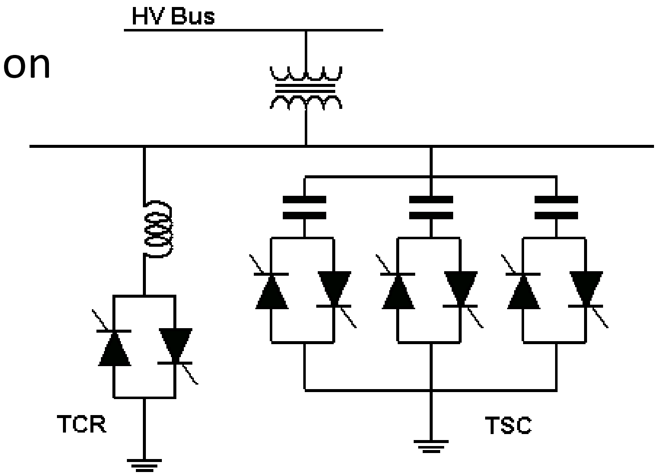
2. Transmission system voltage drops rapidly.

3. SVC detects low voltage and injects reactive energy to quickly rebuild voltage at the wind generator above 0.75 pu threshold

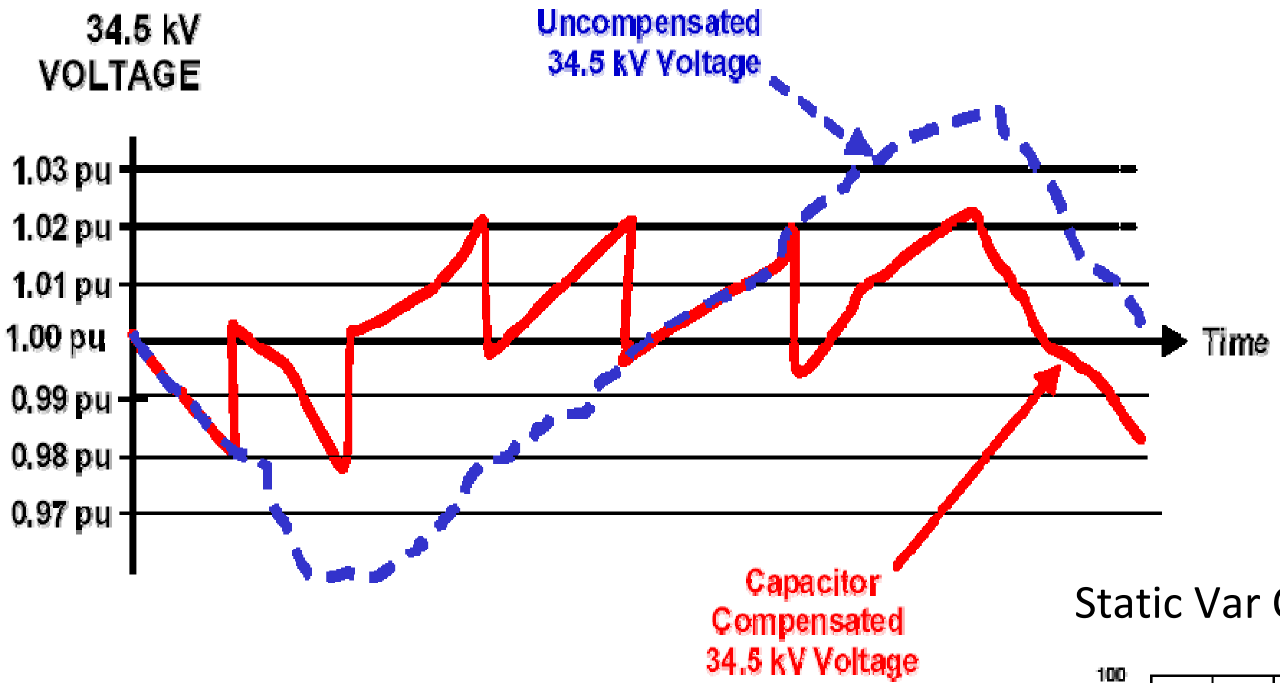
Reactive Power Compensation

- Shunt capacitors, switched in blocks, relatively inexpensive, not good for transient events
- Switching block of capacitance can swing the voltage up or down and this variation is felt as an abrupt change in torque on the turbine gearboxes
- Static var Compensators Provide Continuously Adjustable Dynamic +/- PF Control, Very Expensive

SVC Configuration

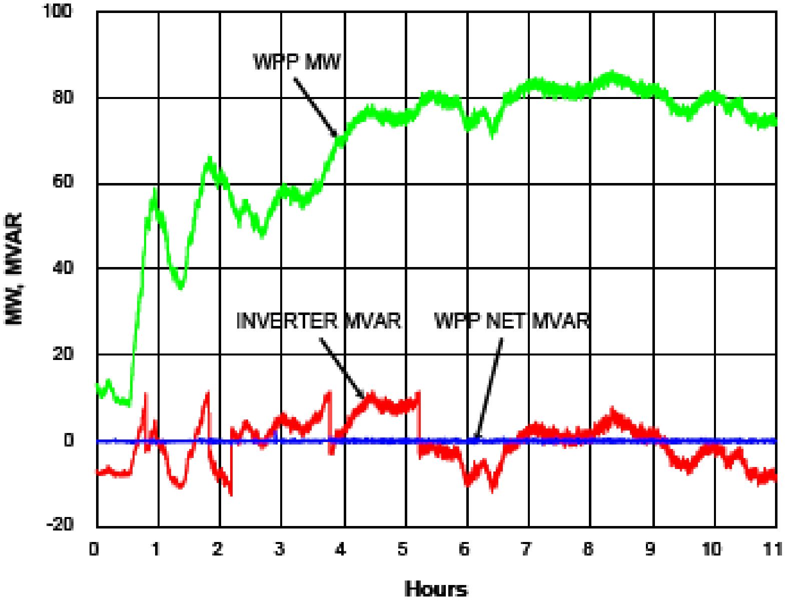


Compensation-Cap Bank vs SVC

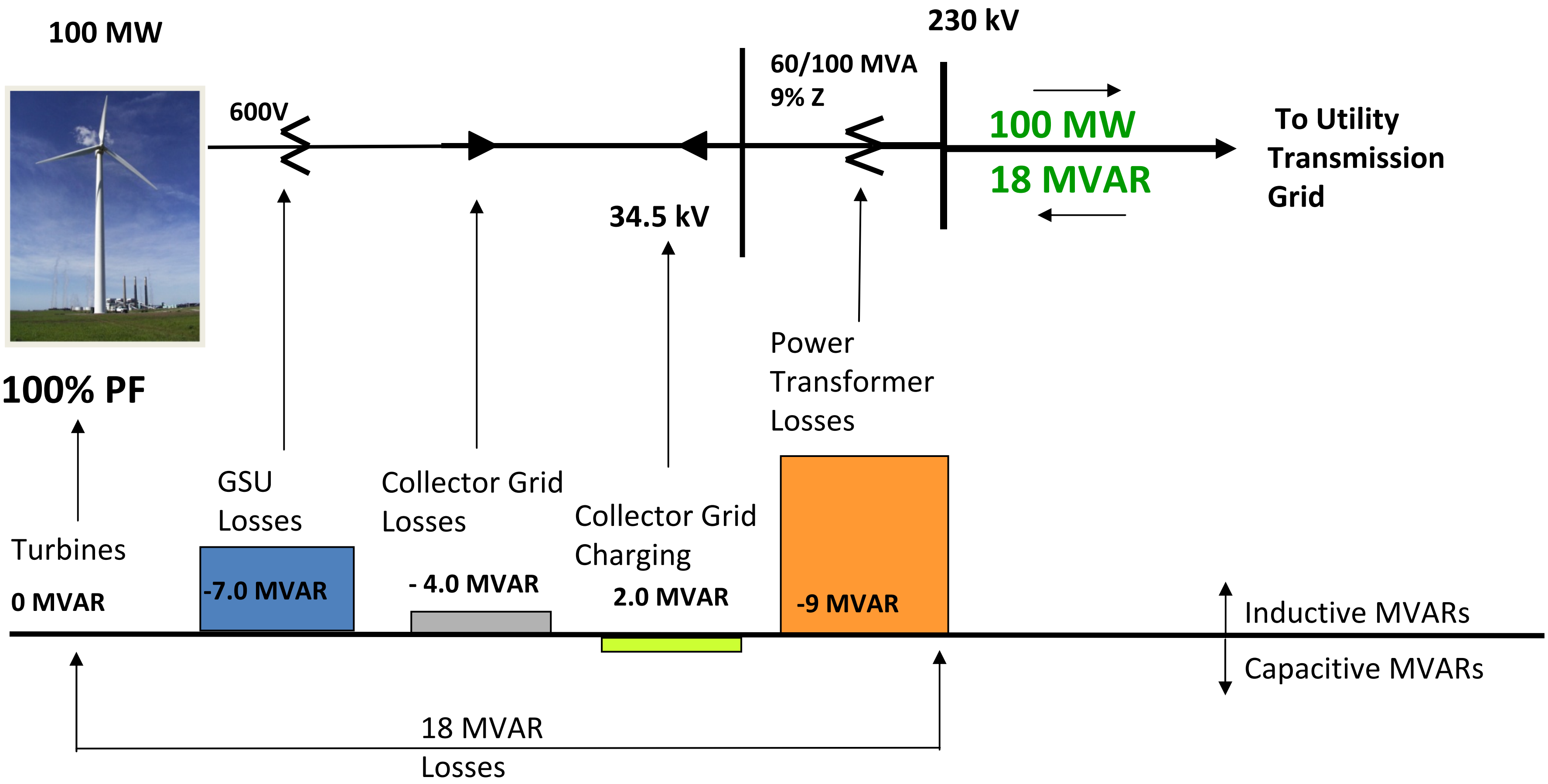


Switched Capacitor Banks

Static Var Compensator with Cap Banks



Typical Uncompensated Wind Farm Losses



100 MW

600V

34.5 kV

60/100 MVA
9% Z

230 kV

100 MW
18 MVAR

To Utility Transmission Grid

100% PF

Turbines

0 MVAR

GSU Losses

-7.0 MVAR

Collector Grid Losses

- 4.0 MVAR

Collector Grid Charging

2.0 MVAR

Power Transformer Losses

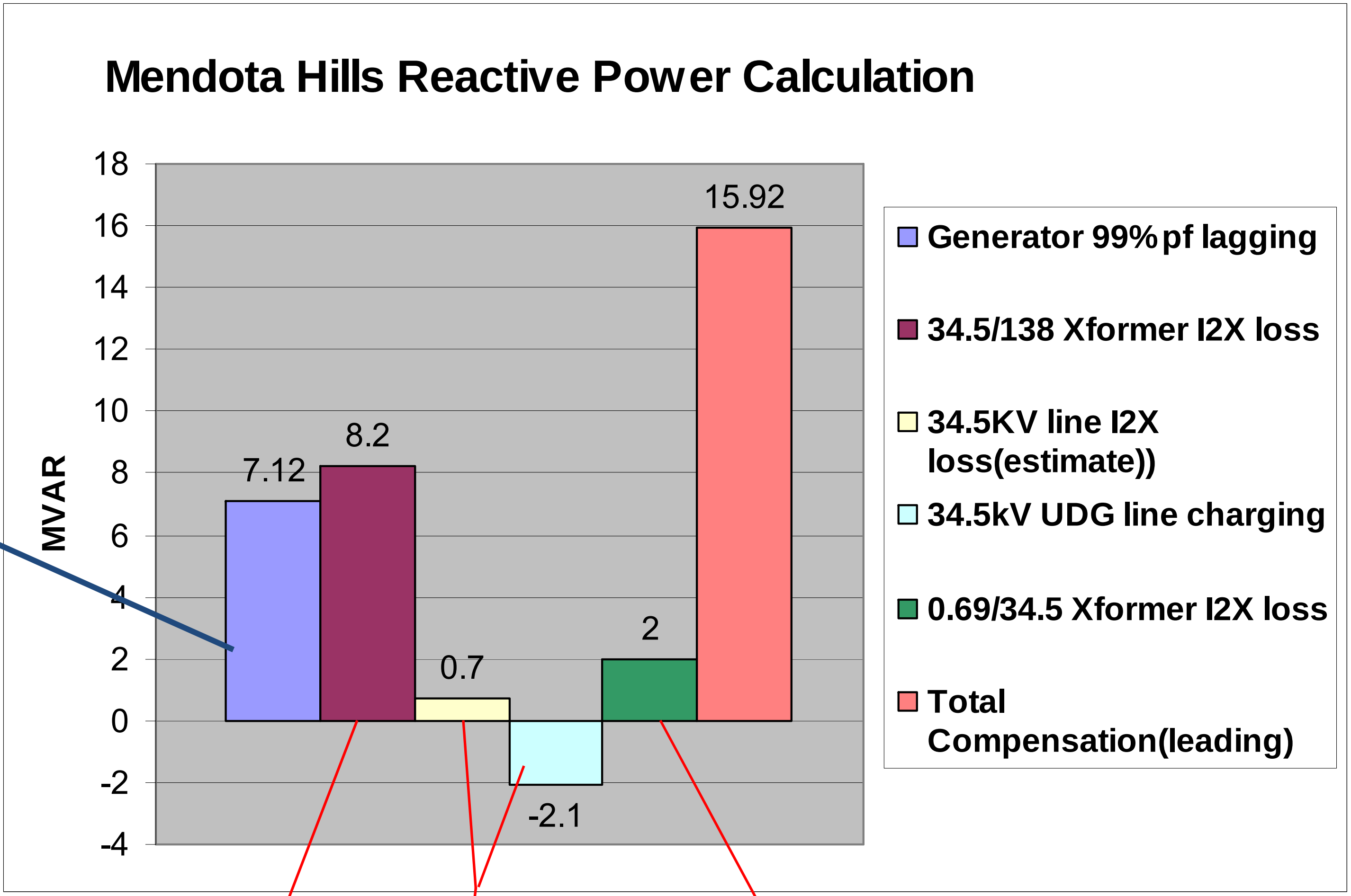
-9 MVAR

Inductive MVARs

Capacitive MVARs

18 MVAR Losses

Reactive Power Budget



50 MW Wind Turbine Generation 0.99 PF

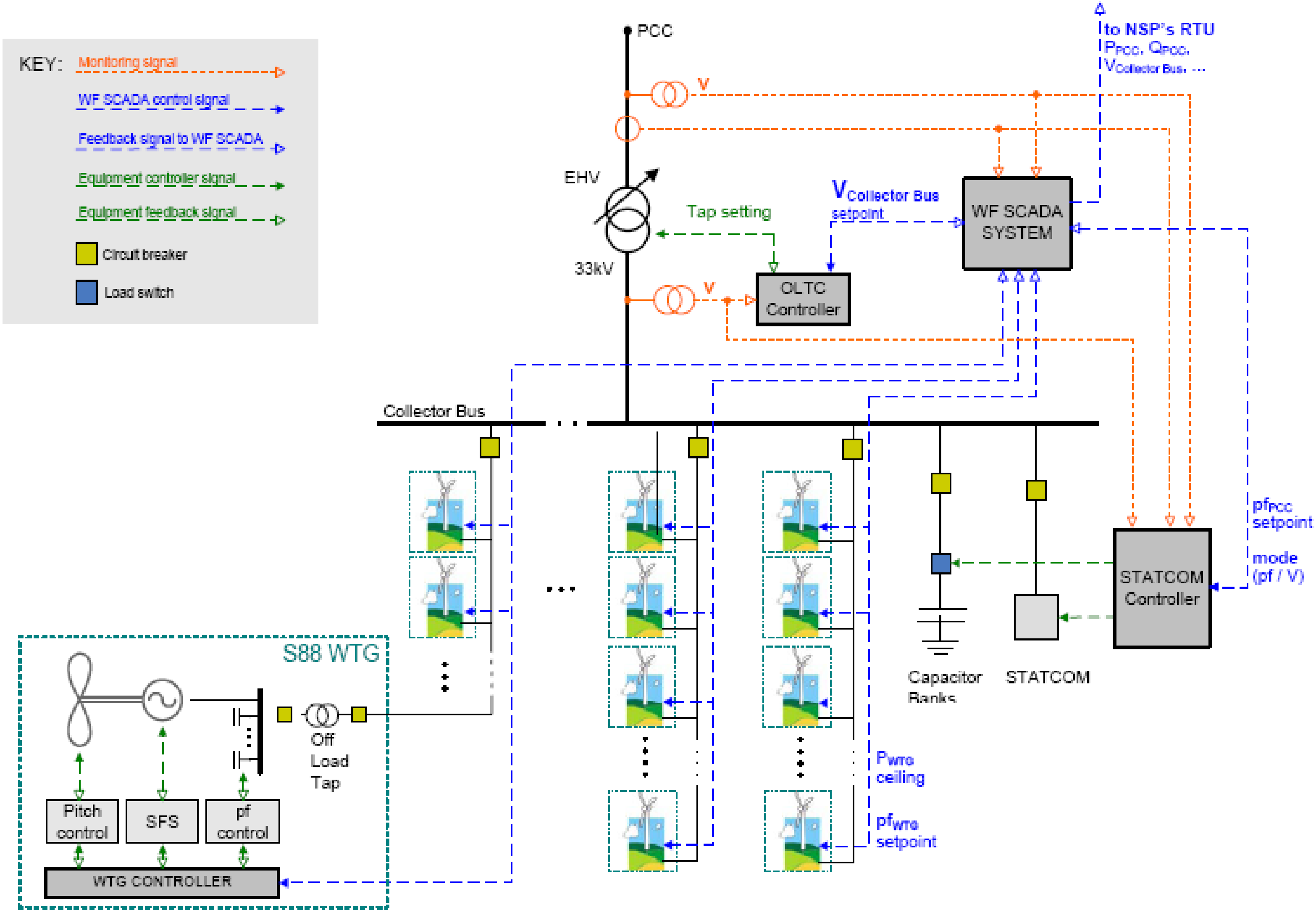
Transformer 138 kV – 34.5 kV MVAR Losses

63 GSU Transformers 34.5 kV – 0.69 kV MVAR Losses

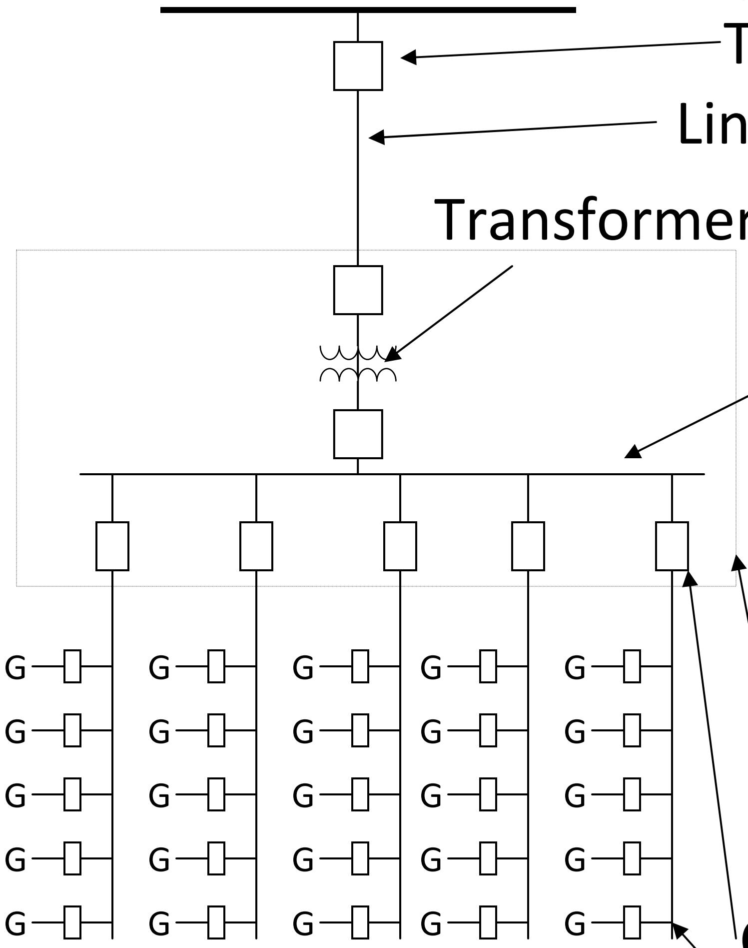
20 miles of 34.5 kV XLPE 133% Insulated cable

Wind Farm SCADA

Provides Integrated Control & Data for Each WTG & Wind Farm System Voltage & PF



Larger Wind Farm System (Units > 1MW)



Utility (115 kV)

Tie Breaker

Line

Transformer

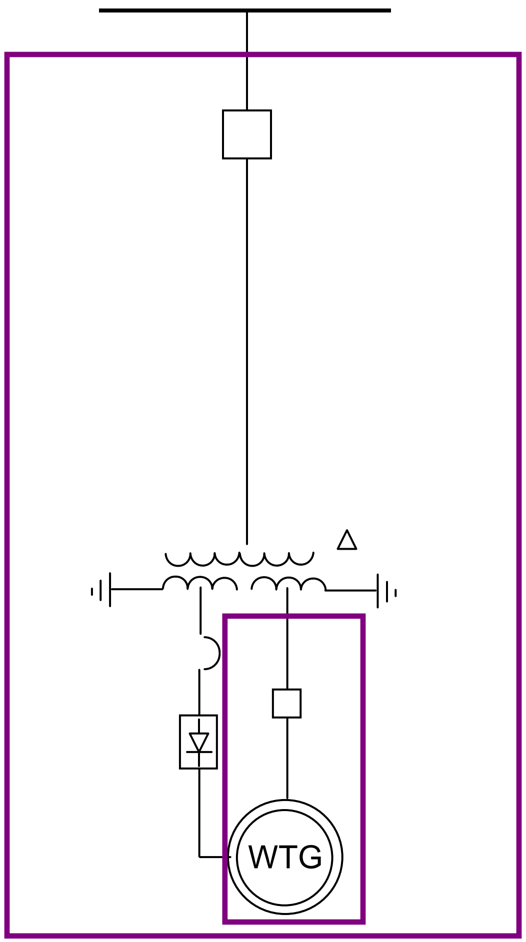
Switchgear or Open Substation

Windfarm Substation (34.5 kV)

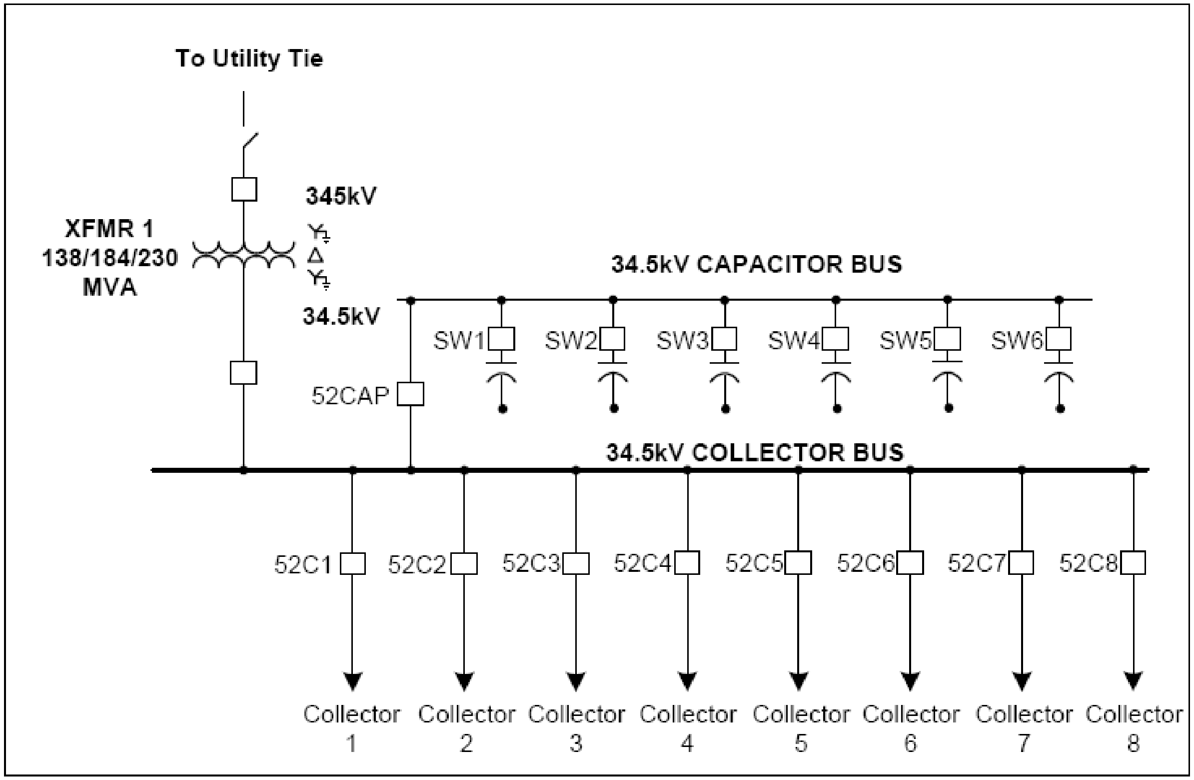
Collector Feeder Breakers

Collector Bus

Wind Farm Transformer Winding Configuration



WTG GSU Delta Primary, Grounded Wye Secondary & Tertiary



Utility Tie Transformer Primary Grounded Wye, Secondary Grounded Wye, Tertiary Delta; sometimes Primary Grounded Wye, Secondary Delta

WTG GSU

KVA 1850

HV 34500

LV 690Y/398

IMPEDANCE @ 85°C %

RATED VOLTS

ORDER NUM RCR955	

BIL HV	BIL LV	MAT HV	MAT LV
150*	30	Al	Al

* 200 KV BIL INSULATING LEVEL WINDINGS ONLY

GALLONS OF OIL TYPE I	512

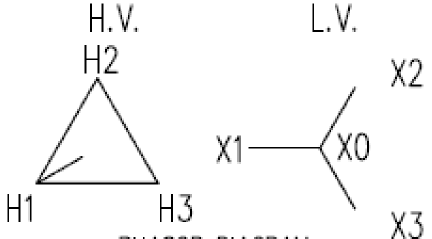
MASS	kg	pounds
CORE & COIL UNTANKING (HEAVIEST PIECE)	2885	6358
TANK	1752	3861
LIQUID OIL TYPE I	1743	3841
TOTAL WT	6380	14060

TAP CHANGER

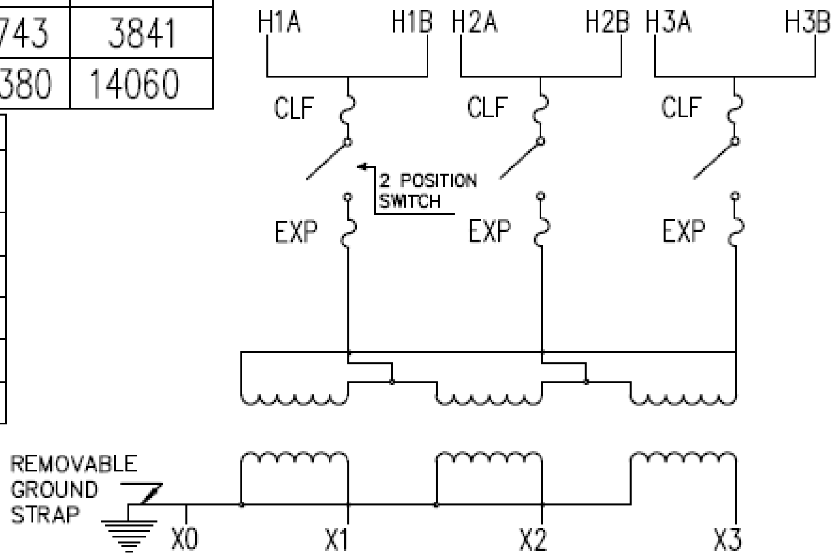
TAP POS	VOLTAGE	65°C AMPS
1/A	36225	29.5
2/B	35362	30.2
3/C	34500	31.0
4/D	33637	31.8
5/E	32775	32.6

LISTED

LIQUID FILLED DISTRIBUTION TRANSFORMER [illegible]

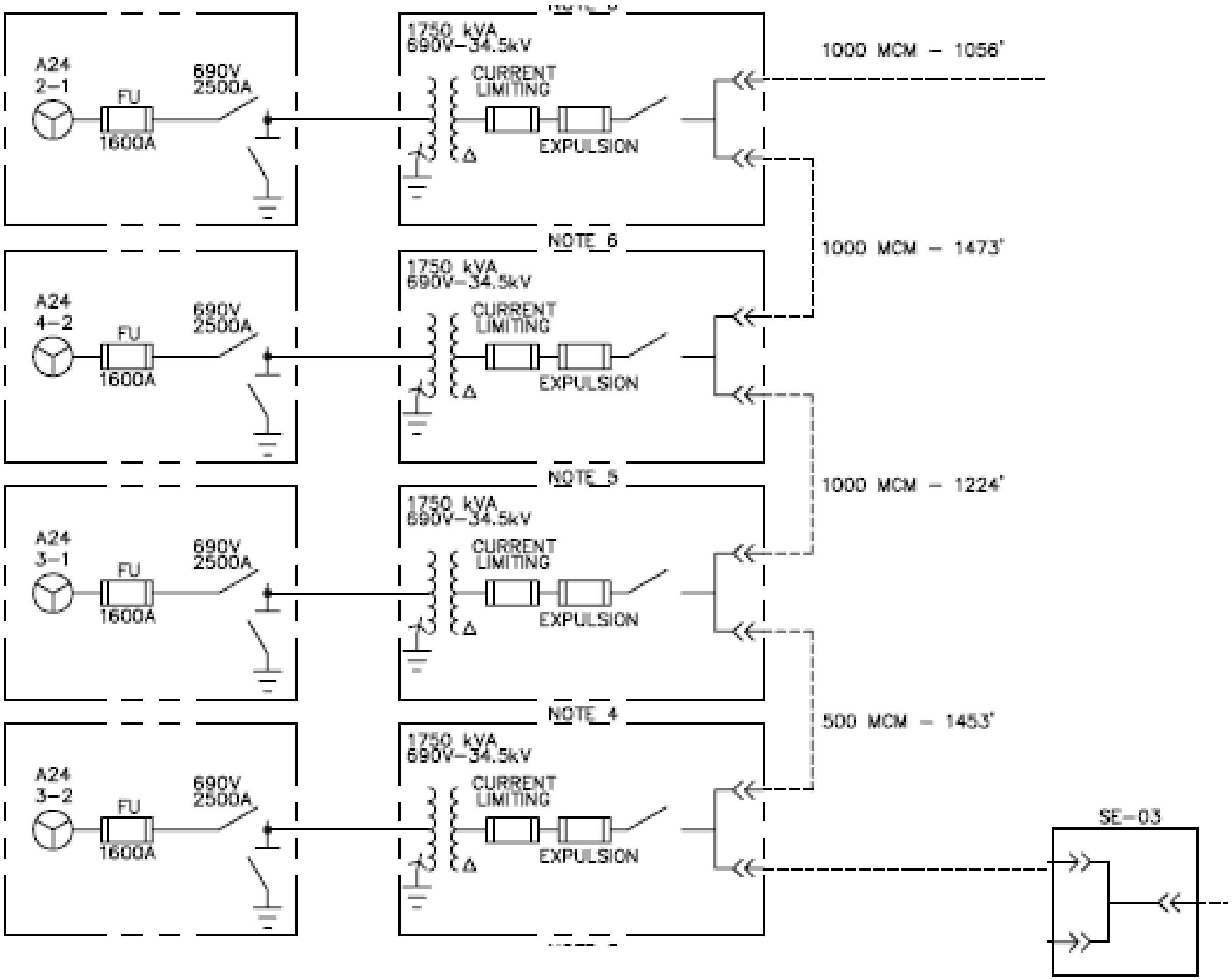


PHASOR DIAGRAM

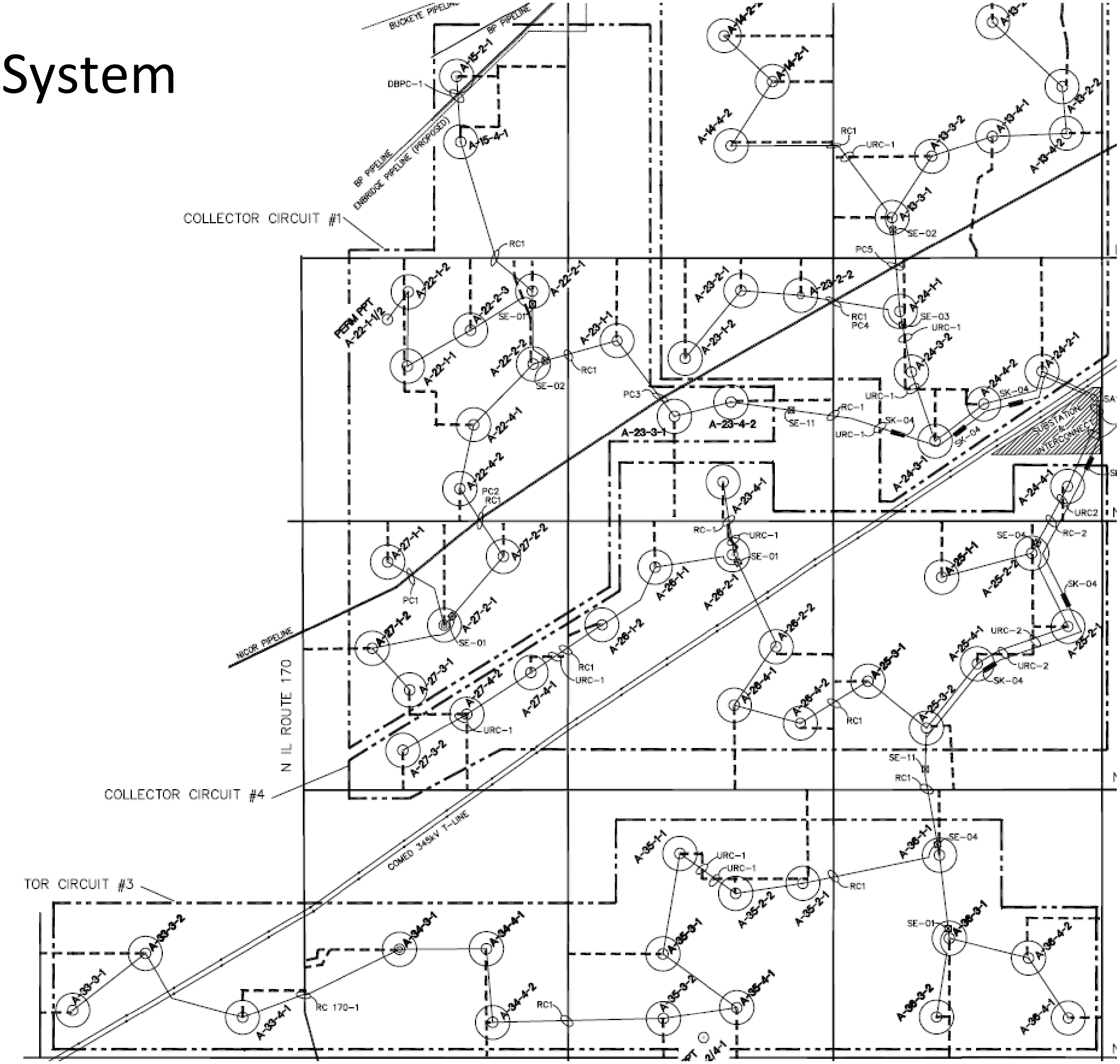


CONNECTION DIAGRAM

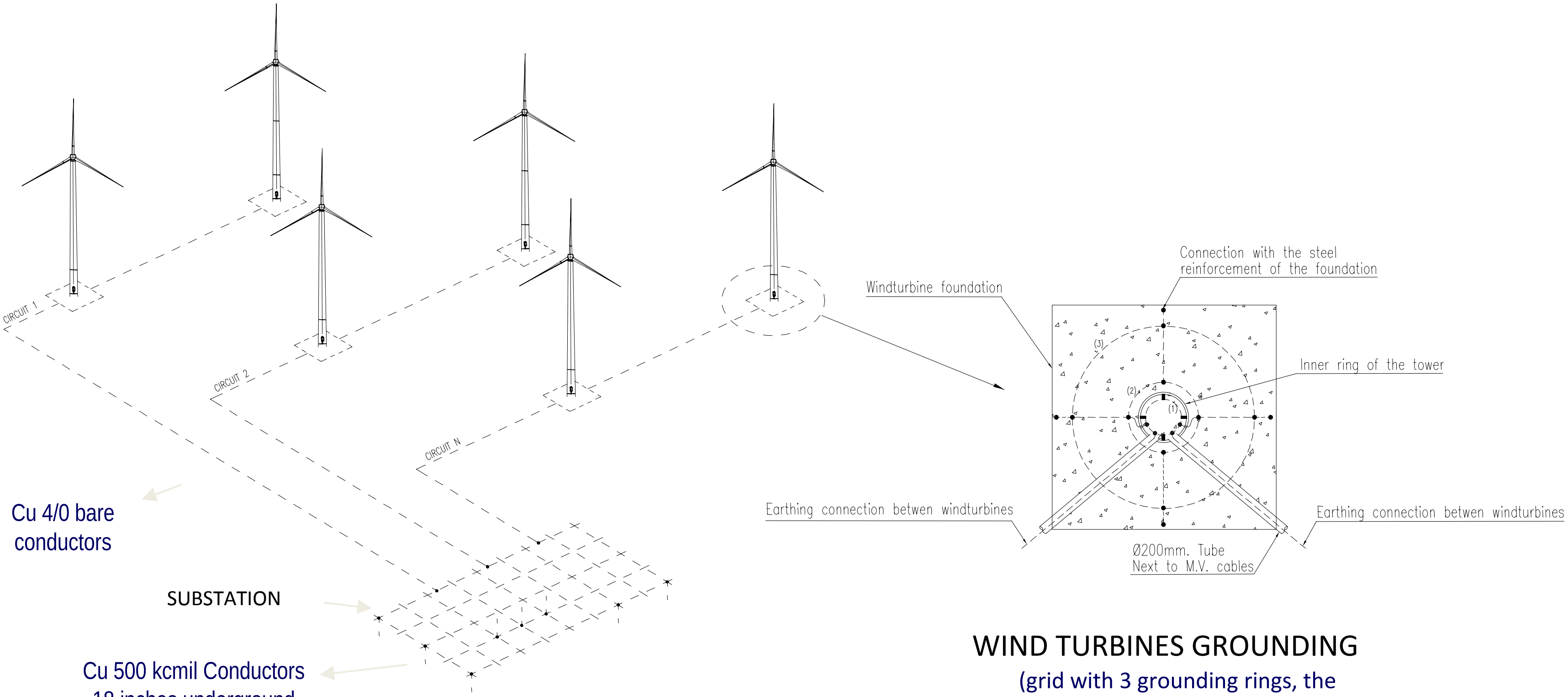
Collector System One Line (Partial)



Collector System
Site Plan



Wind Farm Grounding



WIND TURBINES GROUNDING
(grid with 3 grounding rings, the external two are underground)

The grounding grids of all the W.T. are connected with the substation grid through bare copper conductors, making the whole W.F. to be a equipotential space, such a big amount of grounding conductors embedded in the ground produces a very low W.F. grounding resistance < 0,5 Ω (typical).

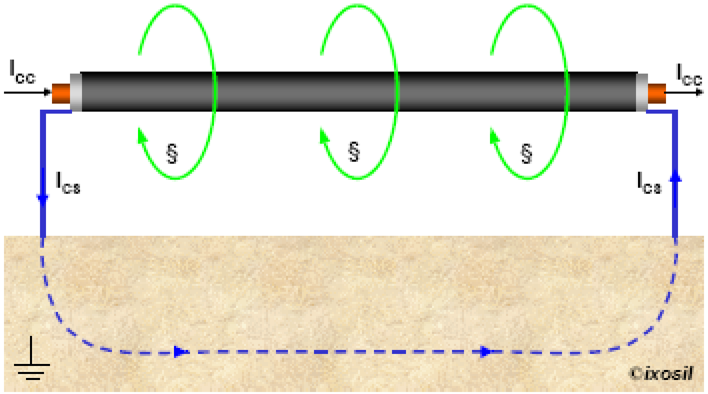
Collector System Cabling

Collector system cable design considerations include the conductor size (based on system ampacity requirements) and the insulation type and level. The two common insulation types are tree-retardant, cross-linked polyethylene (TRXLPE) and ethylene propylene rubber (EPR). The insulation level (100%,133% or 173%) depends on the system grounding as well as the magnitude and duration of temporary phase-to-ground overvoltages under fault conditions.

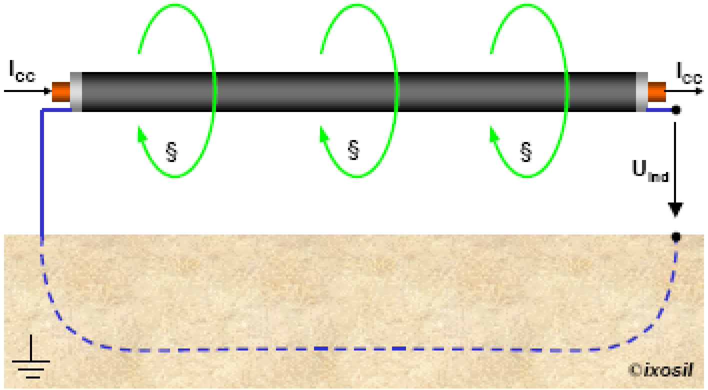
Cable ampacities, and therefore the conductor size, are directly related to five major factors:

- number of circuits,
- cable installation geometry and method,
- thermal resistivity and temperature,
- cable shield voltages and bonding method and
- load factor.

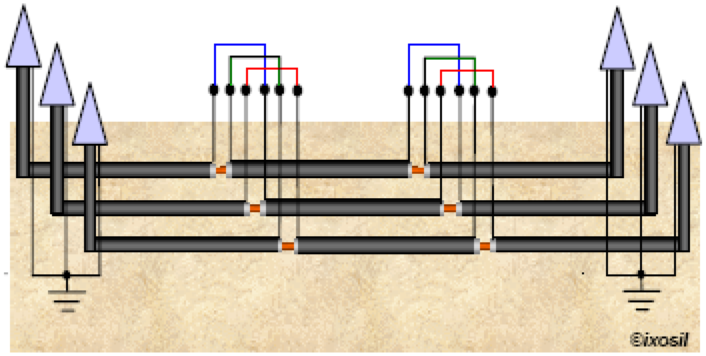
Cable Sheath Grounding



Multi-bonded Shield

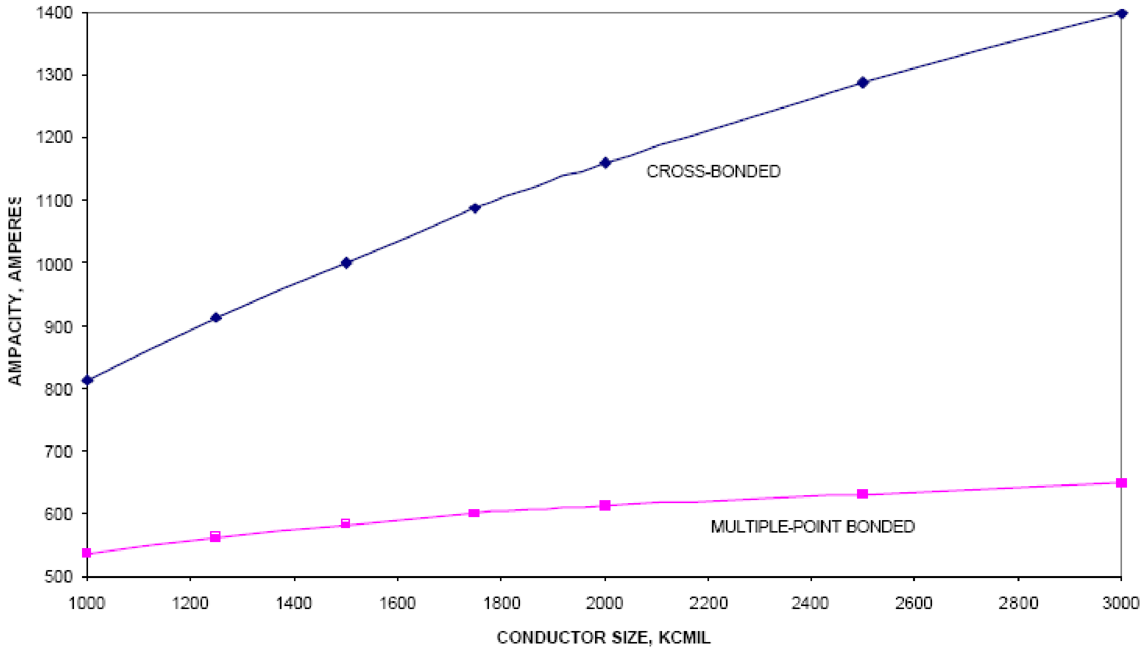


Single-bonded Shield



Cross-bonded Shield
Shields transposed at each junction

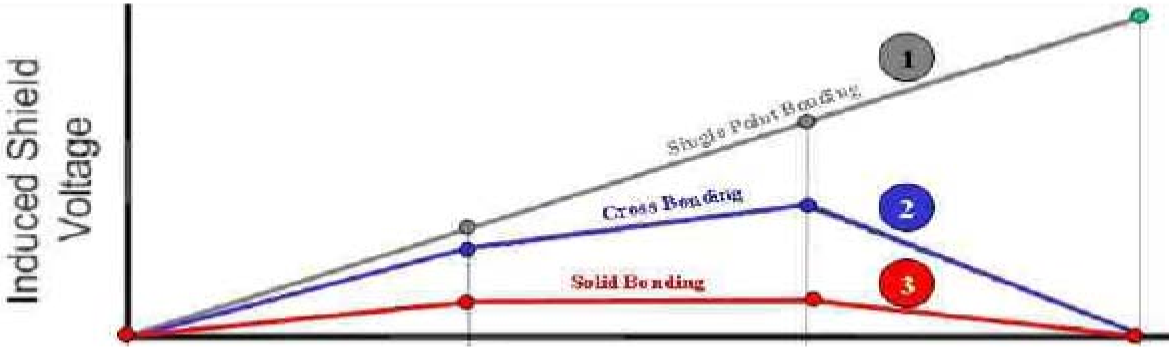
Cable Sheath Grounding Application



Multiple grounded sheath systems have lower ampacities due to heating from sheath currents

Single grounded sheath systems may have excessive sheath voltage

Cross bonded systems require cross bonding at about 7000’ foot intervals



Wind Farm Challenges

If a feeder circuit breaker opens during operation, then that feeder and the operating WTGs will become isolated and form an ungrounded power system. This condition is especially troublesome if a phase-to-ground fault develops on the feeder; a scenario that causes the unfaulted phase voltages to rise to line voltage levels. This fault can also result in severe transient overvoltages, which can eventually result in failure of insulation and equipment damage.

Under Normal Conditions

$V_A=V_N\angle 90°$

$V_B=V_N\angle -30°$

$V_C=V_N\angle -150°$

Grounded System under A-G Fault Conditions

$V_A=0$

$V_B=V_N\angle -30°$

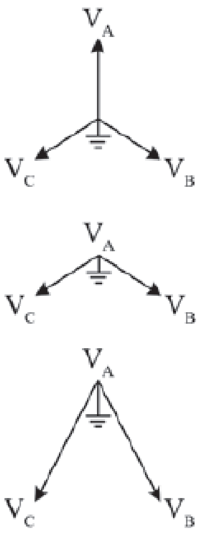
$V_C=V_N\angle -150°$

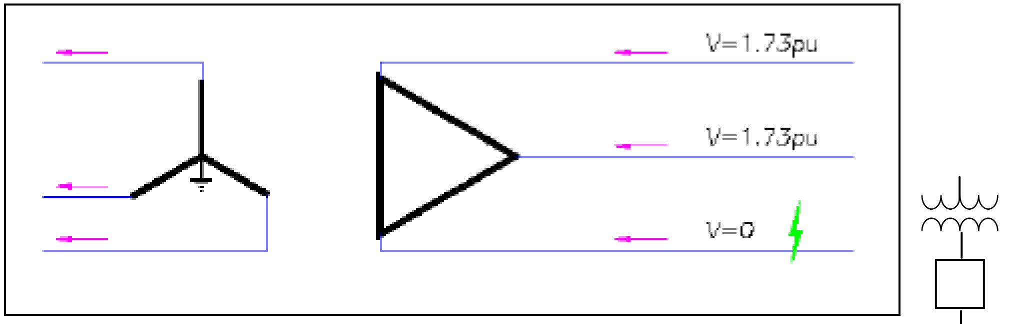
Isolated System under A-G Fault Conditions

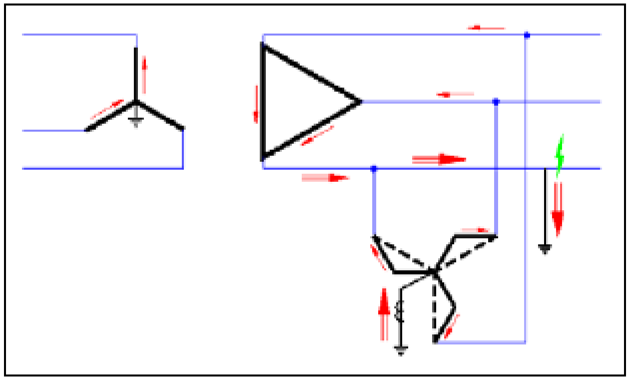
$V_A=0$

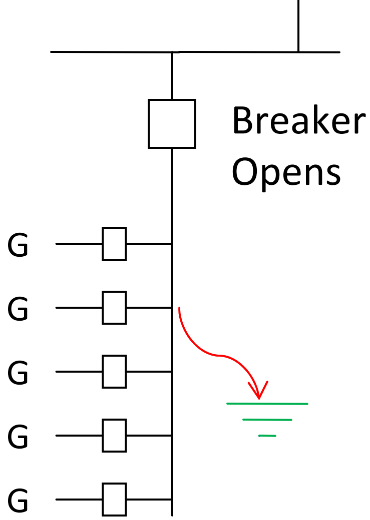
$V_B=\sqrt{3}\cdot V_N\angle -60°$

$V_C=\sqrt{3}\cdot V_N\angle -120°$



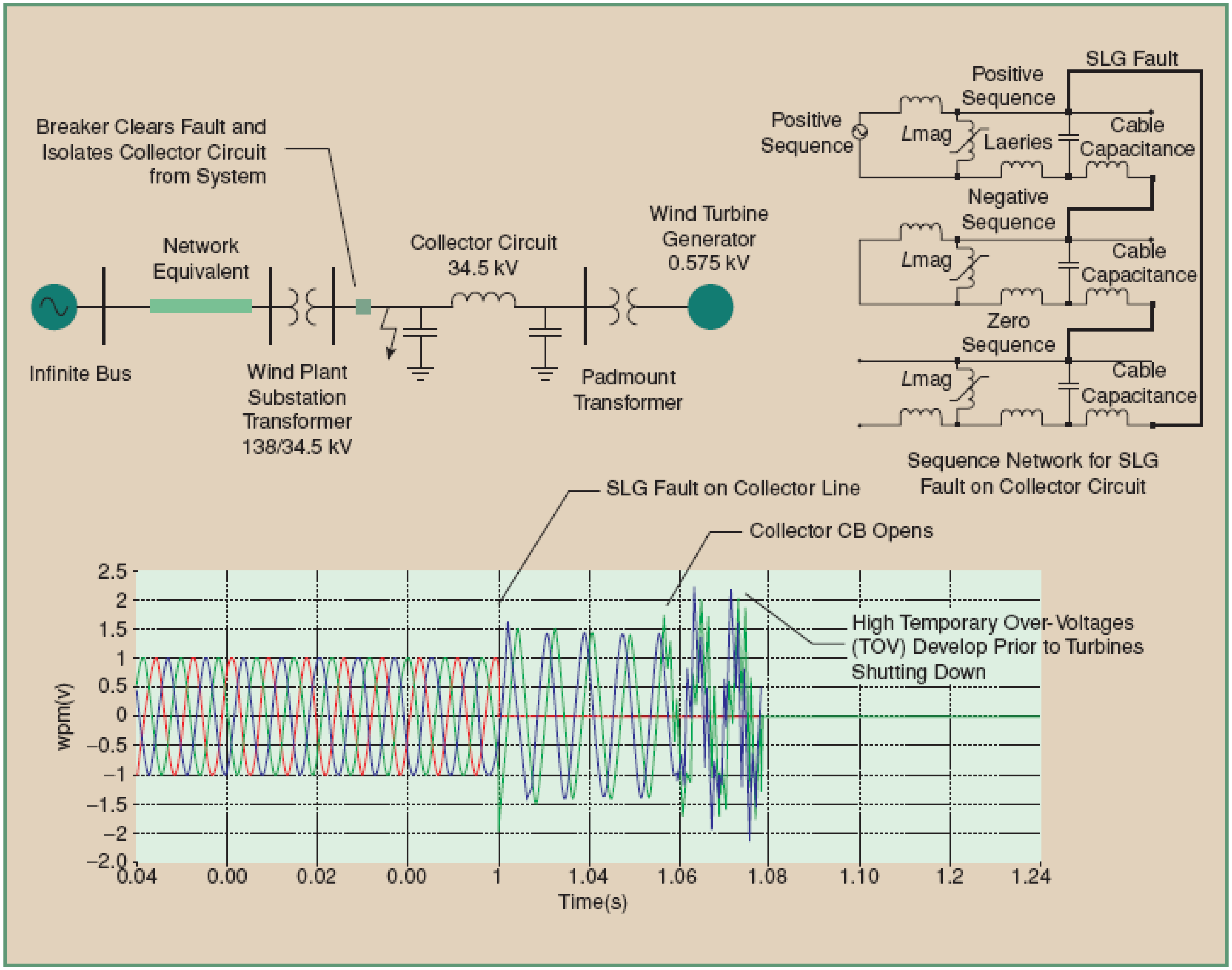






One remedy is to design for the ungrounded system. This results in increased costs due to the higher voltage ratings, higher BIL, and added engineering. Another solution is to install individual grounding transformers on each feeder. This adds to equipment and engineering costs and increases the substation footprint. Another solution is to use transfer trip to open feeder CB after WTG CB’s open

Temporary Overvoltage for SLG Fault

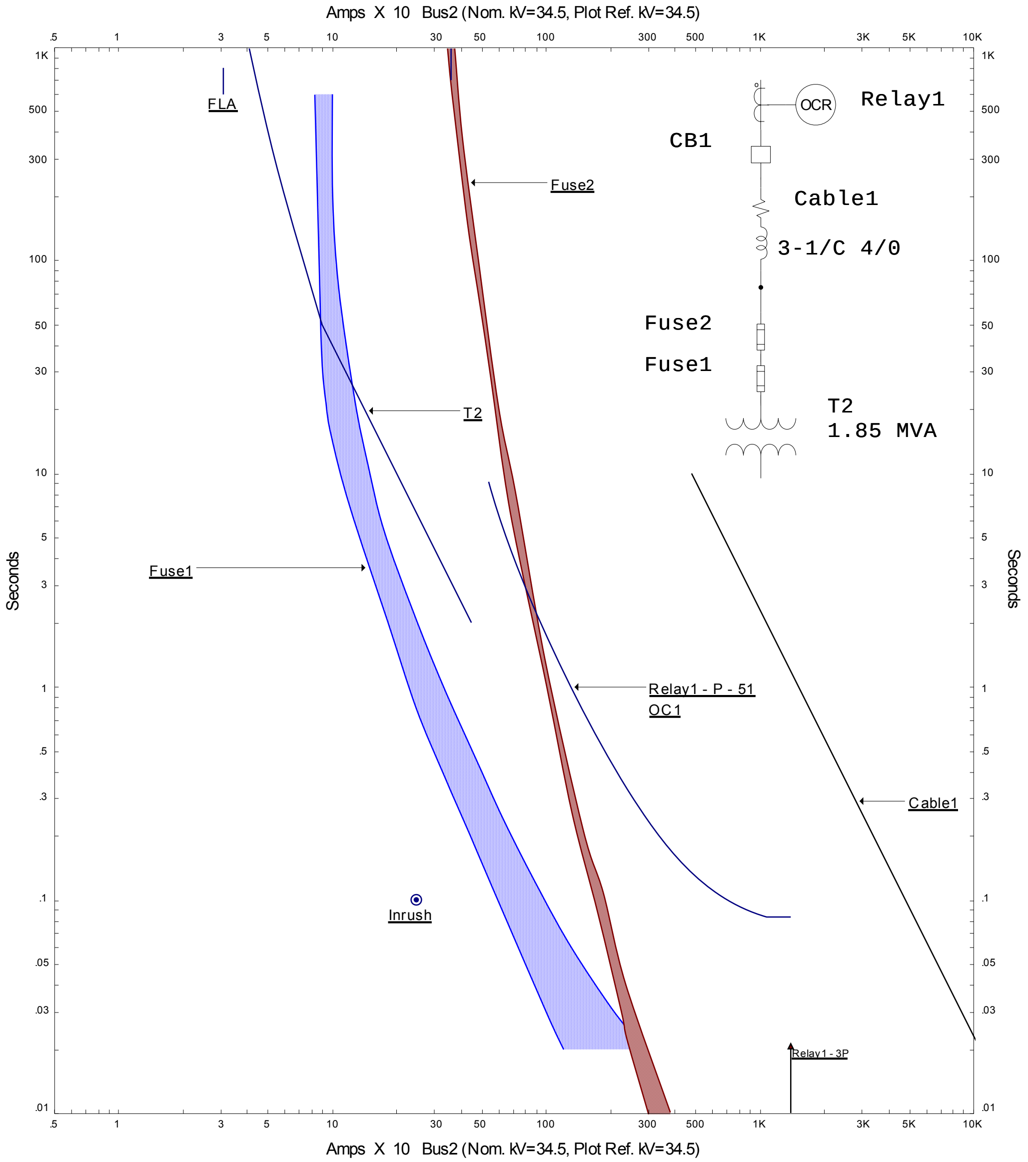


Collector System Relaying

Several collector system design aspects influence overcurrent protection, including:

- long circuit lengths may not allow for easy detection of ground faults,
- system grounding (grounded versus ungrounded or systems grounded through grounding transformers on each feeder),
- selective coordination of collector system circuits can be quite challenging, as it is often difficult to distinguish faults on feeders when grounding transformers are used,
- selective coordination with fuses in downstream pad-mounted transformers at WTGs,
- unfaulted phases can be elevated to phase-to-phase voltage levels with respect to ground during ground faults,
- loss of phase during faults with single-phase tripping and reclosing on the transmission system or downed conductors
- WTG may feed faults for several cycles (even though the feeder breaker tripped open) if sympathetic tripping of WTGs is not implemented

Collector Feeder Coordination

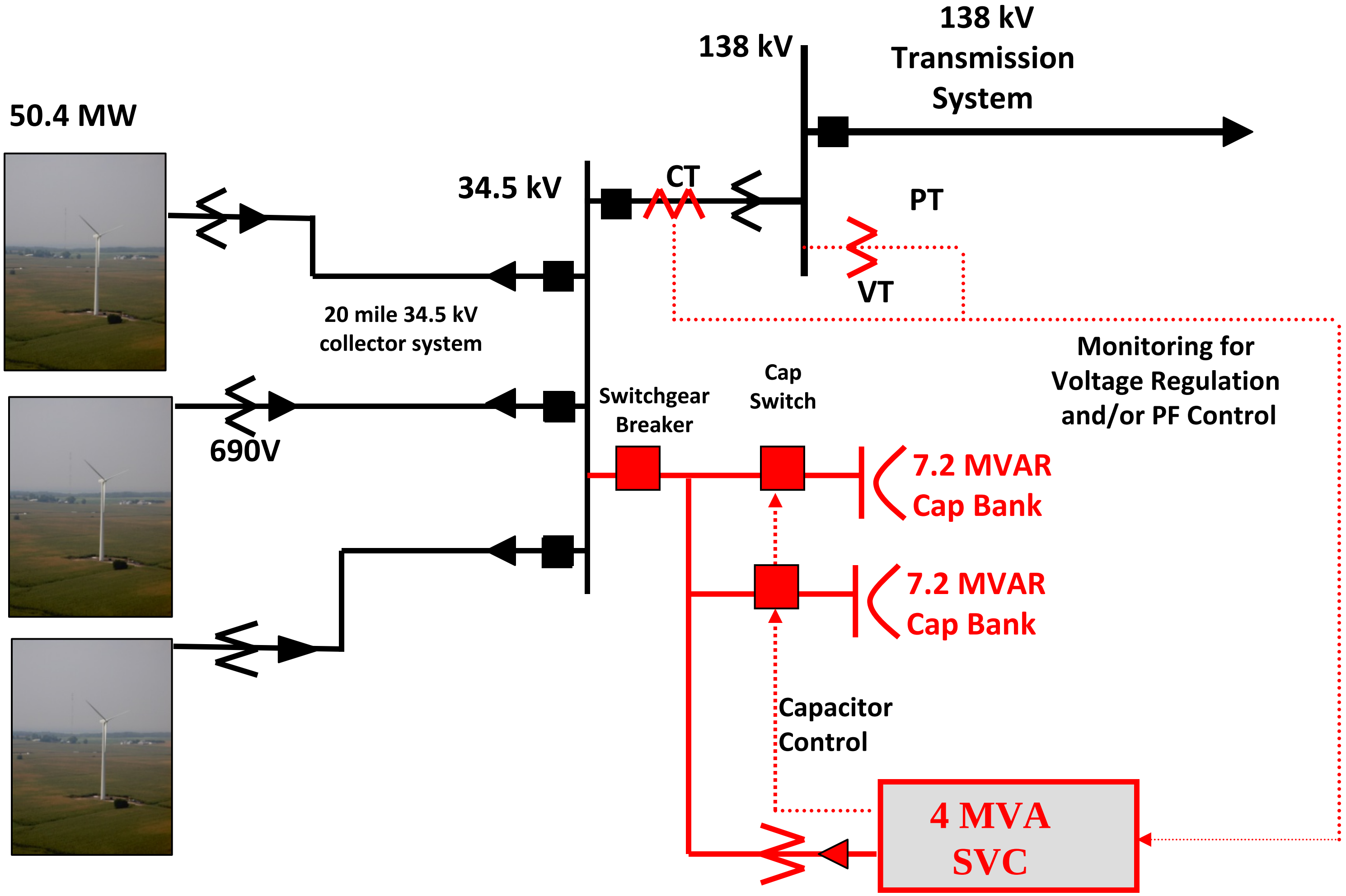


WIND FARM GSU

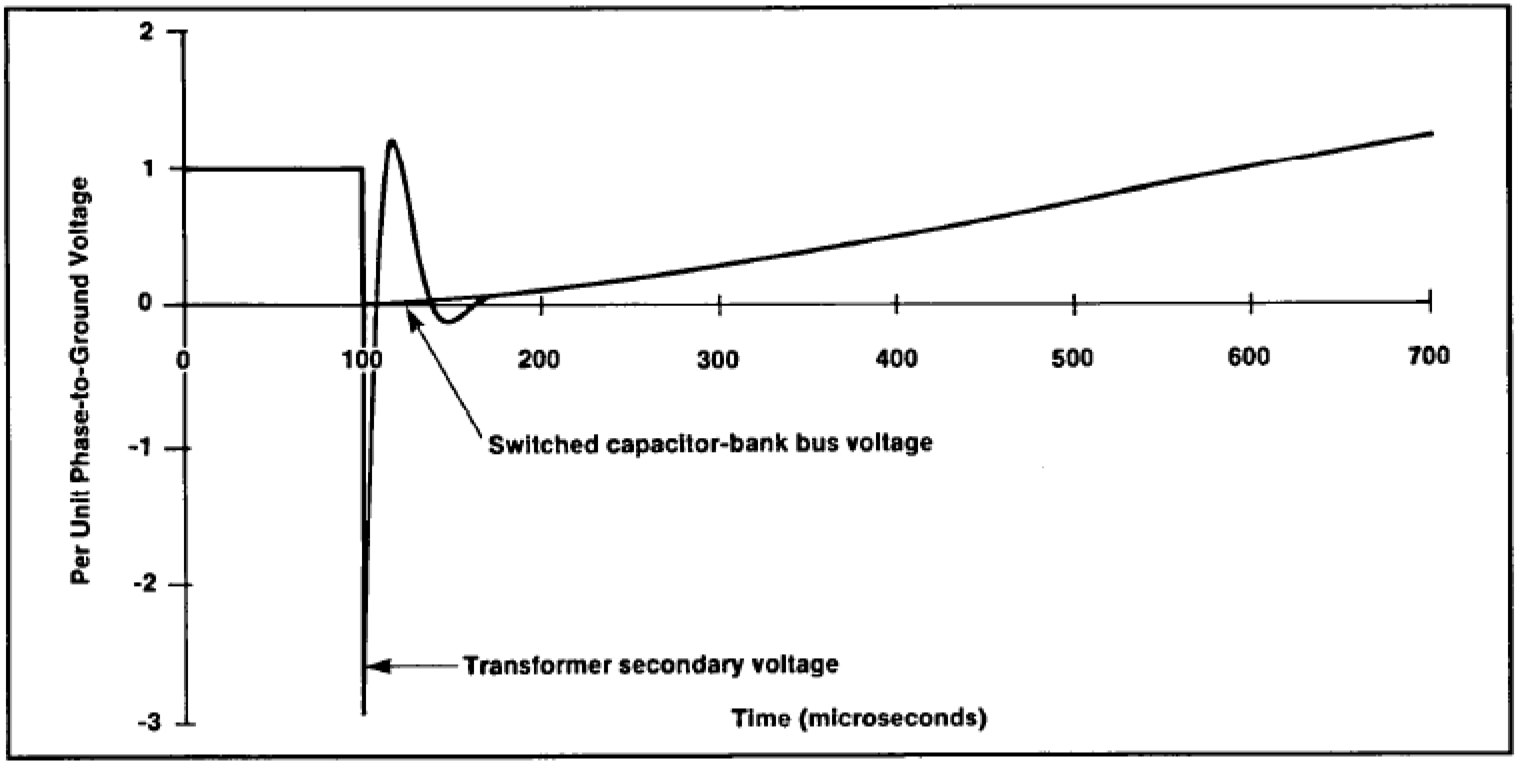
Project:
Location:
Contract:
Engineer:
Filename: C:\ETAP\WINDFARM\WINDFARM.OTI

Date: 11-16-2009
SN: POWERENGI2
Rev: Base
Fault: Phase

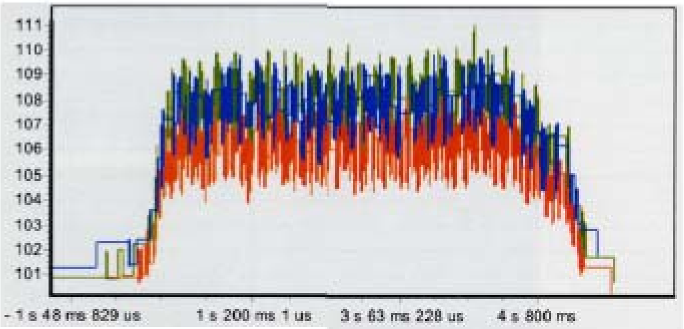
Capacitor Switching Issues



Capacitor Switching Overvoltages & Resonances

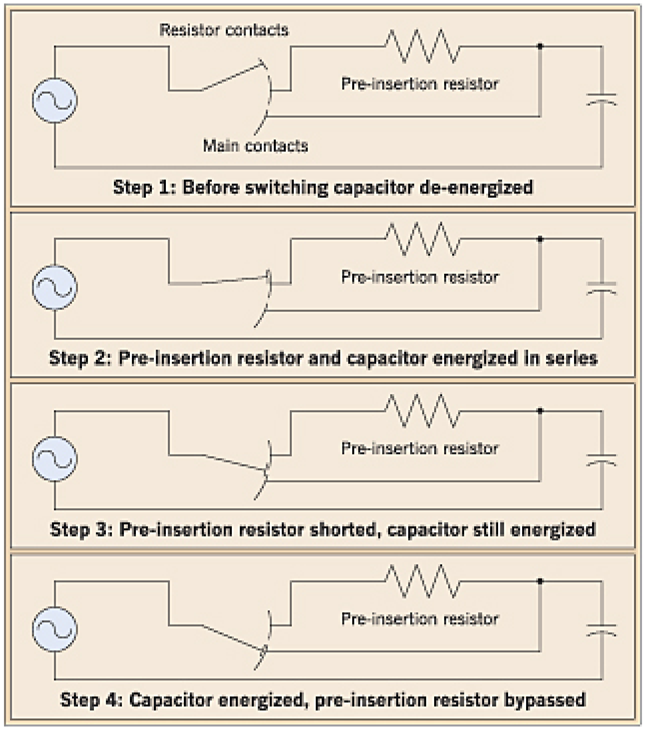


Capacitor Switching Transients

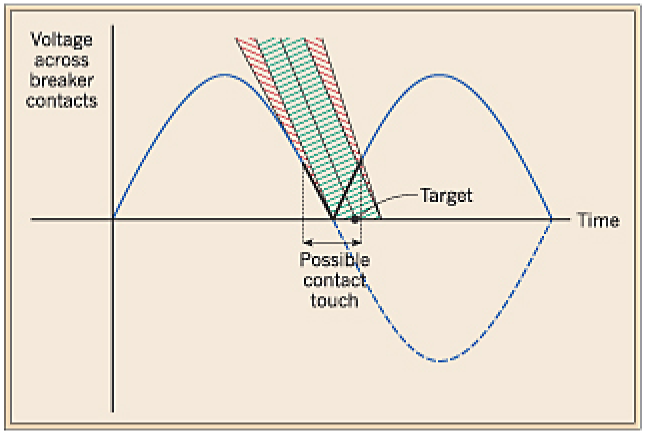


TOV resonance in transformer windings

Capacitor Switching Remediation



Pre-insertion resistors. One technique involves inserting a temporary impedance into the circuit during one of the steps. This approach breaks one large transient into two or more smaller ones. Circuit breakers can be built with internal pre-insertion resistors to reduce the magnitude of switching transients.



Point-on-wave switching. By precisely controlling where on the voltage waveform the contacts touch, it's possible to greatly reduce the magnitudes of the switching transients.

WTG Transformer Failures

Several different types of failure mechanisms have been encountered. The main ones are listed below.

1. Transient voltages on LV side of transformer: Measurements conducted at several sites have shown that overvoltages and abrupt loss of voltage occur quite regularly. These transients generate voltage surges in the medium-voltage winding leading to dielectric failures.
2. Thermal stress: The transformers are subjected to high power levels on a continuous basis. In addition there are often frequent periods of overload due to wind gusts. This overloading can cause premature failure of the transformer.
3. Vibrations: Some transformers are installed in the nacelle. Some transformer failures can be attributed to the vibrations they are subjected to when installed in the nacelle.

Voltage Transformer Failure at WF

VT Secondary Recordings

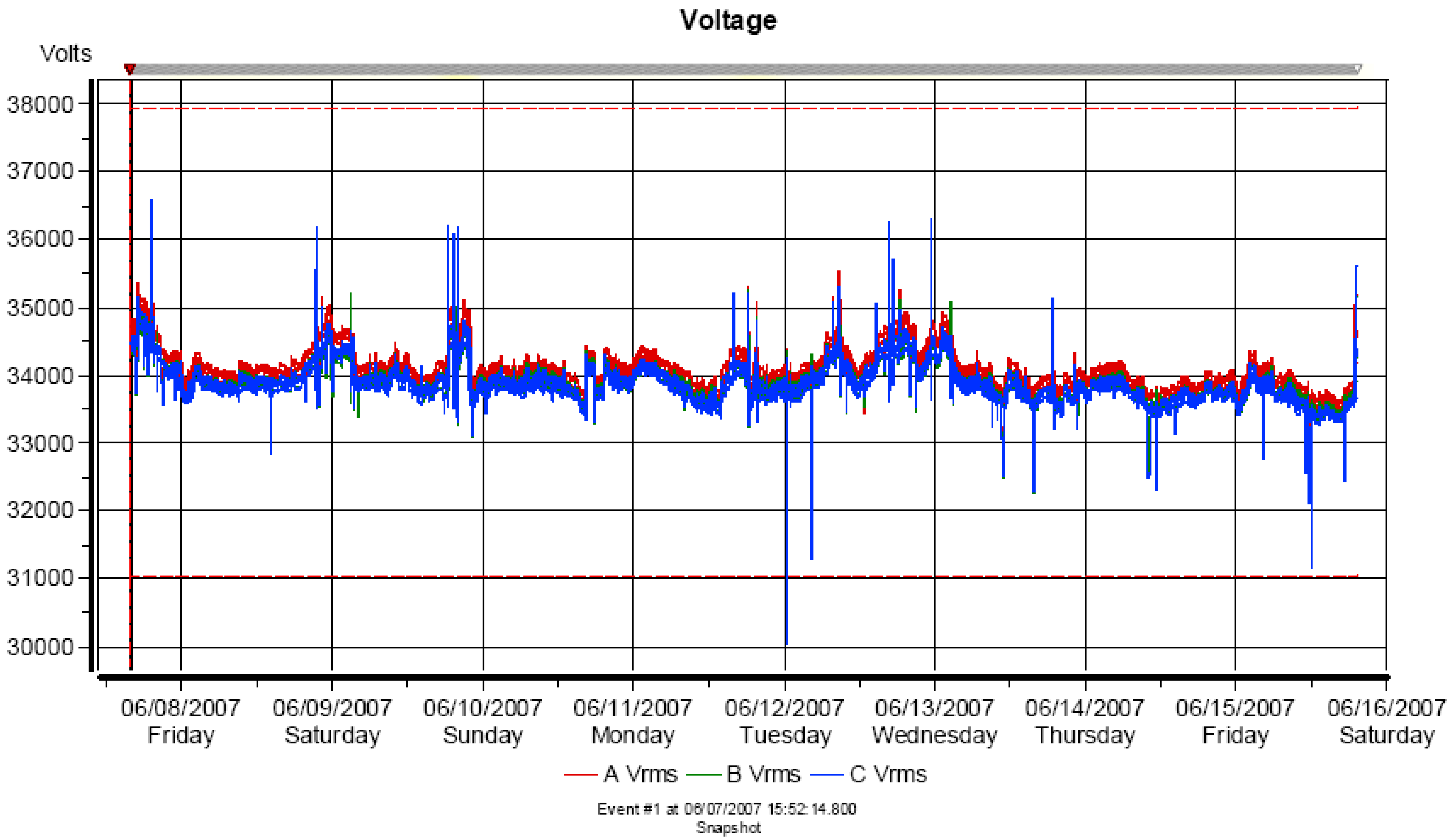
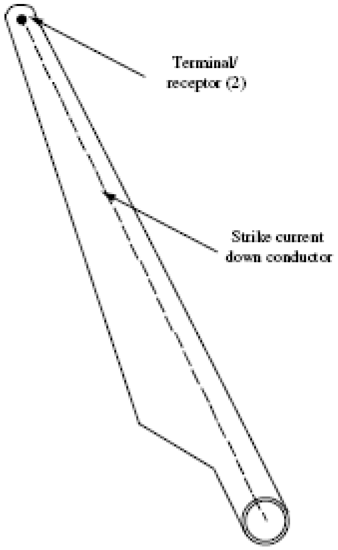
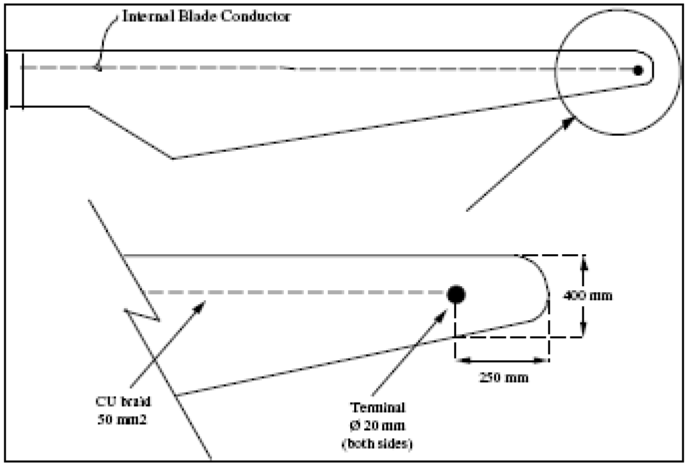


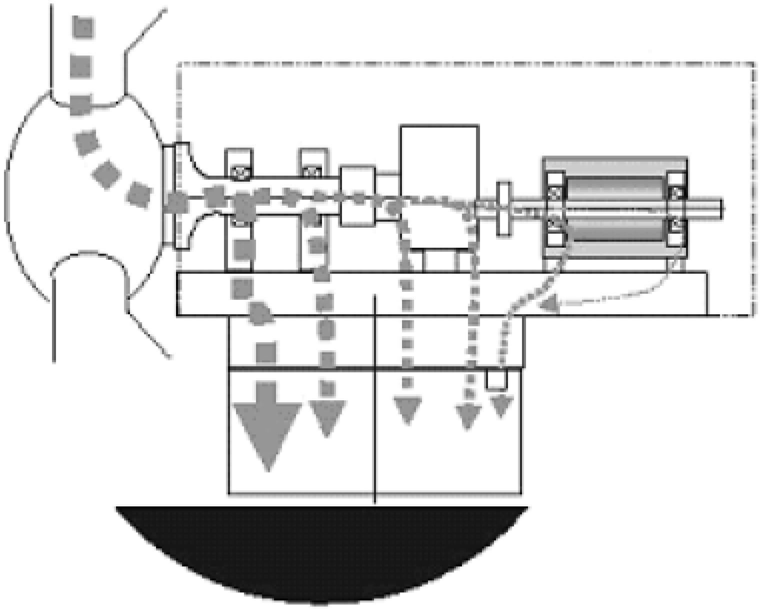
Figure-1: Voltage on secondary of transformer

Blade Lightning Damage

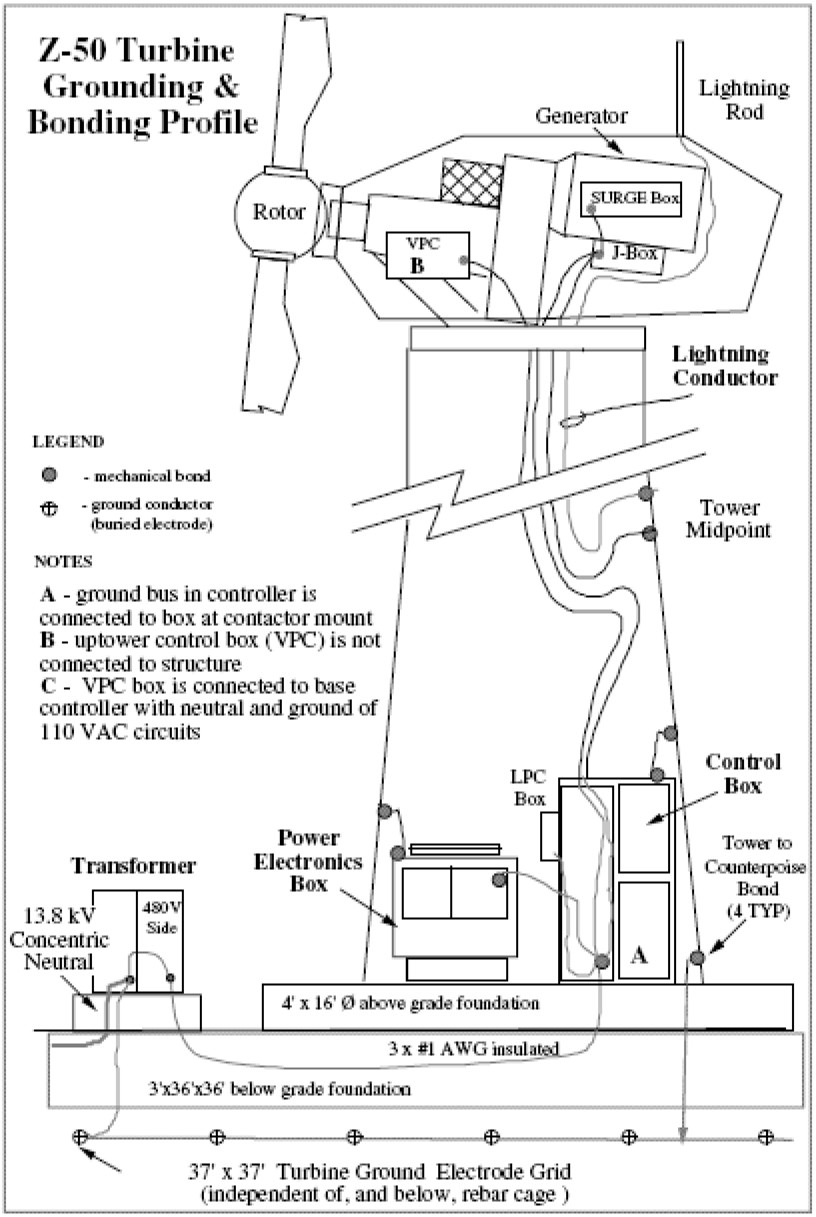




Lightning Protection



Lightning Current Path
Generator Bearings Subjected
To Lightning Current



Z-50 Turbine Grounding & Bonding Profile

LEGEND

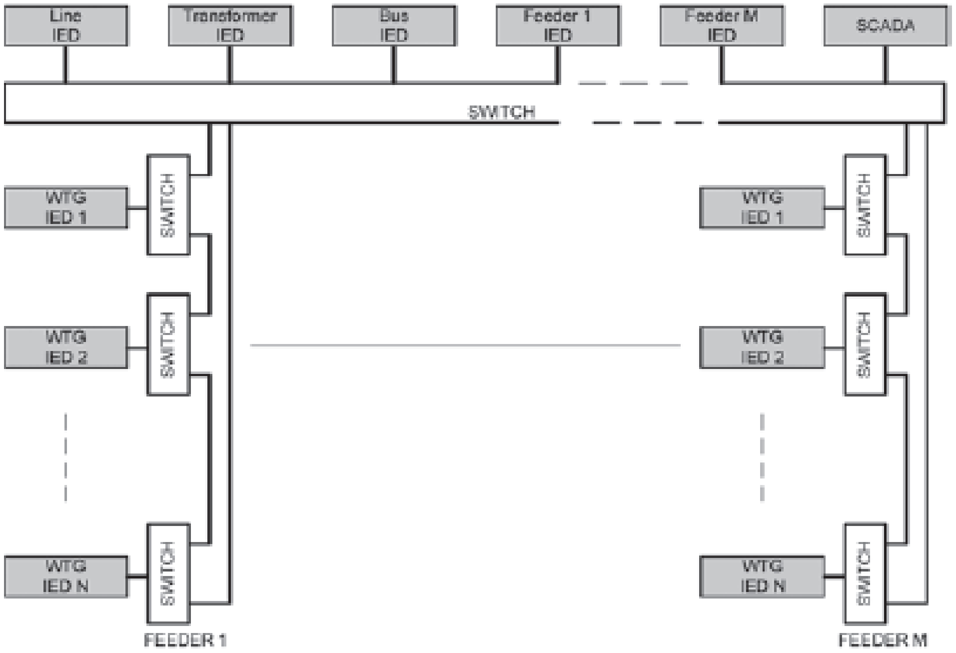
● - mechanical bond
⊕ - ground conductor (buried electrode)

NOTES

A - ground bus in controller is connected to box at contactor mount
B - uptower control box (VPC) is not connected to structure
C - VPC box is connected to base controller with neutral and ground of 110 VAC circuits

Gearbox & Mechanical System Failures

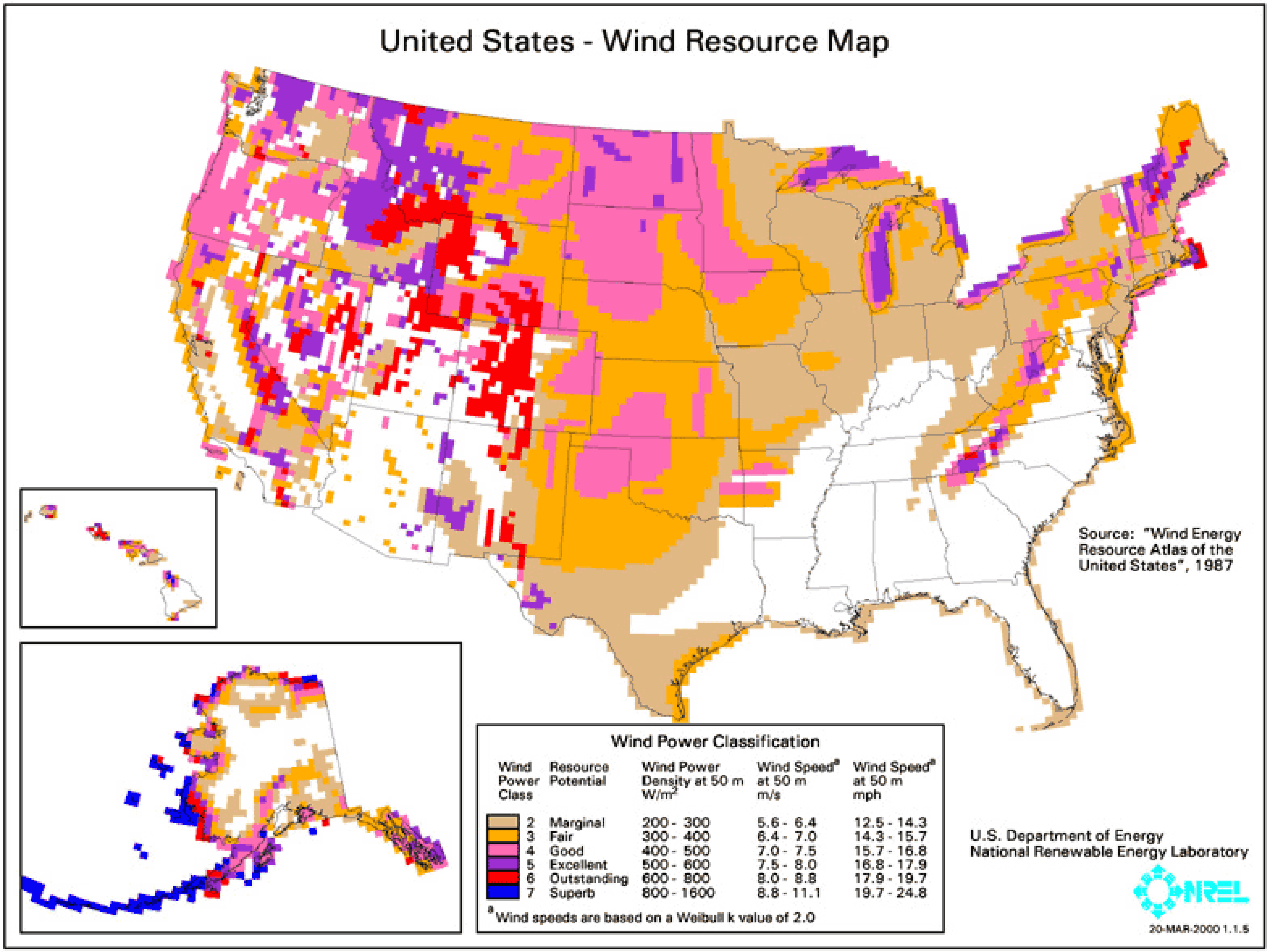
WF Collector Feeder Transfer Trip



An alternative solution is to disconnect the WTGs from the feeder before tripping the feeder breaker. However, the IED protecting the feeder in the substation is the only IED that can selectively detect feeder faults. In this case this IED would then send a transfer trip to all WTGs on the feeder. Once all units are disconnected, opening of the feeder breaker results in a well-behaved collapse of the voltage. Opening of the feeder breaker would be delayed minimally to ensure coordinated tripping.

Event #	Description	Time (ms)
1	Feeder Ground Fault	0
2	Feeder IED detects fault and send transfer trip	32
3a	WTG IEDs receive transfer trip & operate	8
4a	WTG breakers open	60
	WTG clearing time	**100**
3b	Feeder IED time delay	30
4b	Feeder breaker opens	60
	Feeder clearing time	**122**

US Wind Resource Map



Questions ?

GENERATOR Control scheme