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ABB Protective Relay School Webinar Series
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ABB Protective Relay School Webinar Series

Generator Protection Fundamentals

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Aug 19 , 2014

Presenter

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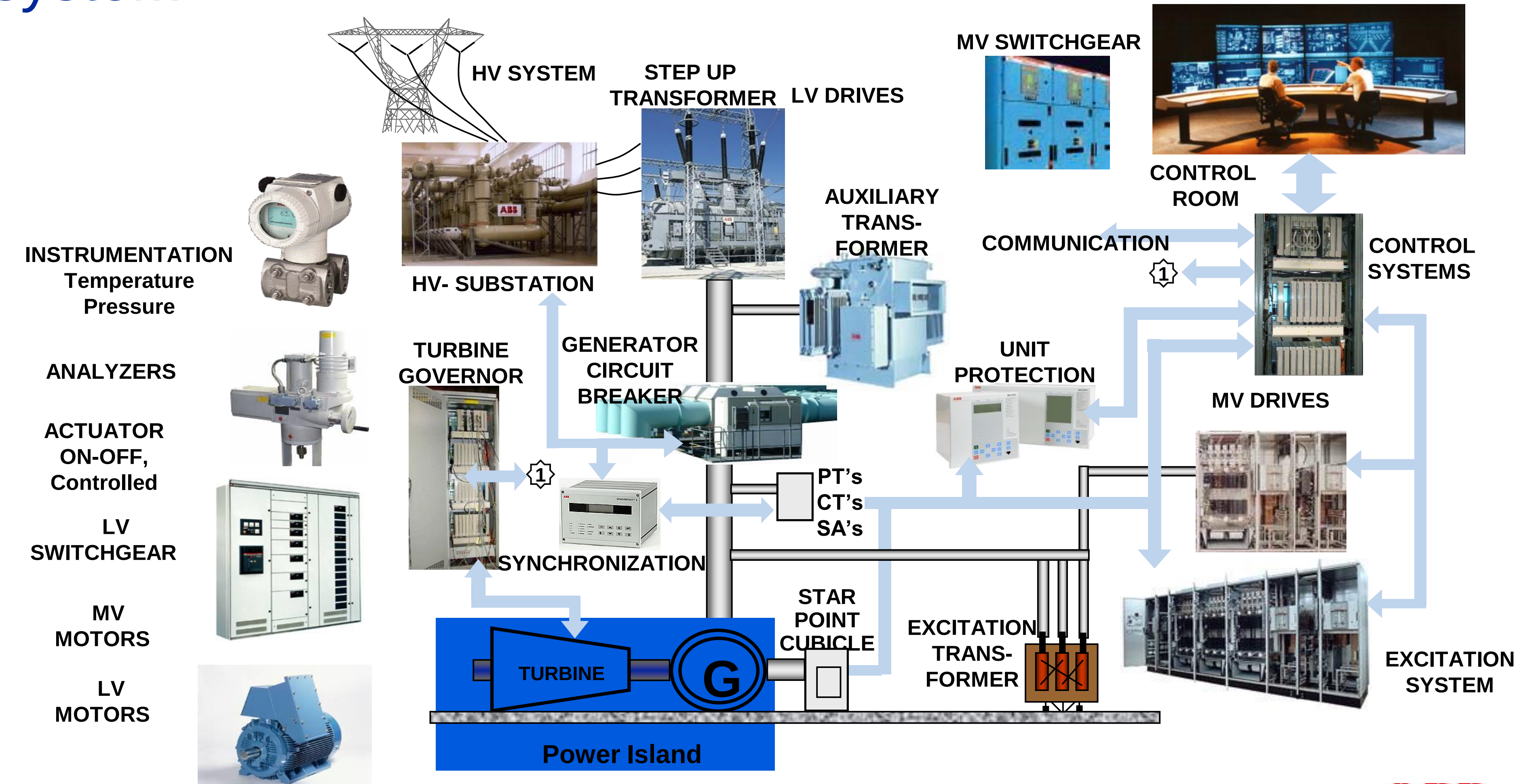
Learning objectives

- Power Generation fundamentals
- Generator Faults
- Generator Abnormal Conditions
- Modern Generator Protective IED Capabilities
- Typical Generator Protection Functions

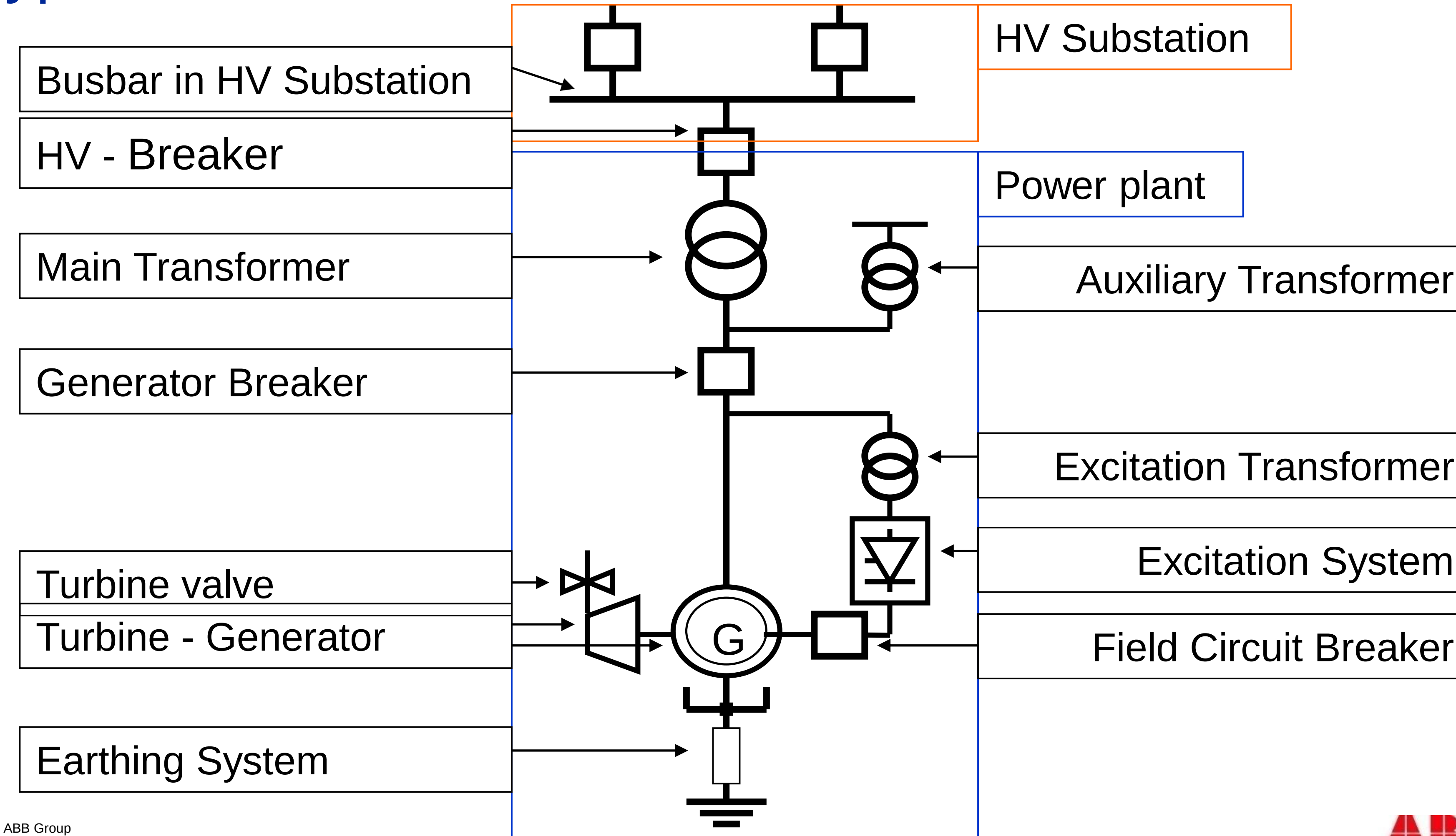
Standards

- C37.101: Guide for AC Generator Ground Protection
- C37.102: Guide for AC Generator Protection
- IEEE Tutorial On The Protection of Synchronous Generator (PSRC)

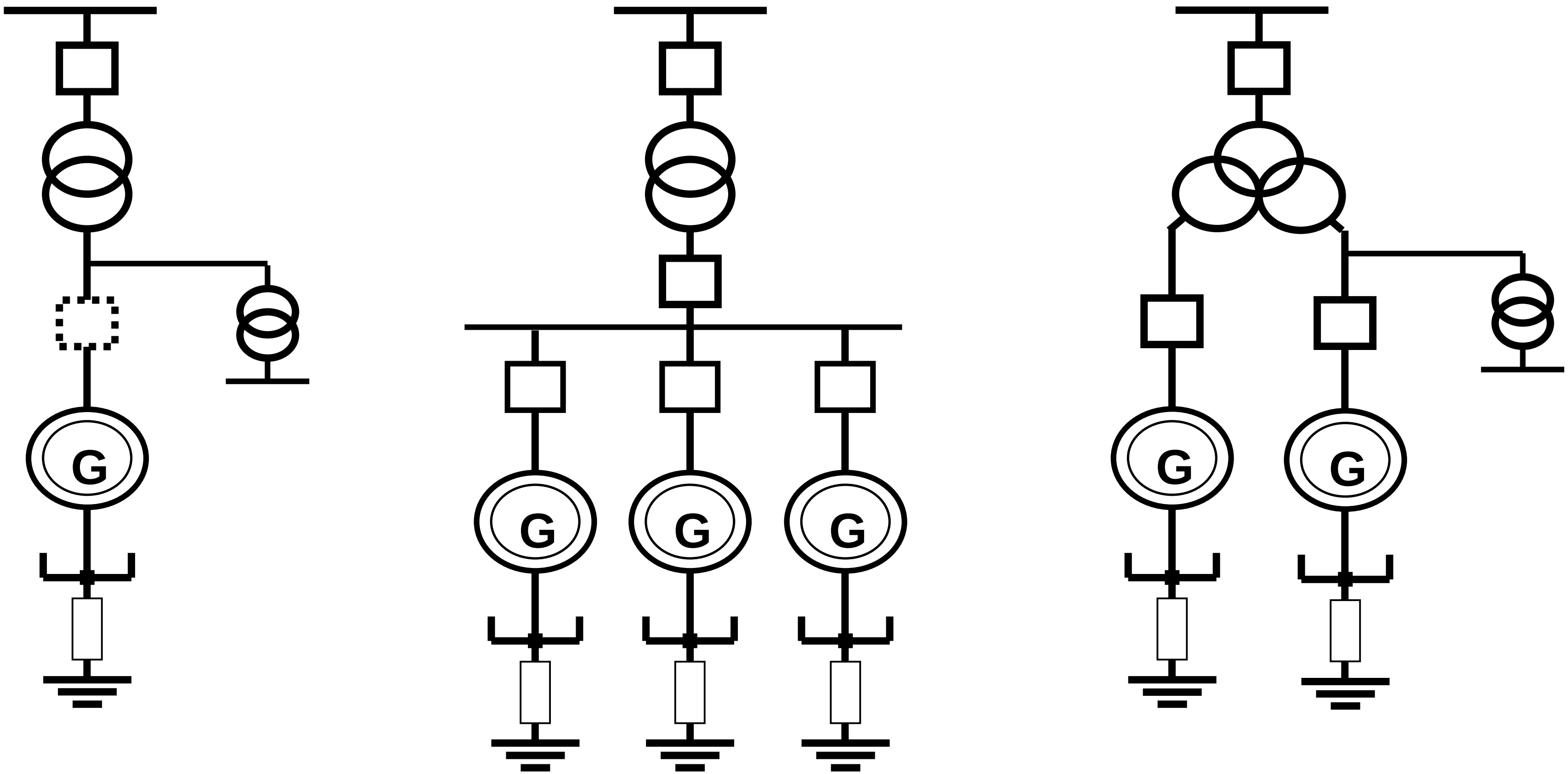
Power station is the most complex part of the power system



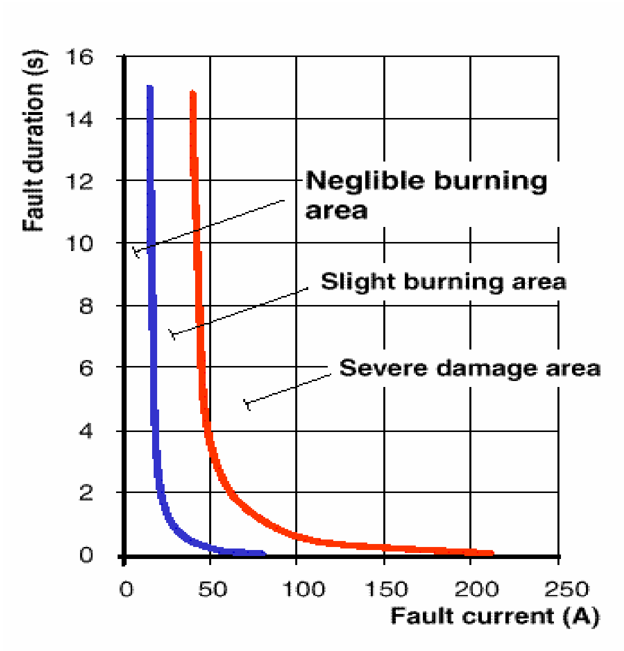
Typical Parts of a Power Plant



Different power plants electrical equipment layouts



Damage to the stator core in case of earth-fault



- Practically all unit connected generators are high-impedance earthed
- Only industrial generators may be low-impedance earthed

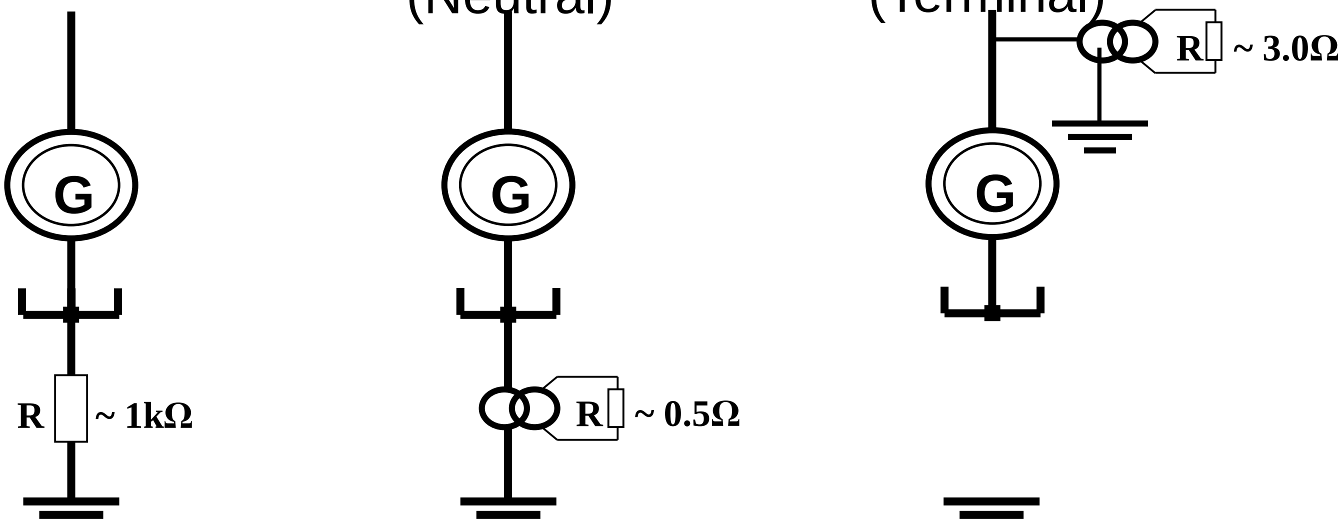
Stator winding earthing practices

Resistive Grounded

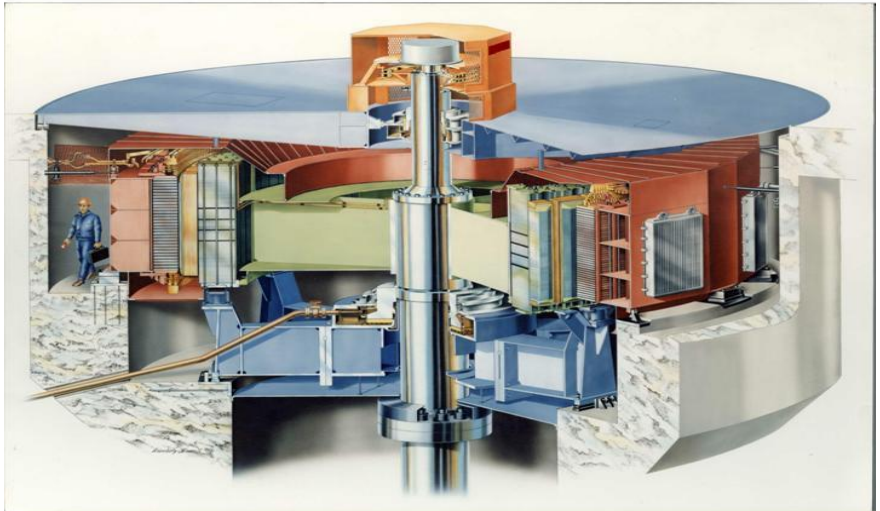
Grounding Transformer (Neutral)

Grounding Transformer (Terminal)

Isolated



Possible faults

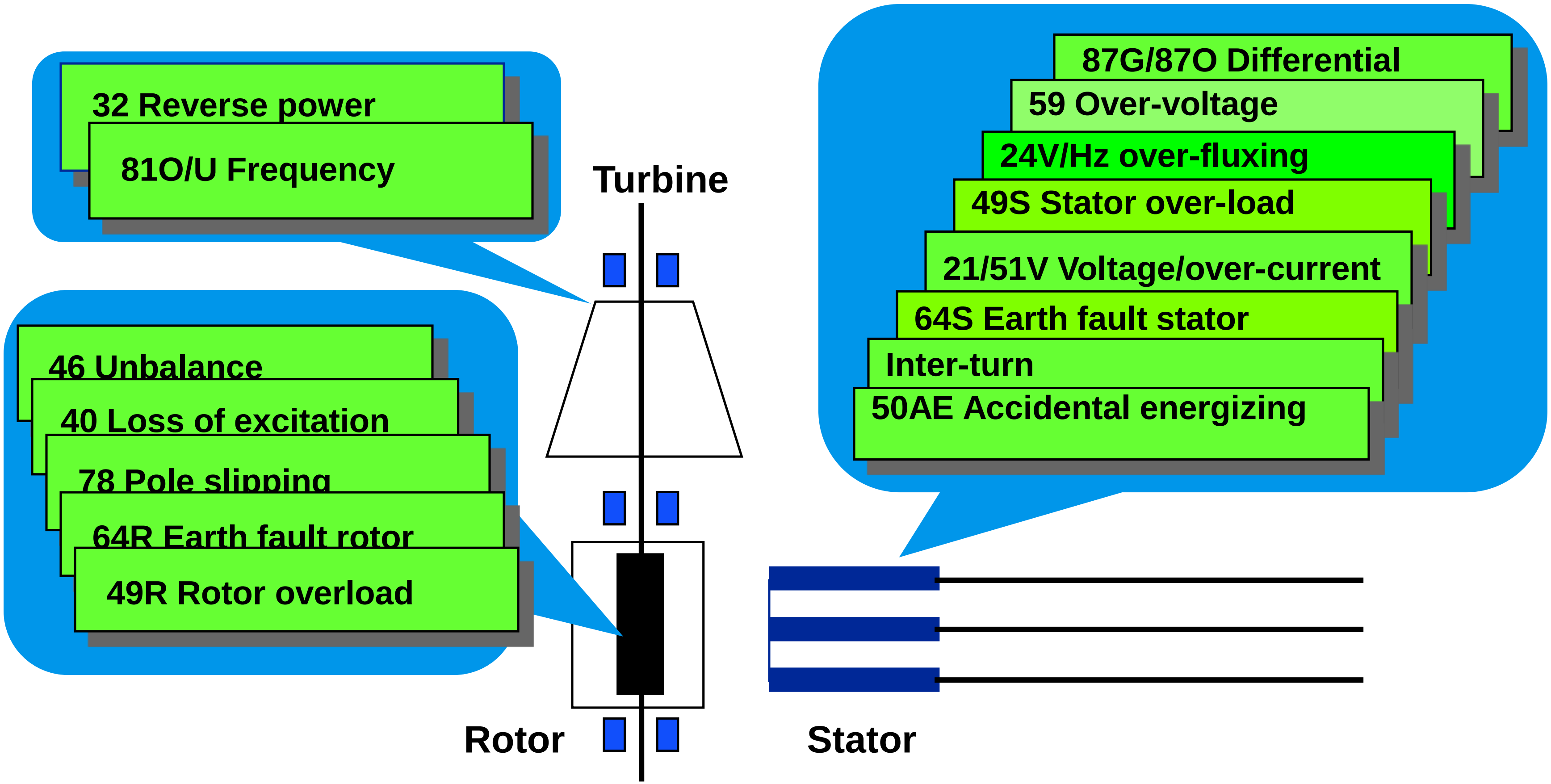


- Stator Earth Faults
- Rotor Earth Faults
- Stator Short Circuits
- Stator/Rotor Interturn faults
- Unit transformer faults
- External faults

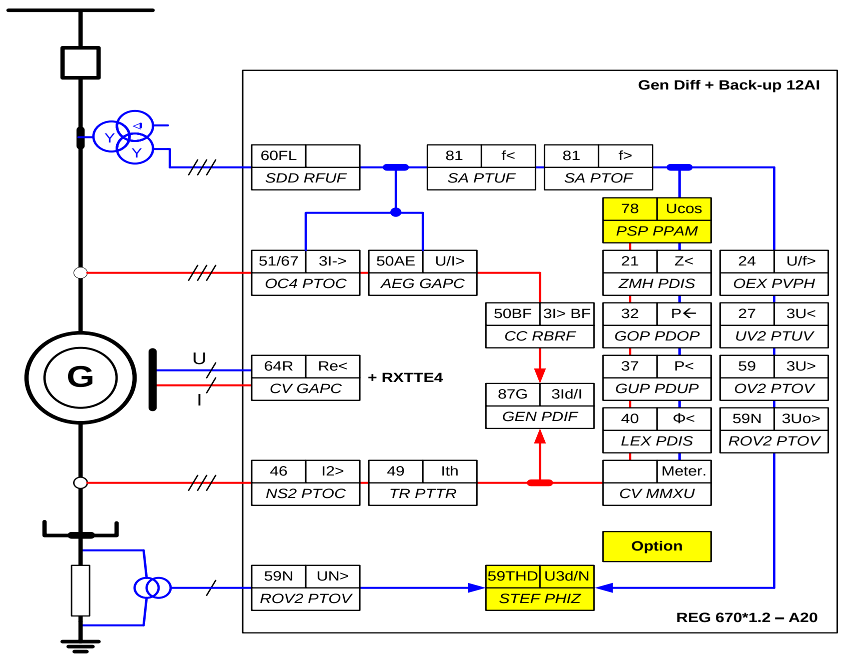
Abnormal operating condition

- overcurrent/overload
- unbalanced load
- overtemperature
- over- and undervoltage
- over- and underexcitation
- over- and underfrequency
- over-fluxing
- asynchronous running
- out of step
- generator motoring
- failures in the machine control system (i.e. AVR or governor failure)
- failures in the machine cooling system
- failures in the primary equipment (i.e. breaker head flashover)
- open phase

Allocation of protection functions



Generator protection



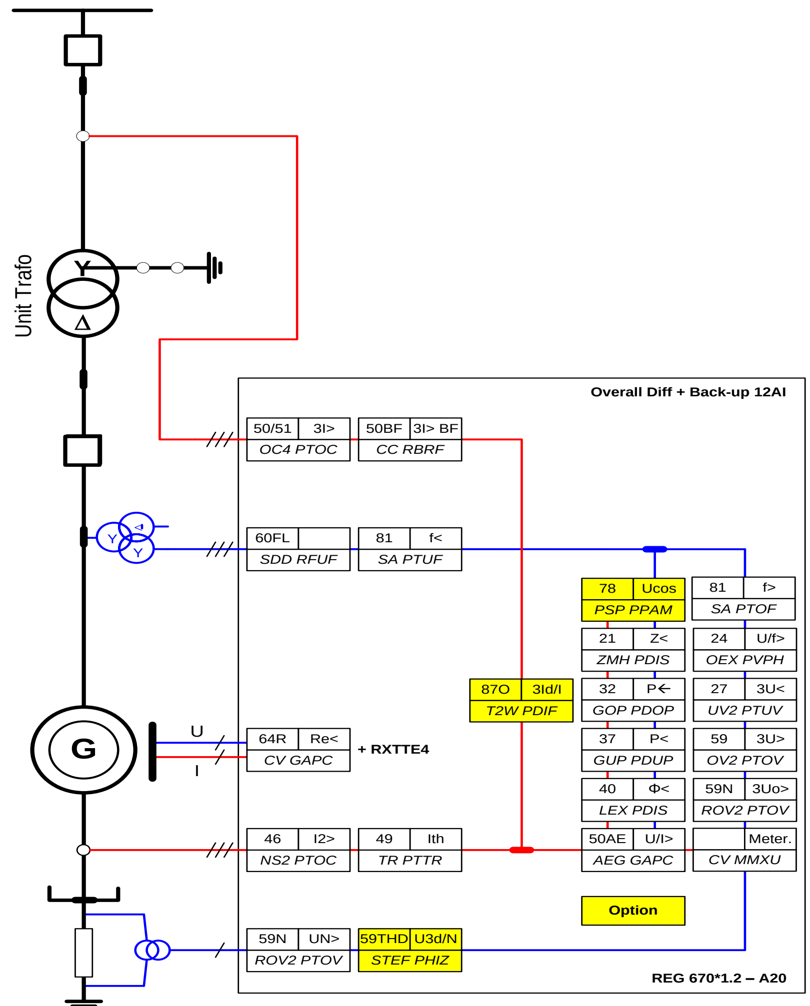
Other functions available from the function library

25	50 3I>>	51/27 U</I>	32N P0->	64S R_{SE}<
SES RSYN	PH PIOC	CV GAPC	SDE PSDE	STTI PHIZ
52PD PD	51/67 3I>	51V I>/U	87CT I2d/I	64R R_{RE}<
CC RPLD	OC4 PTOC	CV GAPC	CCS RDIF	ROTI PHIZ

Function alternatives for 87G/GEN PDIF

87T 3Id/I	87 IdN
T2W PDIF	HZ PDIF

Generator protection with 87T (87O)



Function allocations with older generation relays

- Older type of design:
  - M1 and M2 with different function allocations

Table 3: Example on relay functions divided into two function groups

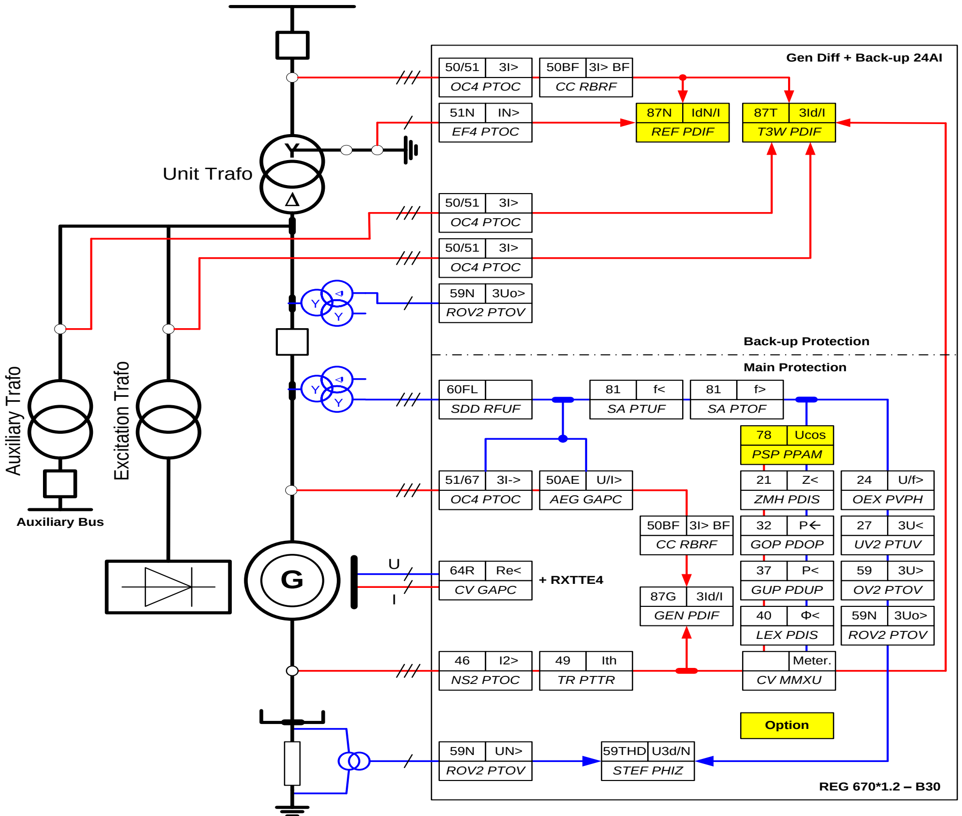
Type of fault	ANSI	Protection function	System	
Generator stator			A	B
Short circuit	87G	Generator differential	X	
	21	Minimum impedance or alternatively		X
	51/27	Overcurrent/undervoltage for thyristor magnetisation		X
	51	Overcurrent		X
Dissymmetry	46	Negative sequence overcurrent		X
Stator overload	49	Thermal overload	X	
Stator earth fault	59	95% stator earth fault	X	X
Loss of excitation	40	Reactive current and phase angle		X
Motoring	32	Reverse power Redundant protection used for large generators	 X	X X
Overspeed	81	Max. frequency	X	
Turbine blade fatique	81	Min. frequency	X	
Interturn fault	59 or 51N		X	(X)
Overvoltage	59	Overvoltage		X
Over magnetization	24	V/Hz	X	
Low voltage	27	Undervoltage		X
Inadvertent breaker closing (Dead-machine protection)	50/27	Overcurrent with low voltage		X
Shaft current	-	Overcurrent, fixed time		X
Generator rotor				
Rotor overload	49	Thermal overload		X
Rotor earth fault	64R	Injected AC Injected DC	X	 X
Step-up (Block) transformer				
Short circuit/earth fault	87T	Differential protection	X	
Overcurrent	50/51	Time overcurrent with instantaneous function		X
Breaker failure protection	50BFR			X
Earth fault differential prot.	87D		X	
Over magnetization prot.	24	V/Hz		X

Complete Protection Scheme

- Generator M1 & M2 protection
  - Two identical IEDs with 87G (low/high impedance based)

- Complete Unit Protection for Smaller Machines
  - One with 87G
  - One with 87T or 87O

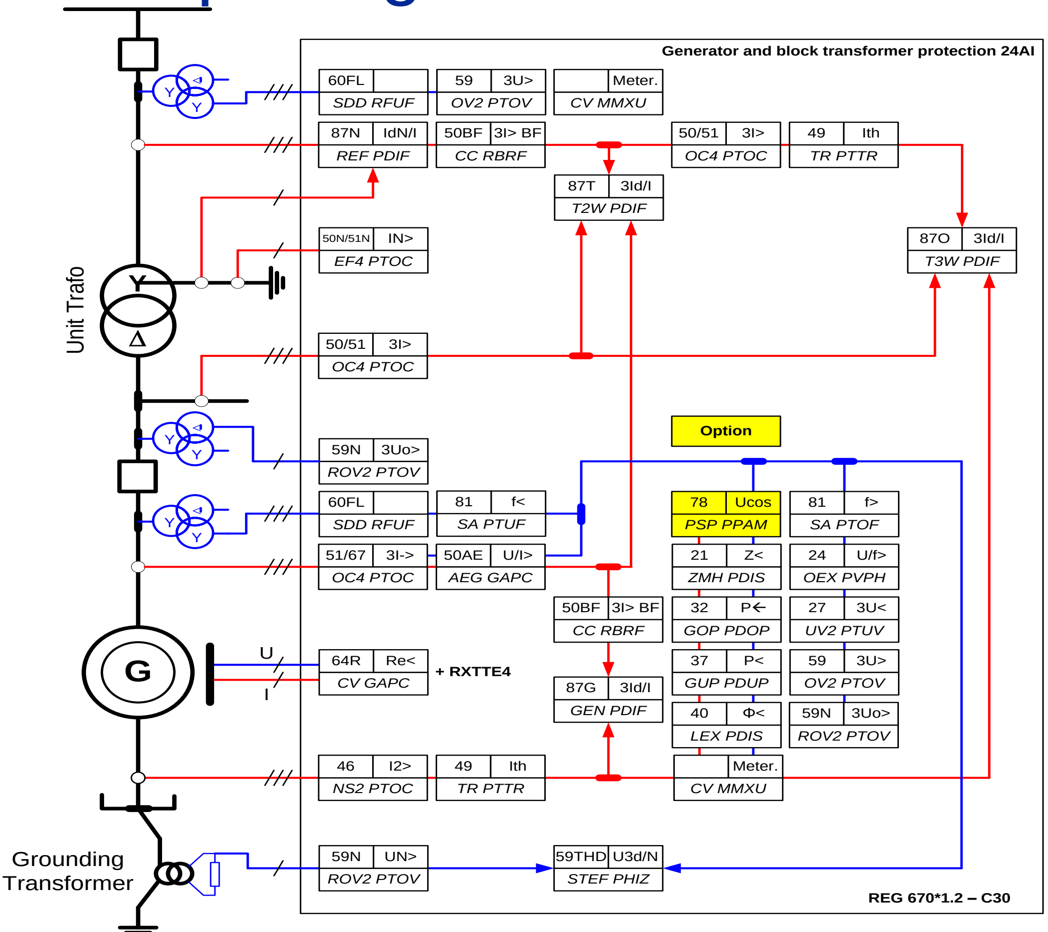
Generator protection & optional transformer protection



Other functions available from the function library

25		50	3I>>	51/27	U</I>	64S	R_{SE}<	87T	3Id/I
SES RSYN		PH PIOC		CV GAPC		STTI PHIZ		T2W PDIF	
52PD	PD	87CT	I2d/I	51V	I>/U	64R	R_{RE}<	32N	P0->
CC RPLD		CCS RDIF		CV GAPC		ROTI PHIZ		SDE PSDE	

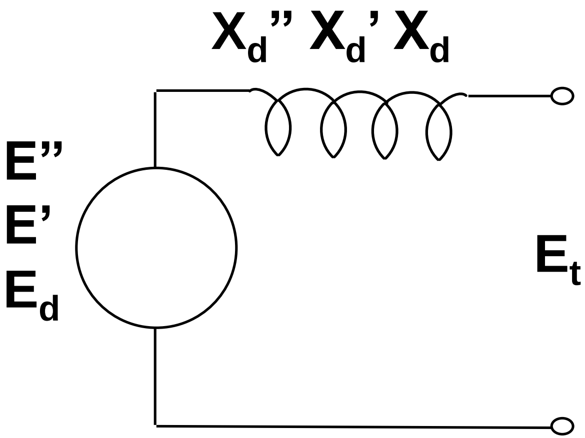
Complete generator-transformer unit protection

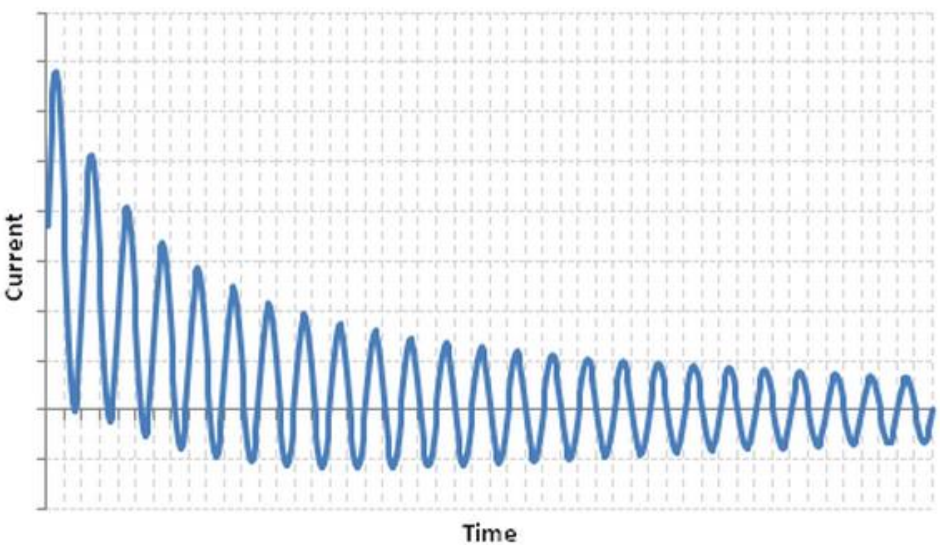


Other functions available from the function library

25 SES RSYN	50 3I>> PH PIOC	51/27 U</I> CV GAPC	32N P0-> SDE PSDE	64S R_{SE}< STTI PHIZ
52PD PD CC RPLD	51/67 3I> OC4 PTOC	51V I>/U CV GAPC	87CT I2d/I CCS RDIF	64R R_{RE}< ROTI PHIZ

Generator terminal short circuit





X_d'' - **Subtransient Reactance**

X_d' - **Transient Reactance**

X_d - **Synchronous Reactance**

- The fault current from the generator change during fault sequence
  - Change of generator reactance X_d'' -> X_d' -> X_d
  - Dependent of the excitation system

Stator short circuit

- Consequence of stator short circuit
  - Insulation, windings and stator core can be damaged
  - Large forces, caused by large fault currents, can give damage to other components in the plant
  - Risk of explosion and fire
  - Mechanical stress on generator- and turbine shafts

Detection of stator short circuits

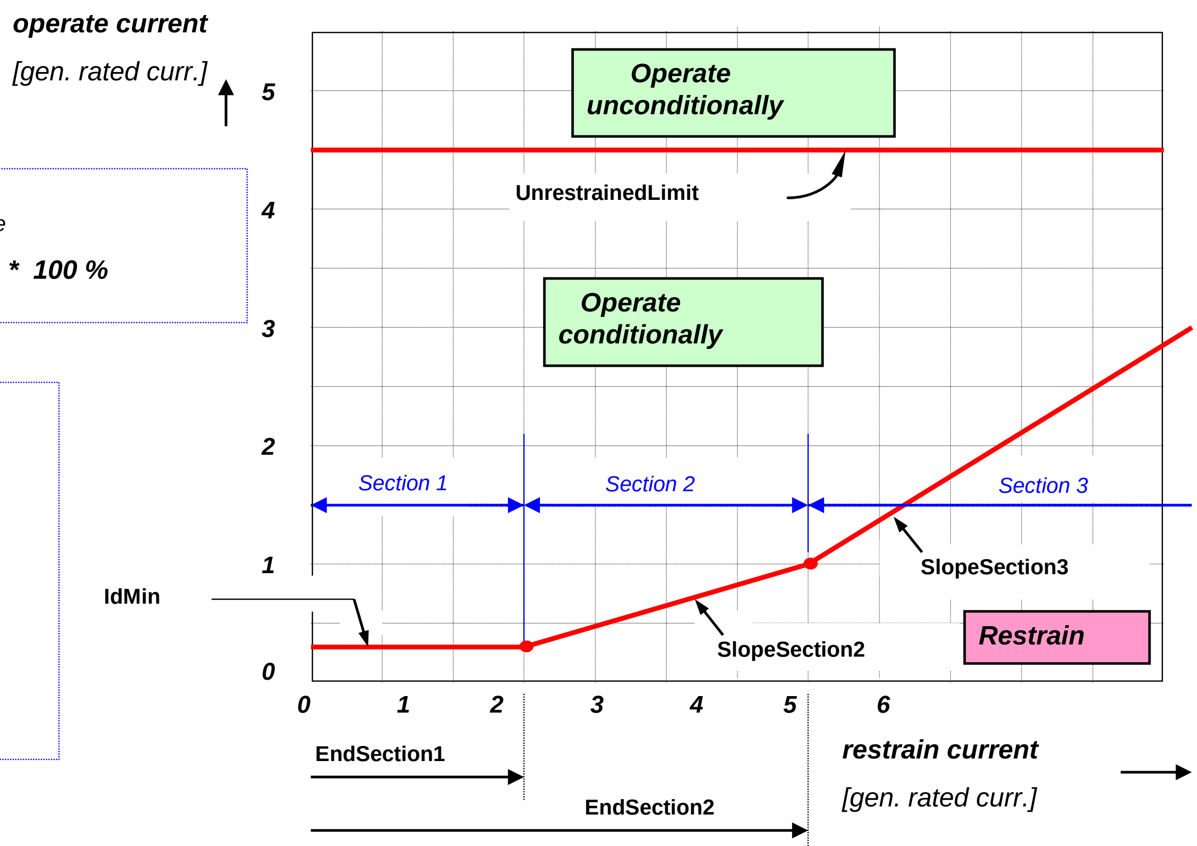
- Protection functions
  - Generator differential protection
  - Block (unit) differential protection
  - Directional negative sequence overcurrent protection
  - Under impedance protection
  - Phase overcurrent protection (sometimes not effective)
  - Voltage dependent phase overcurrent protection
  - Under voltage protection
  - Phase overcurrent protection of the block transformer

Generator differential protection

- Unstabilized differential protection level
- Stabilized differential protection level
  - Harmonic blocking
- Negative sequence unrestrained
  - Combination: bias differential and negative sequence internal/external discriminator; increases speed and security
- Negative sequence sensitive differential protection

Differential protection characteristics

$$slope = \frac{\Delta I_{operate}}{\Delta I_{restrain}} * 100\ \%$$



The restrained characteristic is defined by the settings:

****

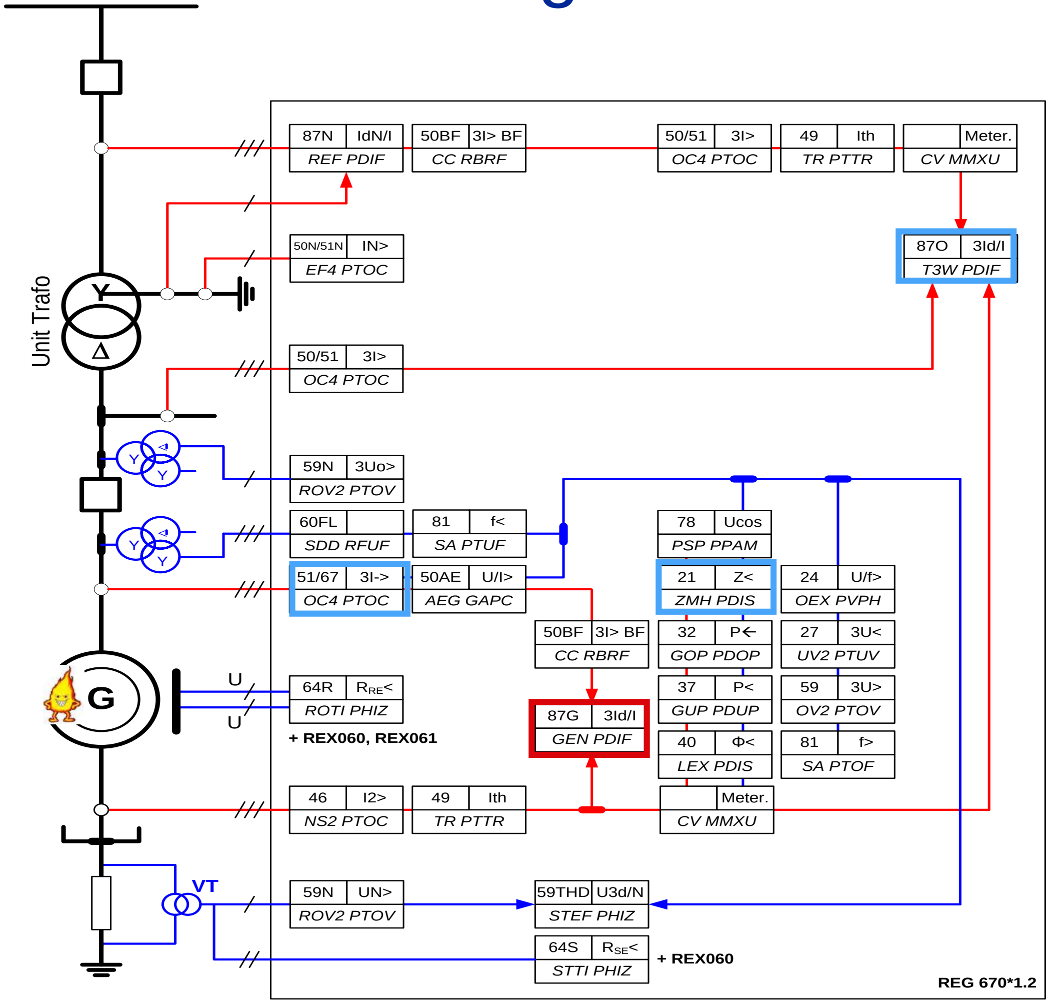
1. IdMin
2. EndSection1
3. EndSection2
4. SlopeSection2
5. SlopeSection3

Generator unit (overall) differential protection

- Identical to transformer differential protection
  - Zero sequence current elimination
  - Vector group compensation
  - Transformer ratio compensation
  - Unstabilized differential protection
  - Stabilized differential protection
    - Harmonic blocking
    - Waveform blocking
  - Negative sequence unrestrained
    - Combination: bias differential and negative sequence internal/external discriminator
  - Negative sequence sensitive differential protection

Phase to phase fault in the stator winding

- Endangering condition
  - Overcurrent
- Protected object
  - Stator winding
- Consequences
  - Heating
  - Forces
  - Smelted stator core

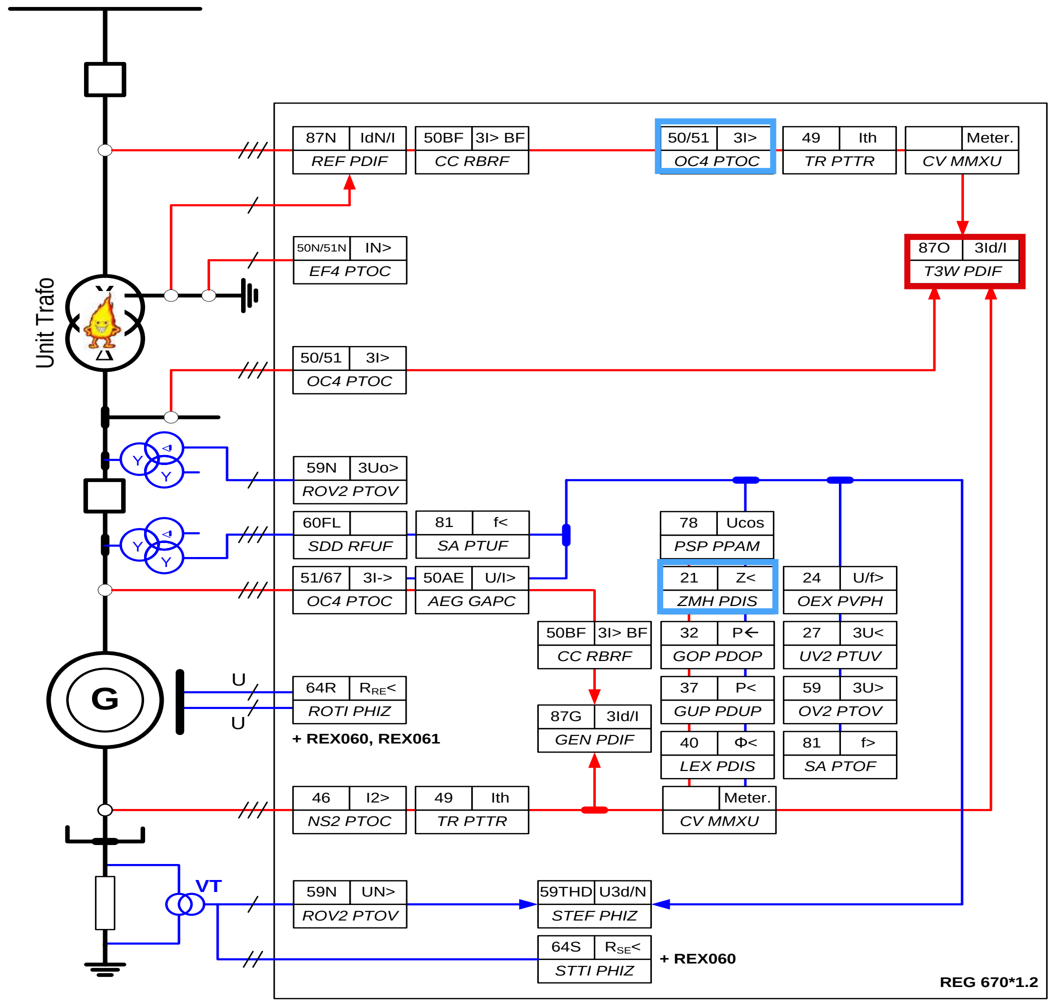


Main Protection Function

Reserve Protection Function

Phase to phase fault in the XFMR, and bus work

- Endangering condition
  - Overcurrent
- Protected object
  - XFMR, bus work
- Consequences
  - Heating
  - Forces
  - Smelted trafo core

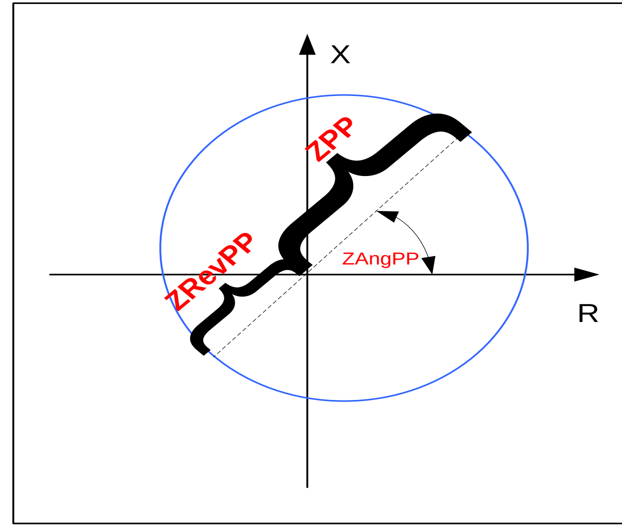


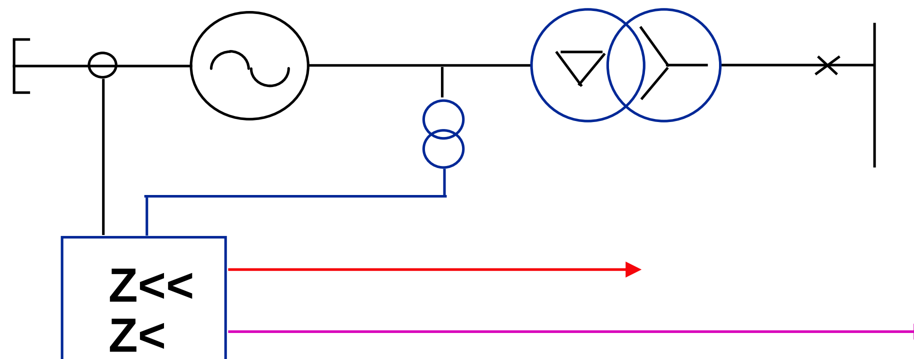
Main Protection Function

Reserve Protection Function

Under-impedance protection

- Backup protection for internal short circuits in the generator or the unit transformer
- Backup or main protection for fault at the busbar where the plant is connected to the power system
- Backup protection for line-faults at lines out from the power plant
- Up to 3-zones with offset mho characteristic

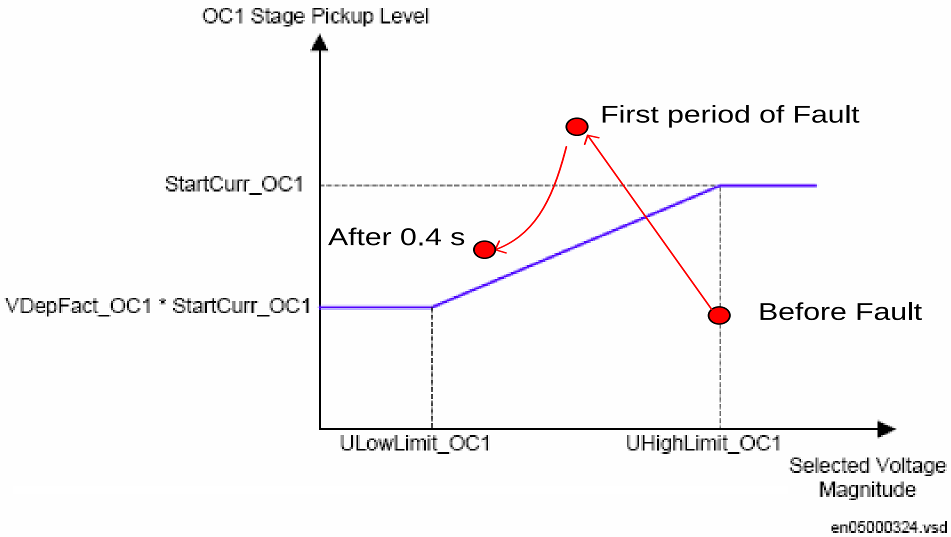


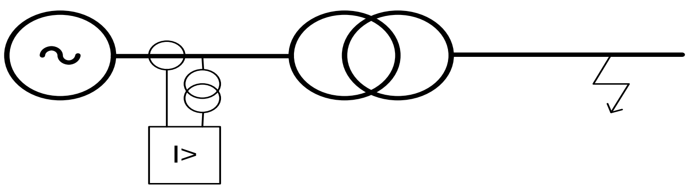


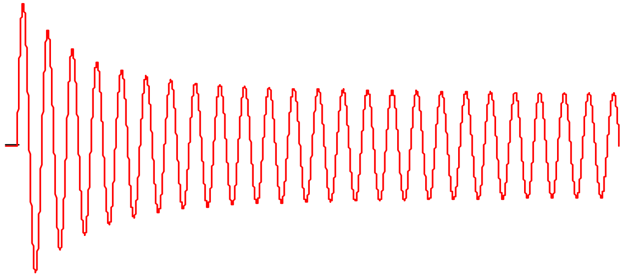
Phase overcurrent protection

- Backup protection for internal short circuits in the generator or the unit transformer
- Backup or main protection for fault at the busbar where the plant is connected to the power system
- Backup protection for line-faults at lines out from the power plant

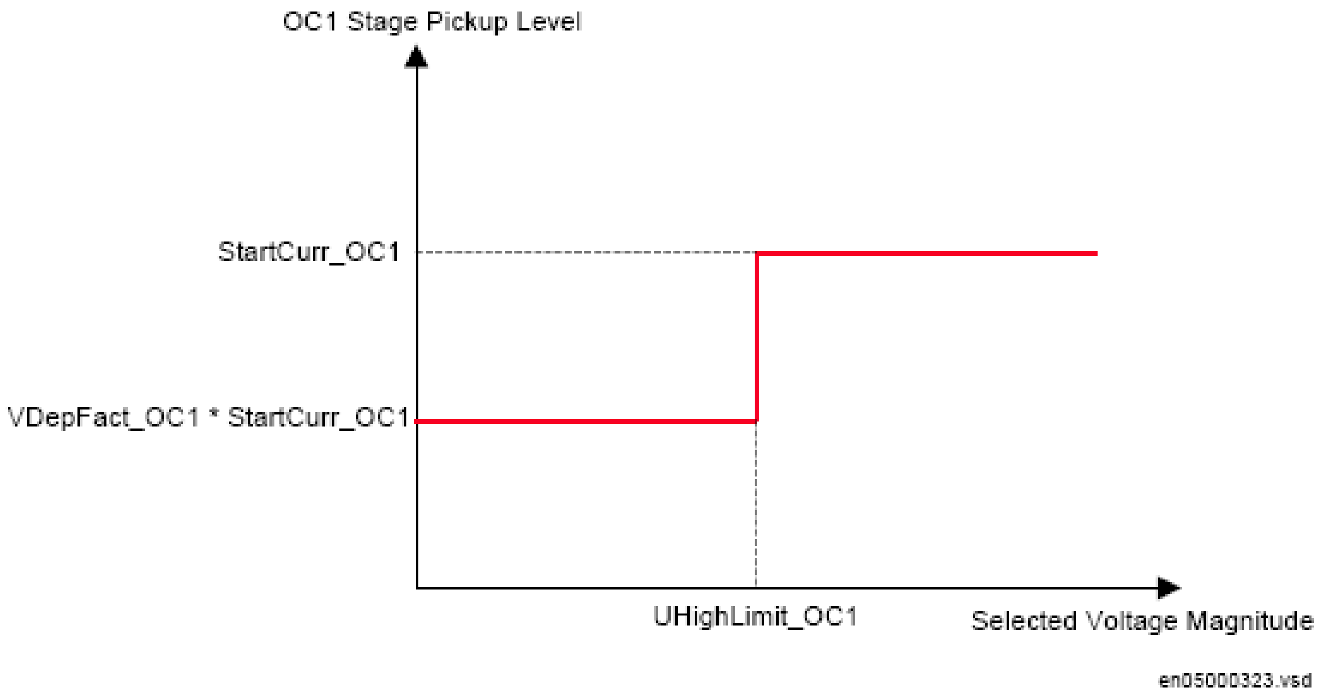
External short circuit







Voltage controlled phase overcurrent protection

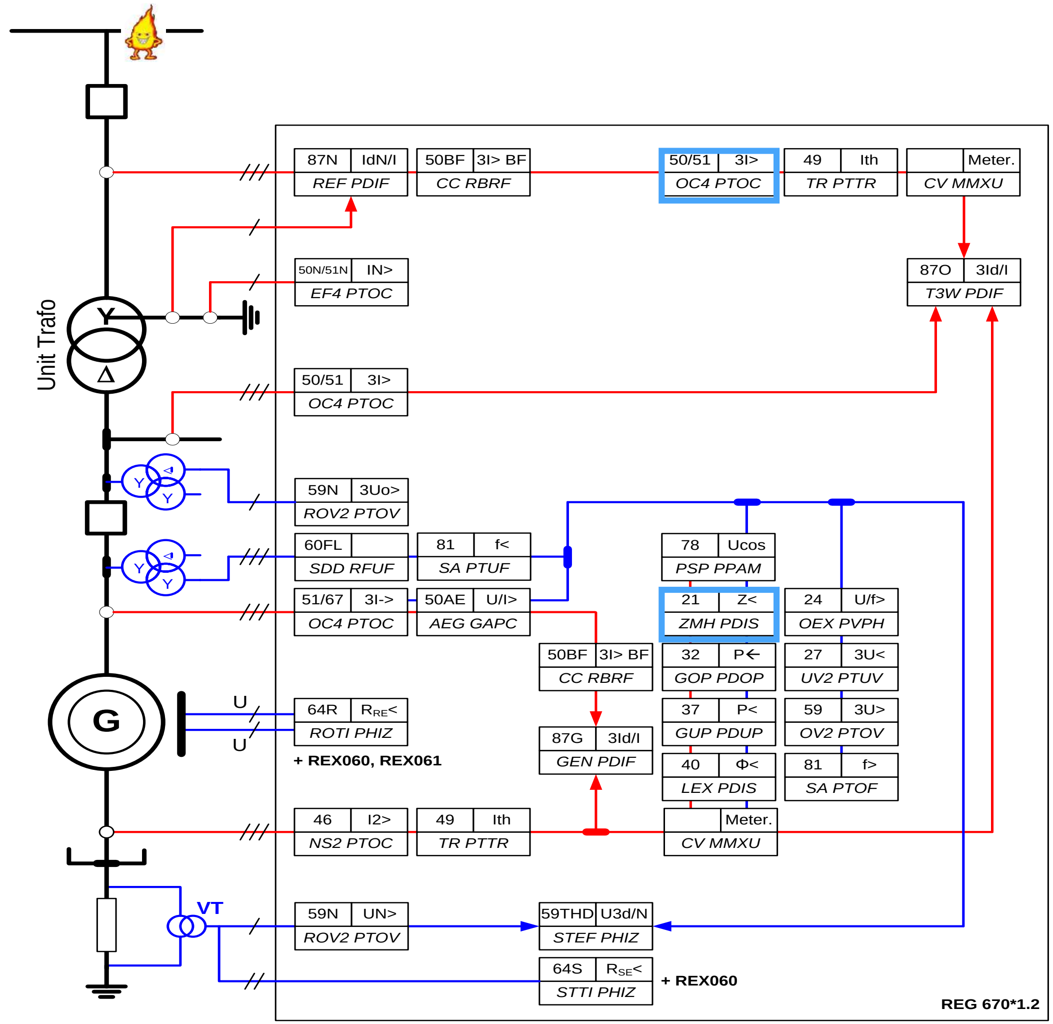


External faults

- Endangering condition
  - Overcurrent
- Protected object
  - External power system parts.
- Consequences
  - Heating
  - Forces
  - Mechanical damages

Main Protection Function

Reserve Protection Function

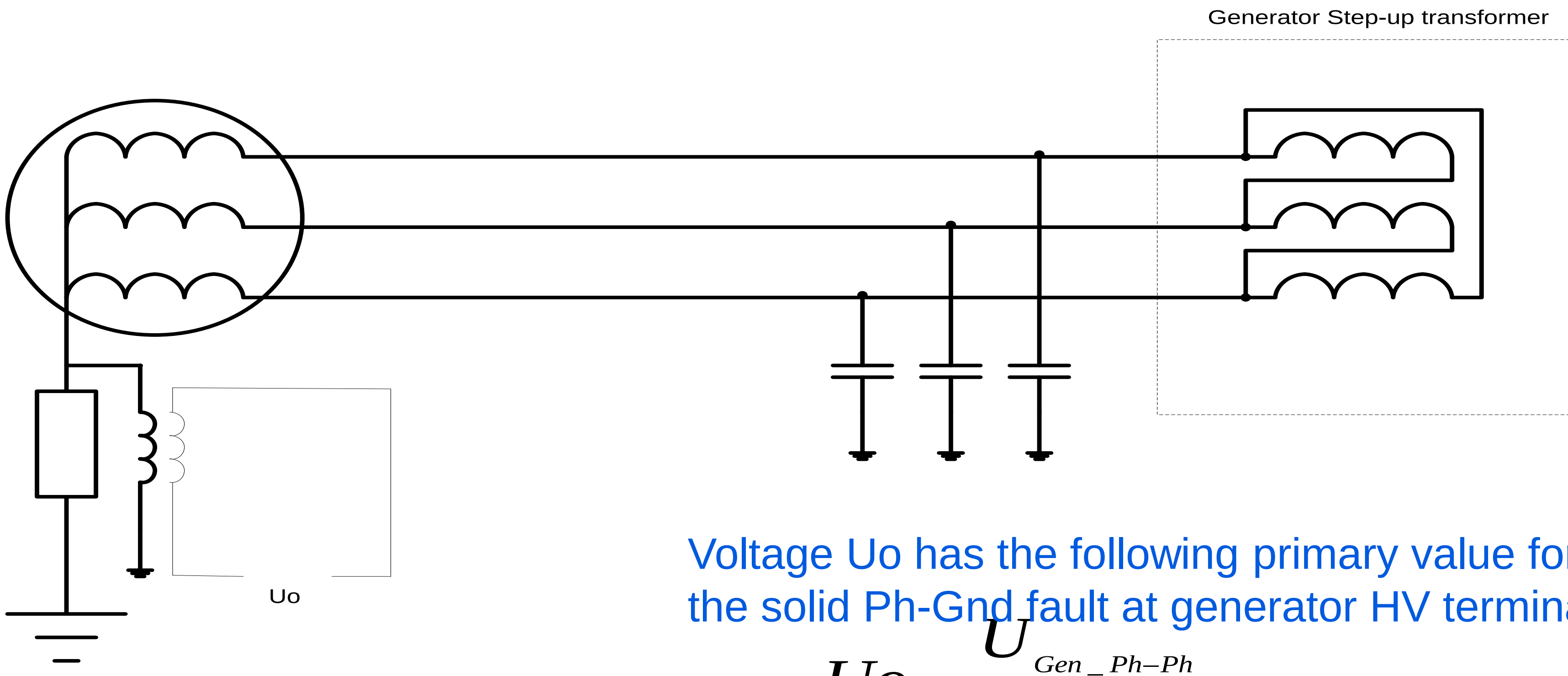


Stator earth fault

- Damages on the stator iron
- Increased voltage on “healthy phases”
- Small fault currents
- Sensitivity requirements on fault clearance
- The fault resistance is normally low at stator earth fault
- The residual voltage and earth fault current is highly dependent on fault location in the generator

Voltage based 95 % stator earth fault protection

Neutral point voltage transformer used to measure Uo voltage

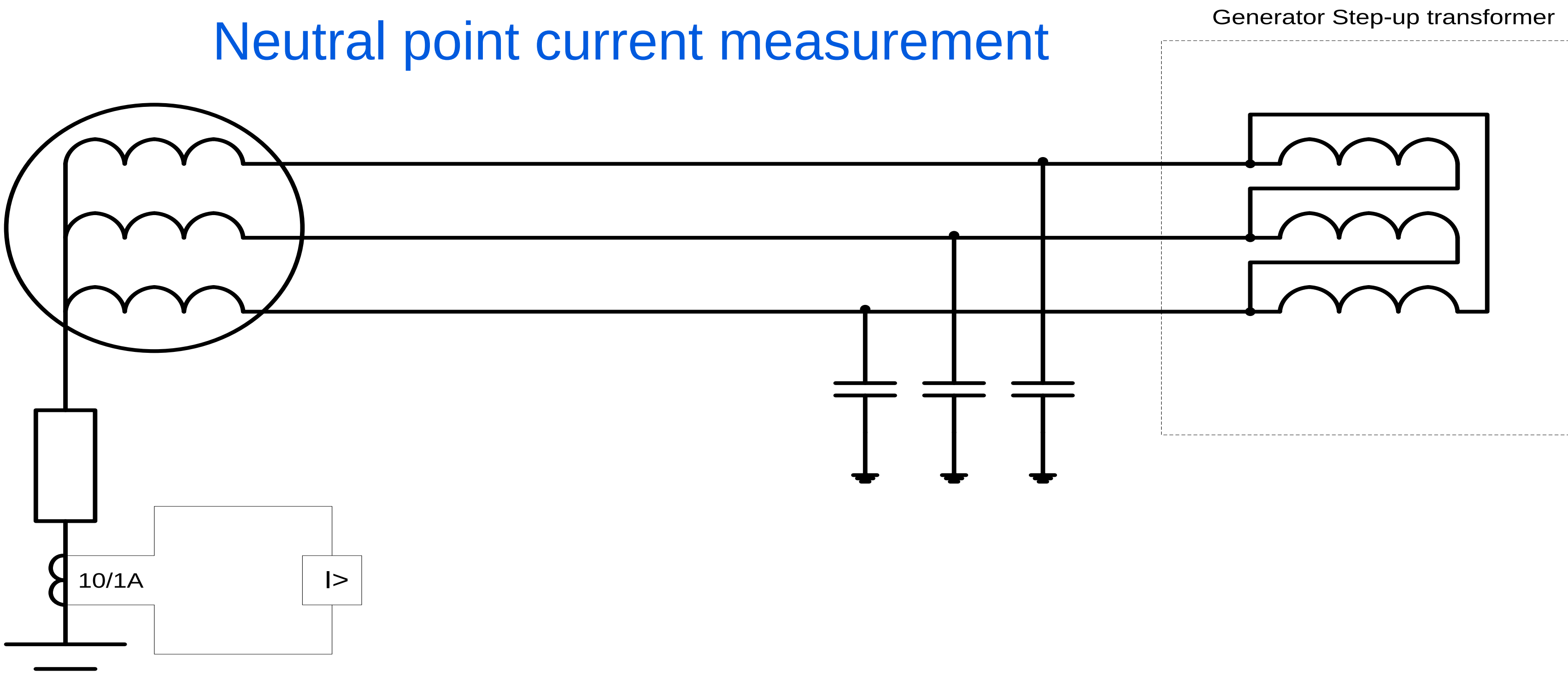


Voltage Uo has the following primary value for the solid Ph-Gnd fault at generator HV terminals

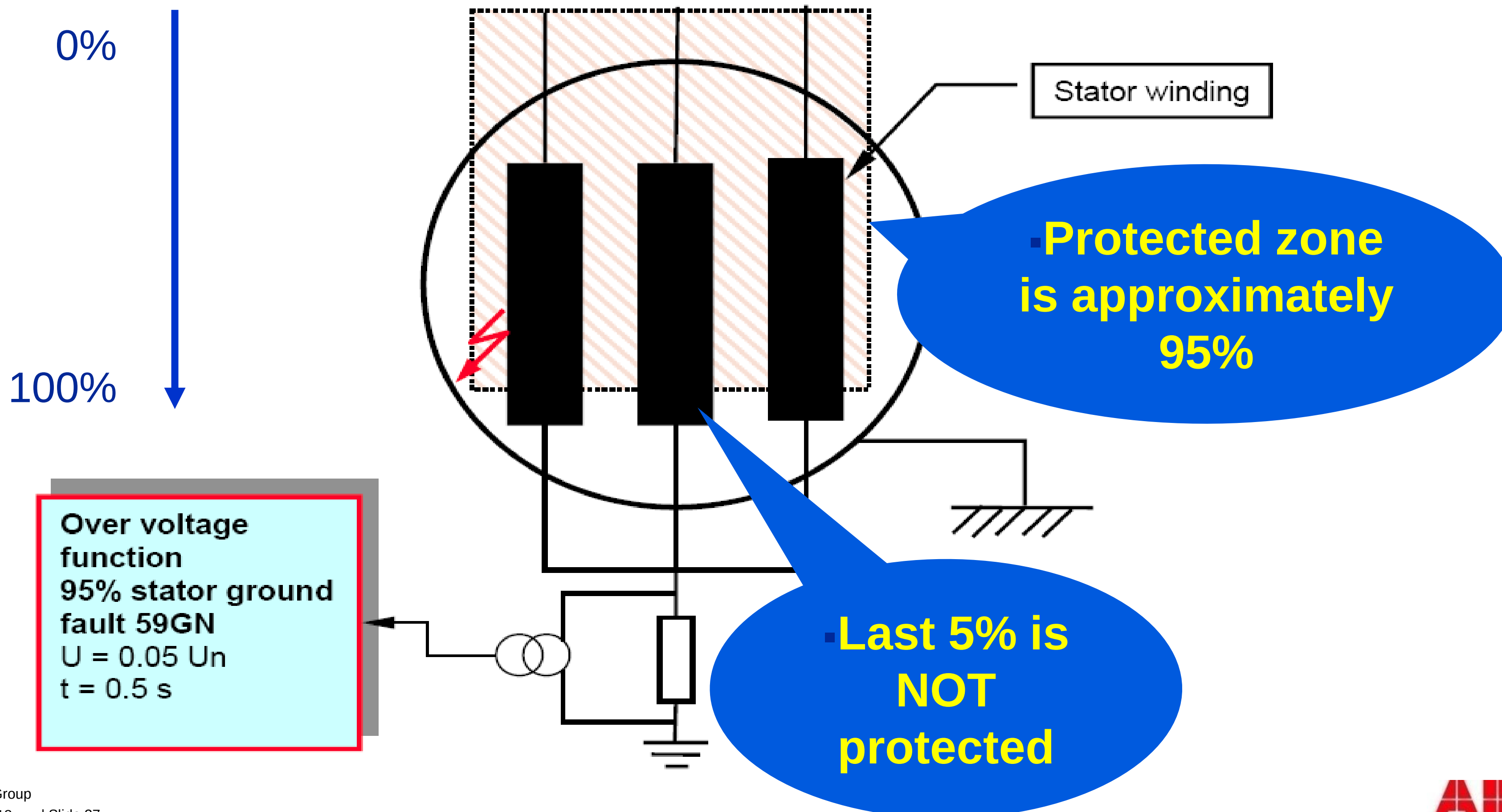
$$Uo = \frac{U_{Gen\_Ph-Ph}}{\sqrt{3}}$$

Current based 95 % stator earth fault protection

Neutral point current measurement



Why 95 % and 100% stator ground fault protection?



Possible 100 % stator earth fault protection solutions

- Measurement of the ”natural” third harmonic voltage induced in the generator can be used to protect against EF close to the generator neutral point
(i.e. 3rd harmonic based principle; 59THD)

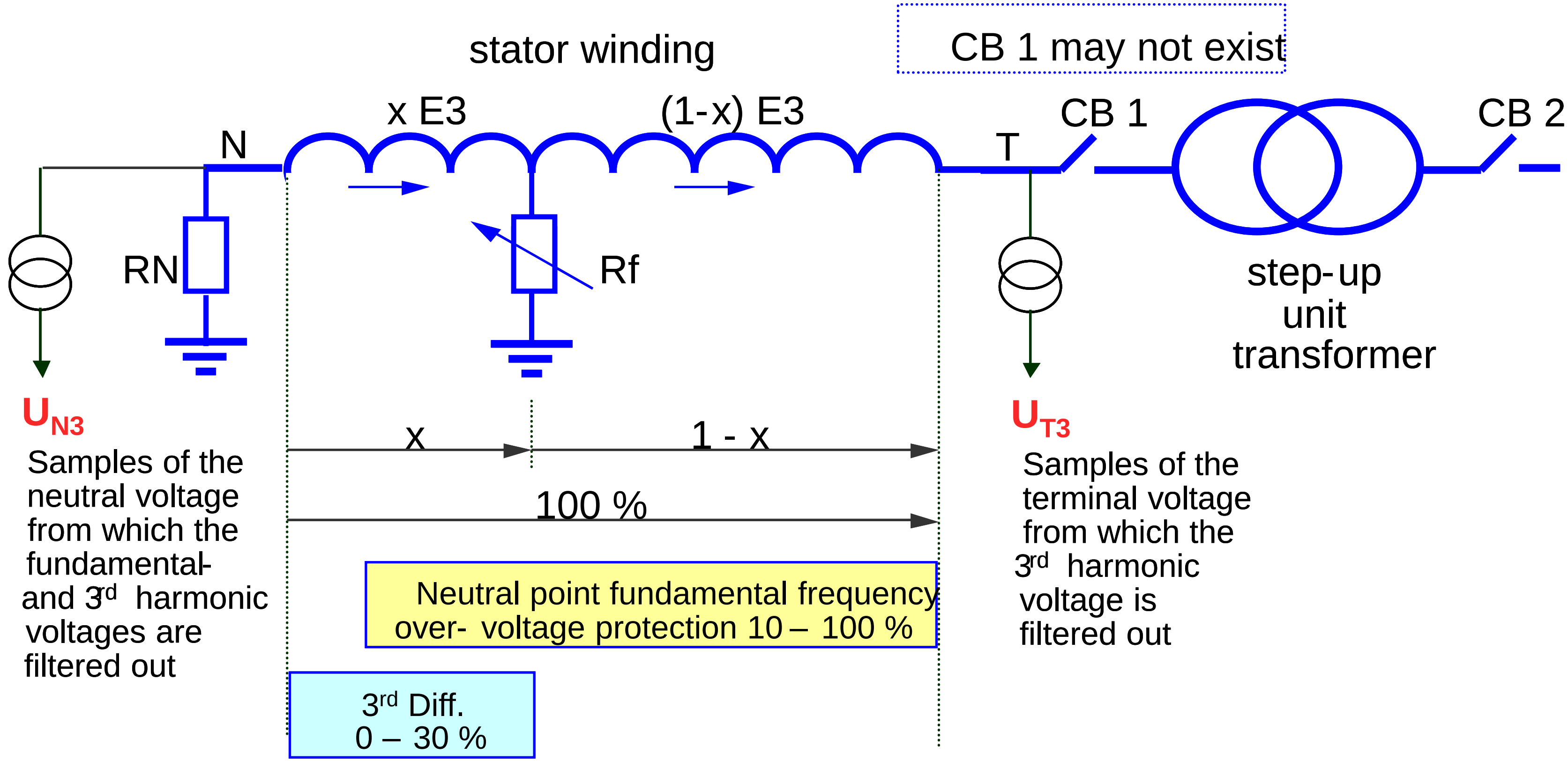
- Neutral point voltage injection where the injected voltage has non-harmonic frequency
(i.e. injection principle; 64S)

3rd harmonic 100% stator ground fault

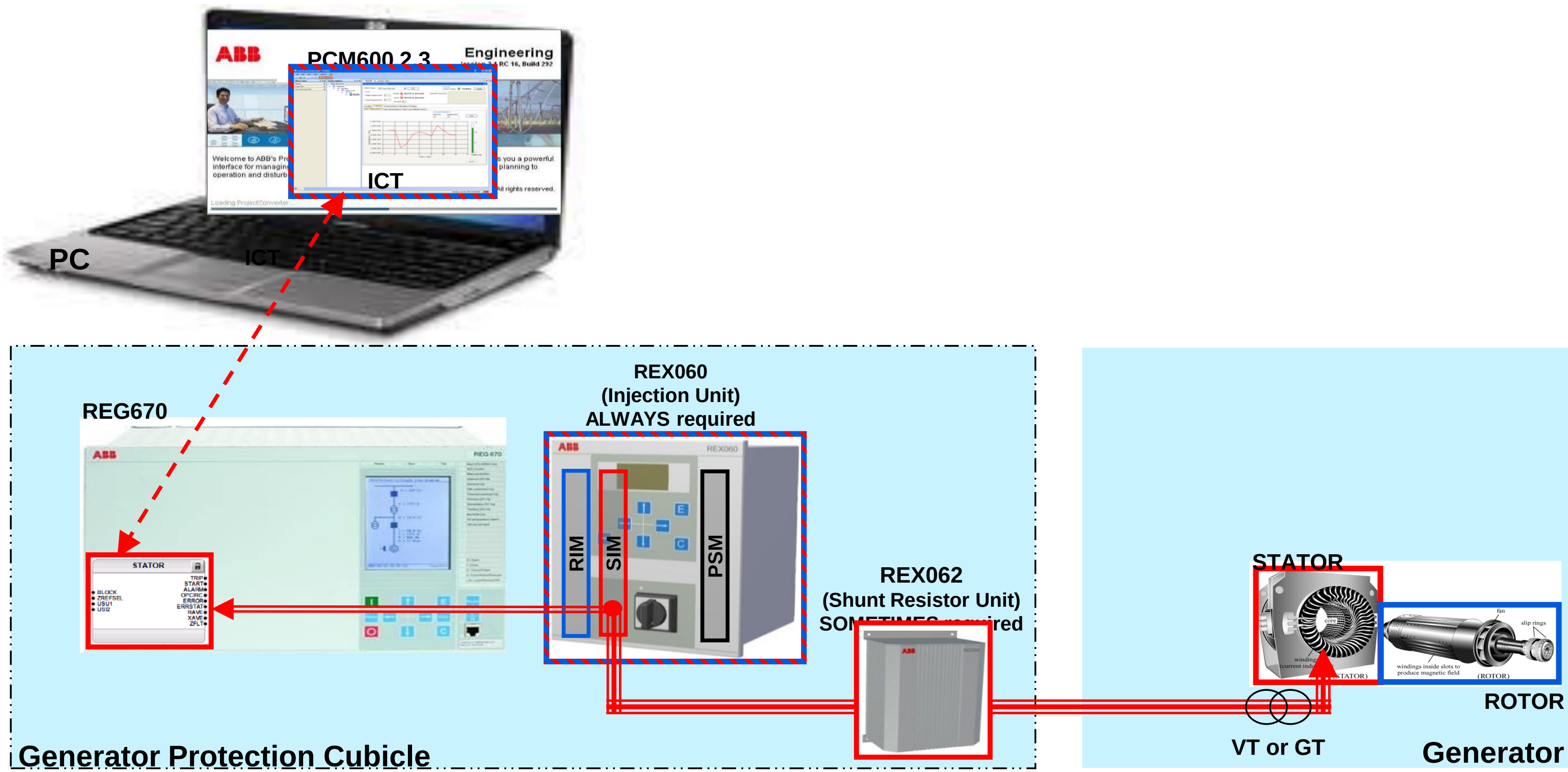
- Simplest approach :
  - 3rd harmonic under-voltage in the neutral (i.e. U_{3N}<)
  - 3rd harmonic over-voltage at generator terminals (i.e. U_{3T}>)
  - Possible problems:
    - Generator start-up
    - Generator shut-down
    - Different generator loading
- 3rd harmonic differential principle

$$\left|U_{N3} + U_{T3}\right| \geq Beta \cdot \left|U_{N3}\right|$$

3rd harmonic based 100% stator earth-fault



Stator injection

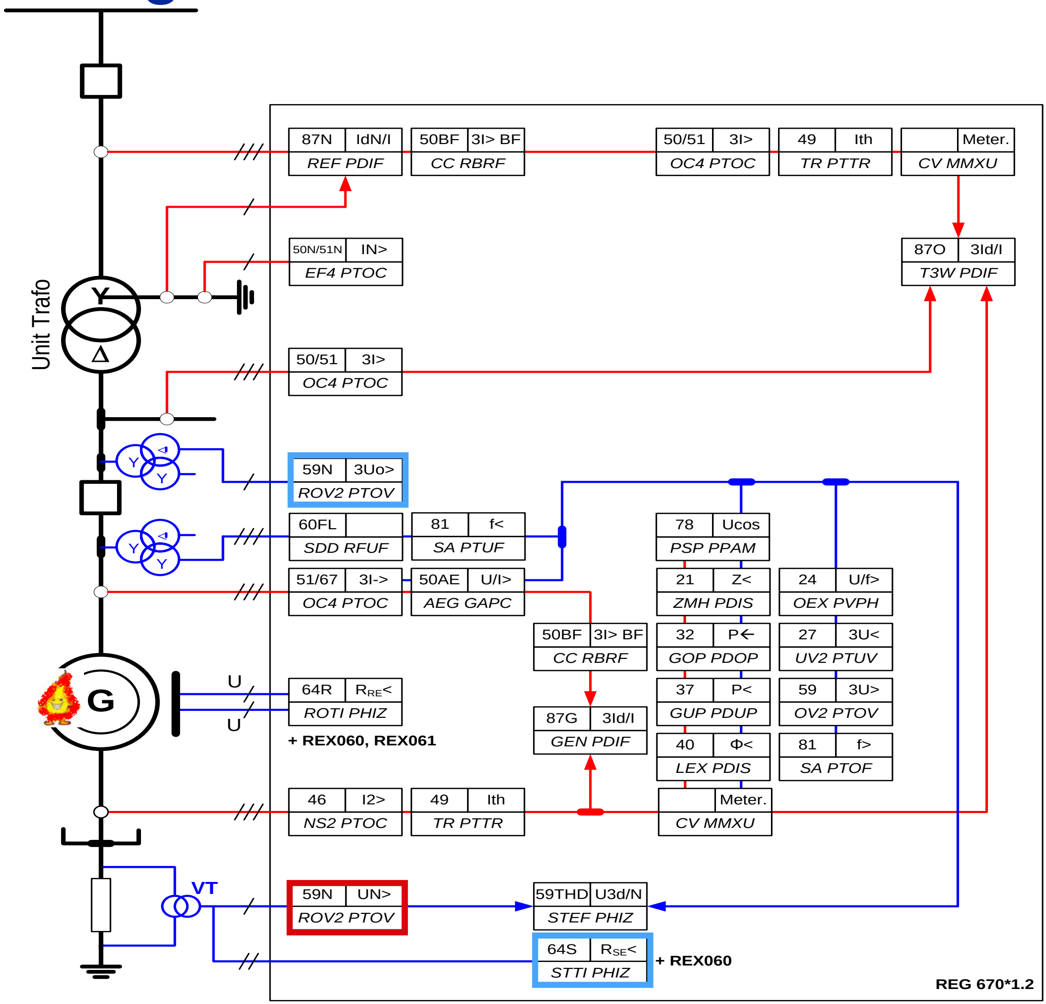


Earth fault in the stator winding

- Endangering condition
  - Overvoltage in two healthy phases
  - Voltage in the star point
  - Relatively small earth fault current
- Protected object
  - Stator winding
- Consequences
  - Damage to the stator core
  - Risk of second earth fault

Main Protection Function

Reserve Protection Function

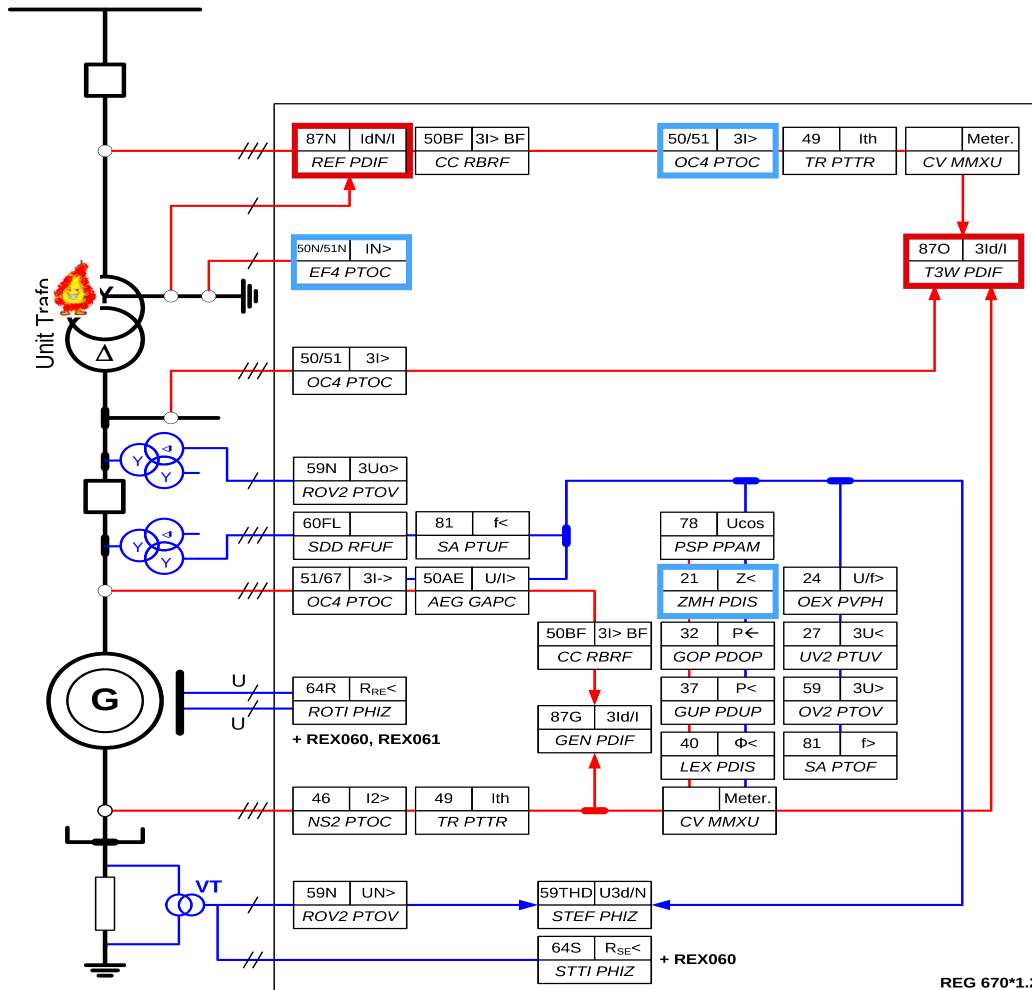


Earth fault in transformer HV winding

- Endangering condition
  - Overcurrent
- Protected object
  - Transformer windings
- Consequences
  - Heating
  - Forces
  - Smelted trafo core

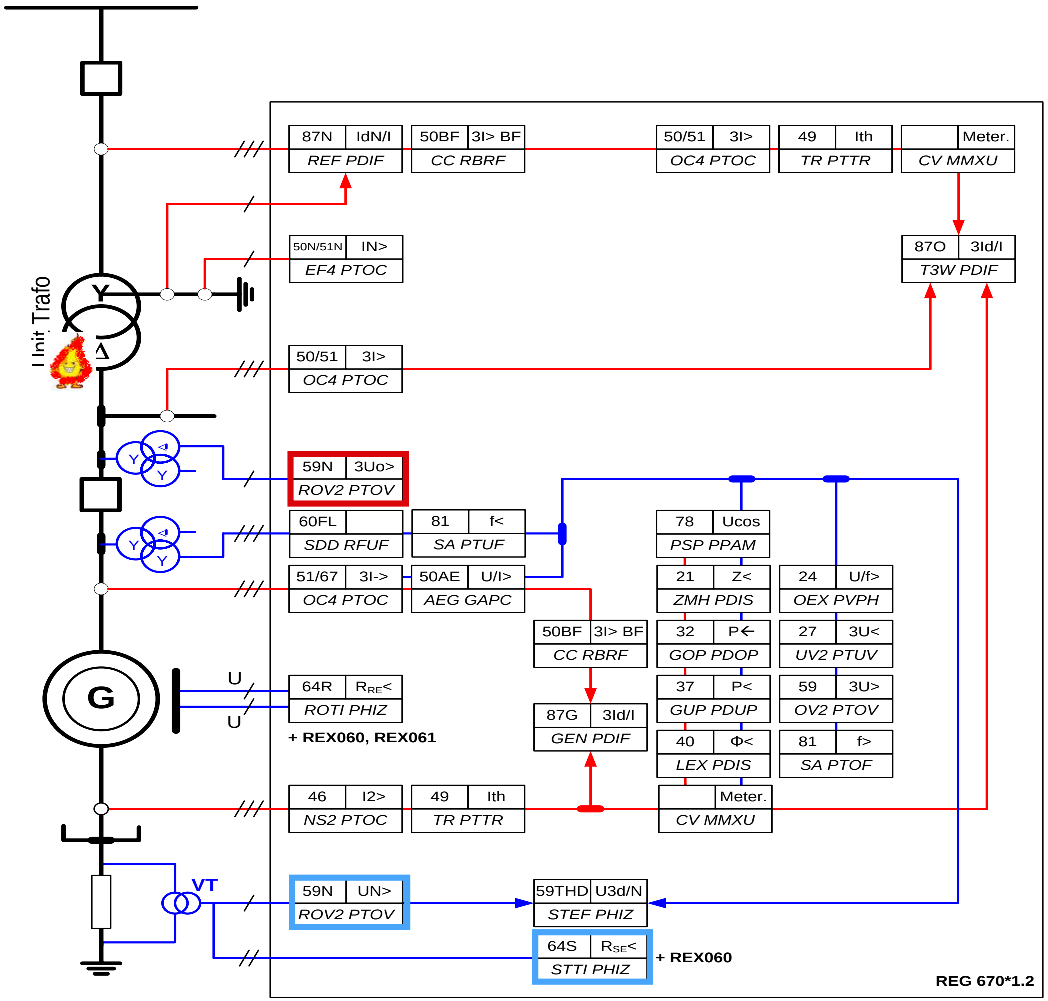
Main Protection Function

Reserve Protection Function



Earth fault in transformer LV winding

- Endangering condition
  - Overvoltage in two healthy phases
  - Voltage in the star point
  - Relatively small earth fault current
- Protected object
  - Transformer winding
- Consequences
  - Small possibility to damage trafo core
  - Risk of second earth fault



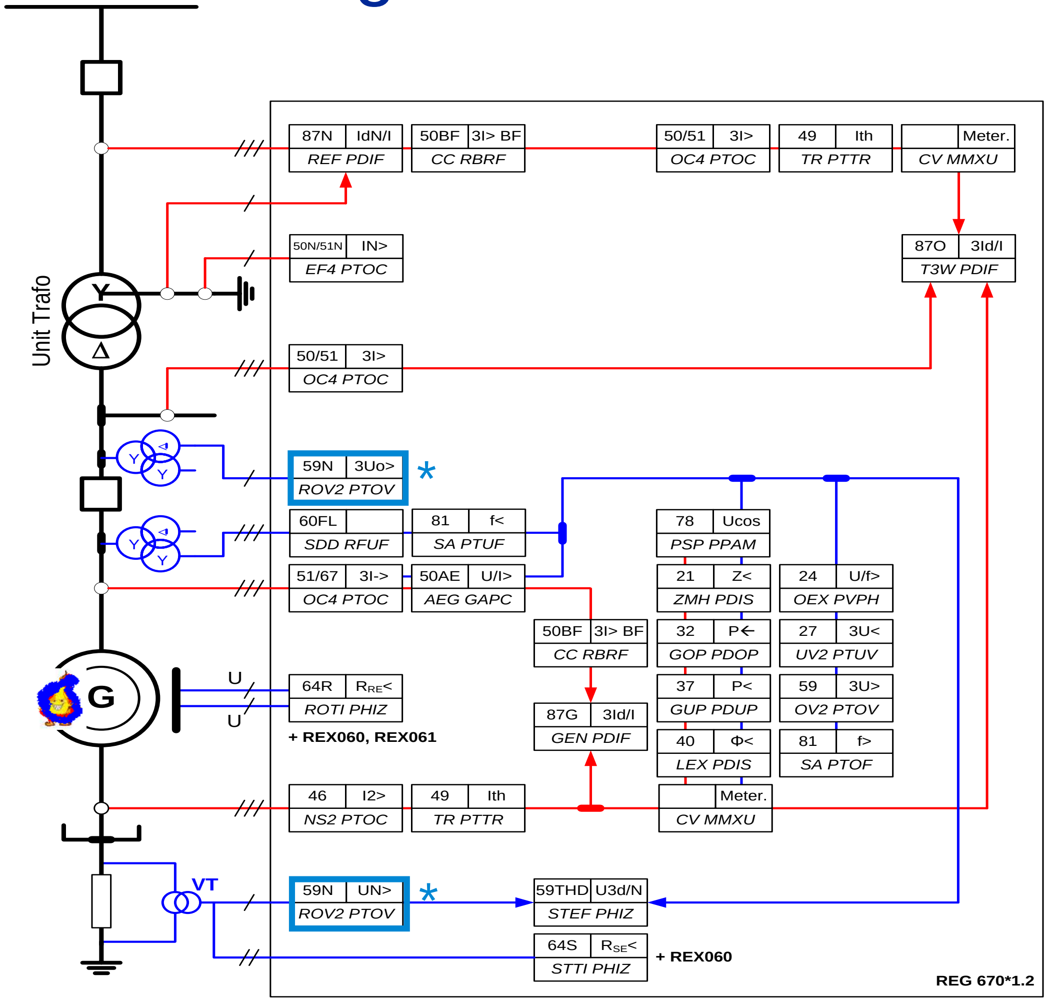
Main Protection Function

Reserve Protection Function

Turn to turn fault in the stator winding

- Endangering condition
  - Circulating currents
  - Asymmetrical phase currents
- Protected object
  - Stator winding
- Consequences
  - Damage to the stator core
  - Risk of evolving into earth fault

*** 59N will detect this fault when develops into an earth fault**



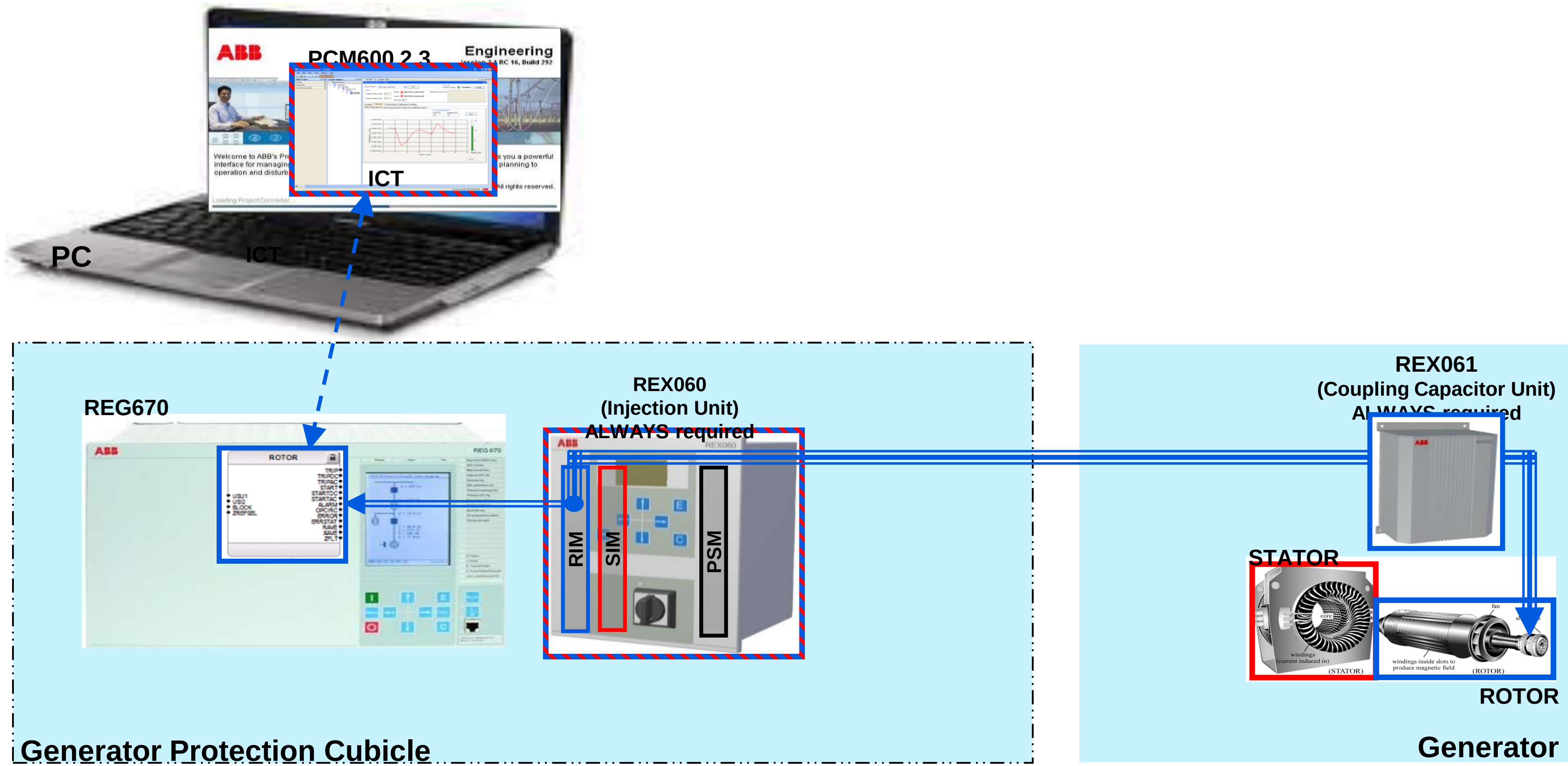
Main Protection Function

Reserve Protection Function

Rotor earth fault

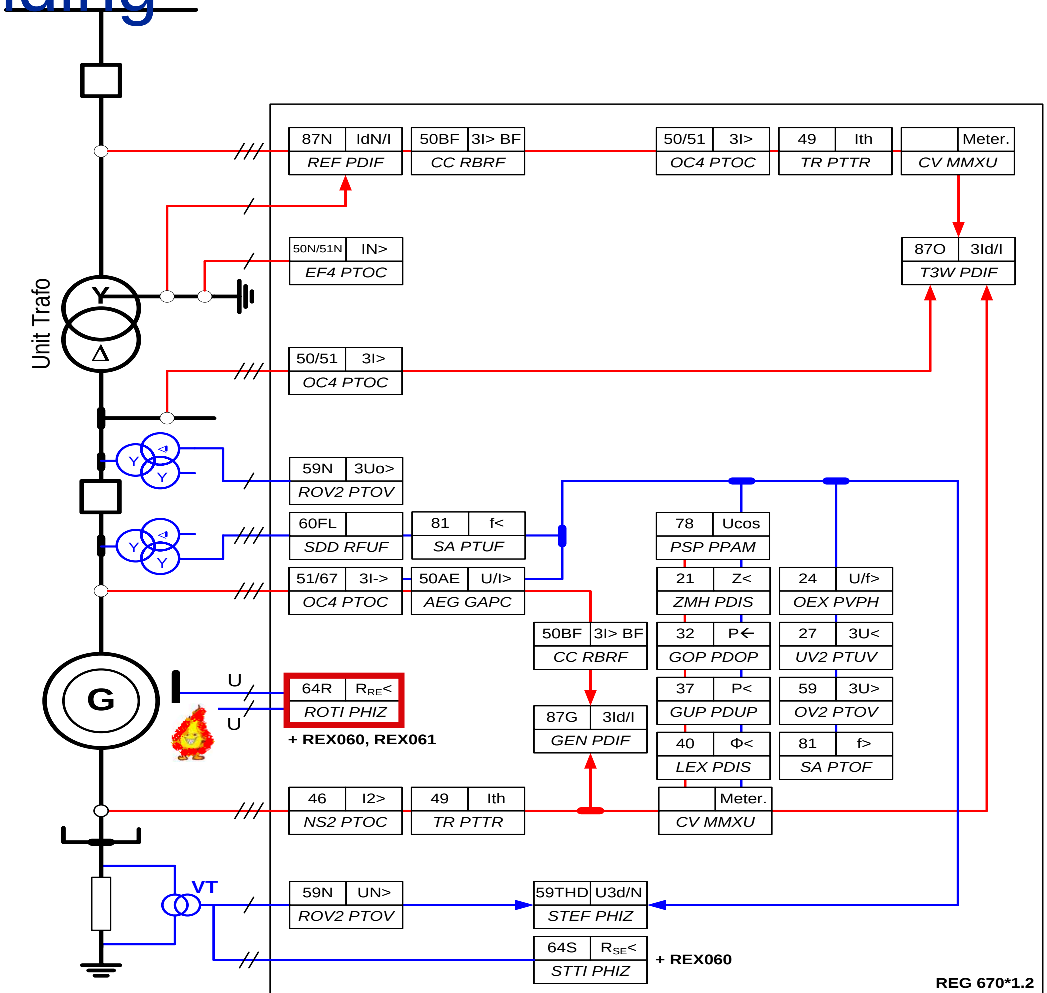
- The field circuit of the generator is normally isolated from earth
- With a single earth fault in the rotor circuit it is possible to have continuous operation without generator damages
- There however creates an increased risk of a second rotor earth fault. In such a case there will be large current and risk of severe damages.
- Major damages ensue following a second ground fault
- The requirement of fast fault clearance is moderate

Rotor injection



Earth fault in the rotor winding

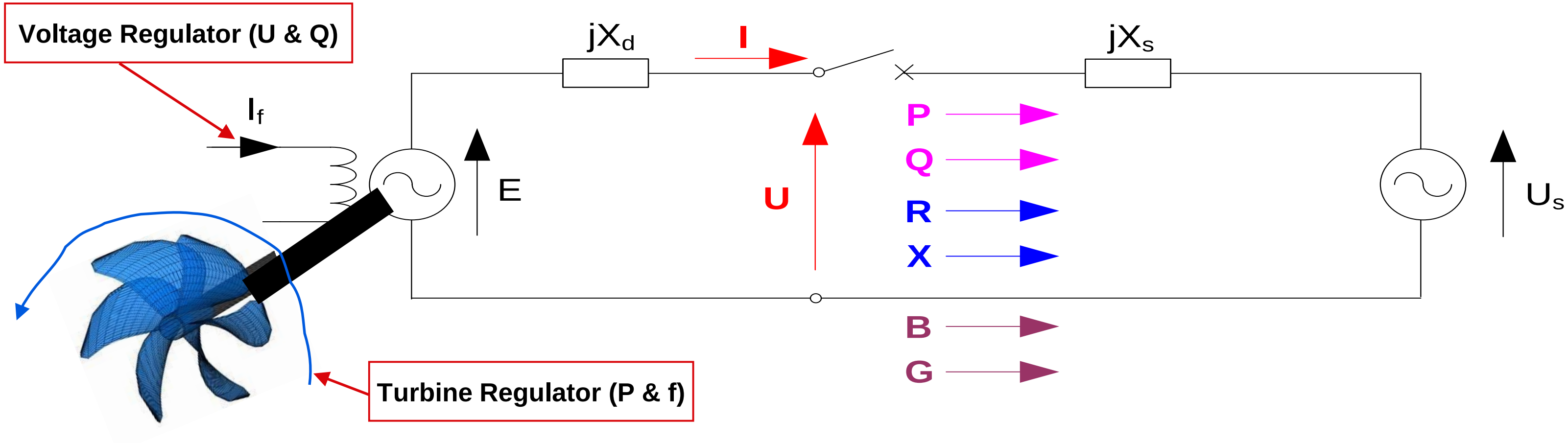
- Endangering condition
  - None
- Protected object
  - Rotor winding
- Consequences
  - Risk of evolving into double earth fault



Main Protection Function

Reserve Protection Function

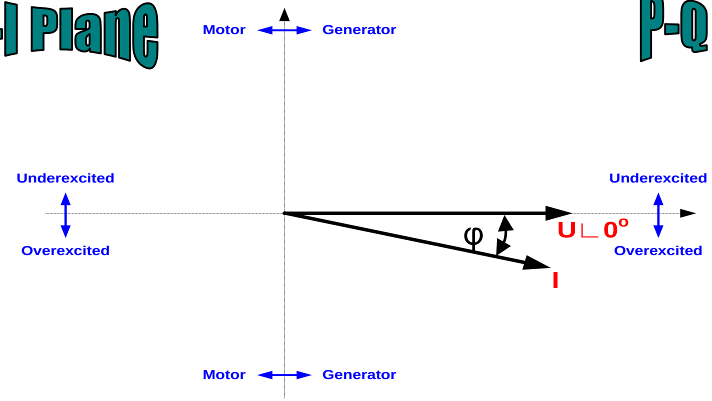
Performance of synchronous machine



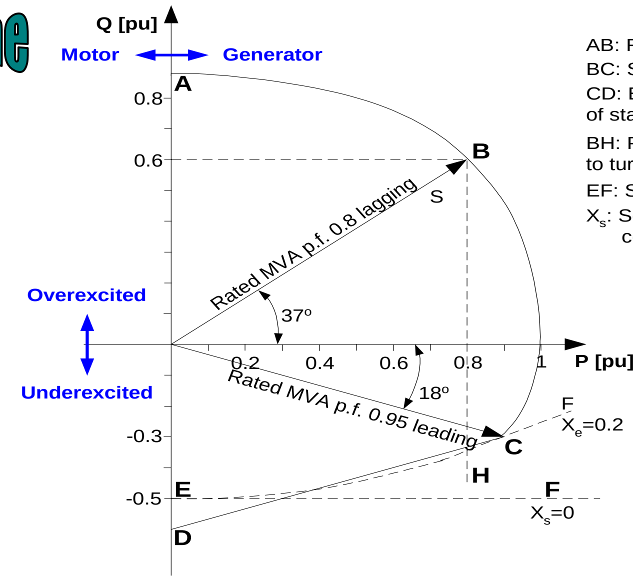
- Synchronous machine operating in a parallel with a large power system can:
  - supply active power to the system (operates as generator)
  - receive active power from the system (operates as motor)
  - supply reactive power to the system (overexcited machine; operates as shunt capacitor)
  - receive reactive power from the system (underexcited machine; operates as shunt reactor)
  - Note: machine shall have fixed rotating speed at all times

Different protection operating planes

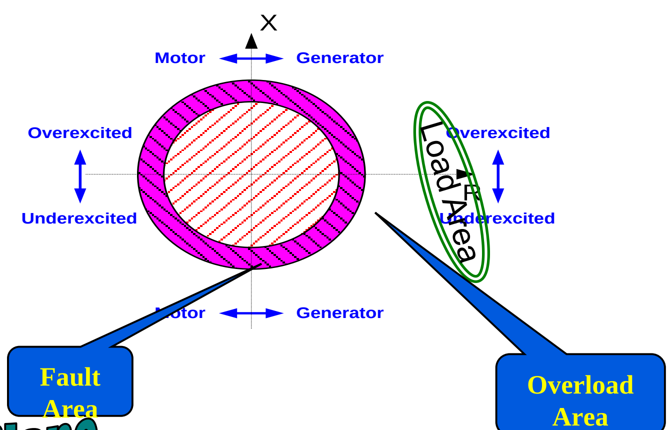
U-I Plane



P-Q Plane



AB: Field current limit
BC: Stator current limit
CD: End region heating limit of stator, due to leakage flux
BH: Possible active power limit due to turbine output power limitation
EF: Steady-state limit without AVR
X_s: Source impedance of connected power system



R-X Plane

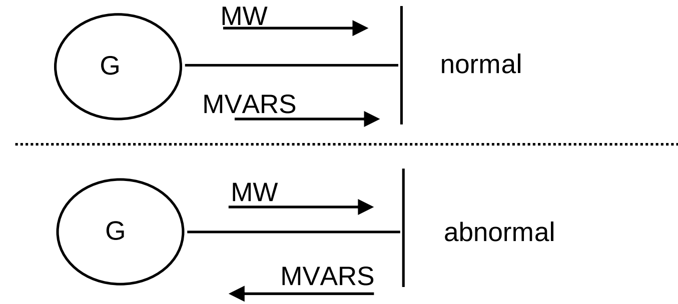
Loss of/under excitation 40

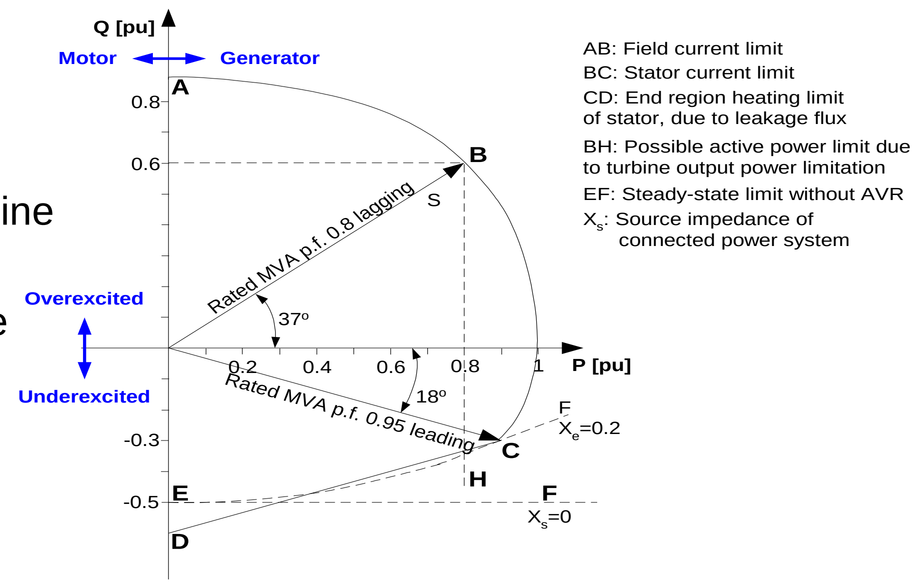
Causes

- open field circuit
- field short circuit
- accidental tripping of the field breaker
- AVR failure
- loss of field at the main exciter

Consequence

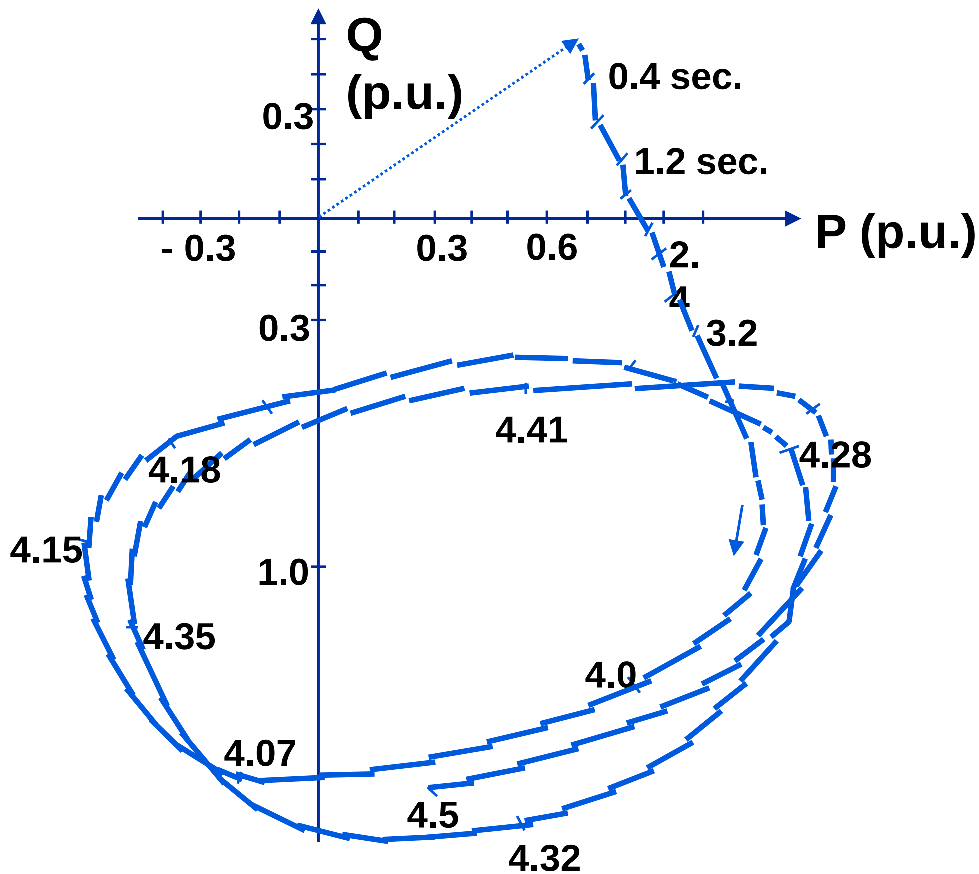
- Asynchronous running of a synchronous machine **without excitation** – induction generator
- Start drawing reactive power - voltage collapse
- Stator end-core heating
- Induced rotor currents





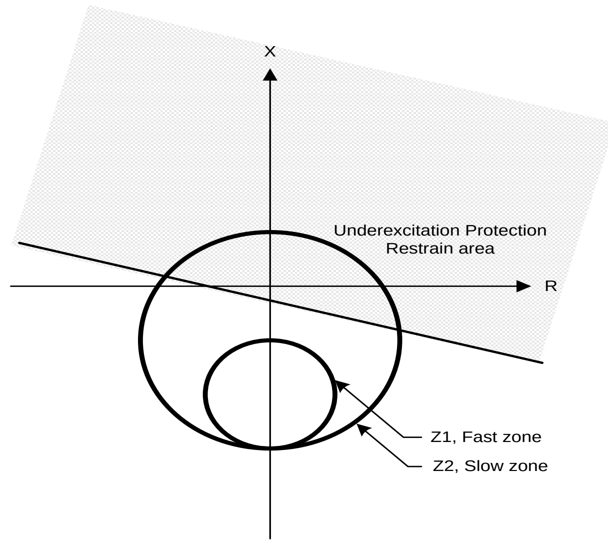
Loss of/under excitation 40

Generator apparent power S during loss of excitation

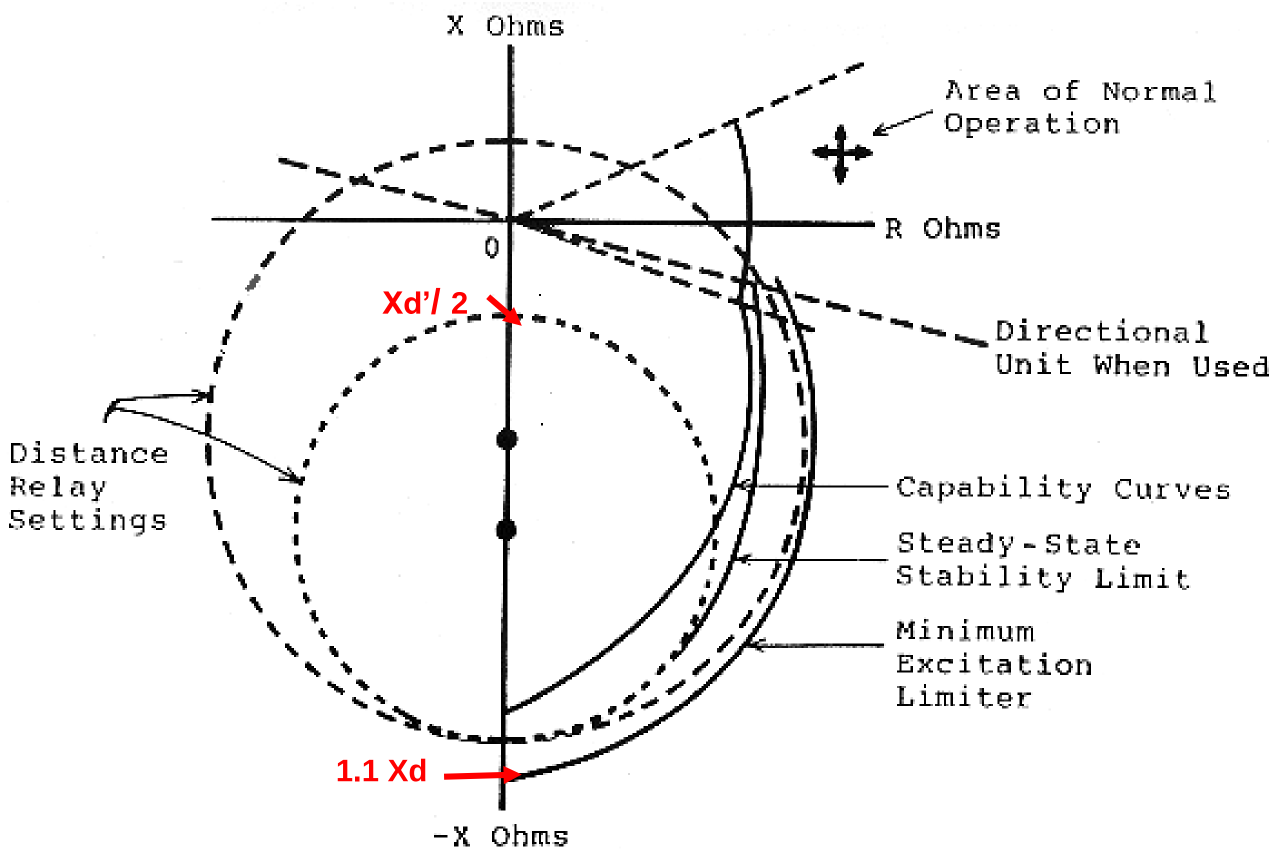


Loss of/under excitation 40

- Loss of/under excitation is based on under-impedance measurement (offset Mho)
- Main features:
  - Two zones Z1 and Z2, with independent block and trip
  - Directional element for additional zone restriction (eg. under-exiting operation)



Loss of Excitation Protection

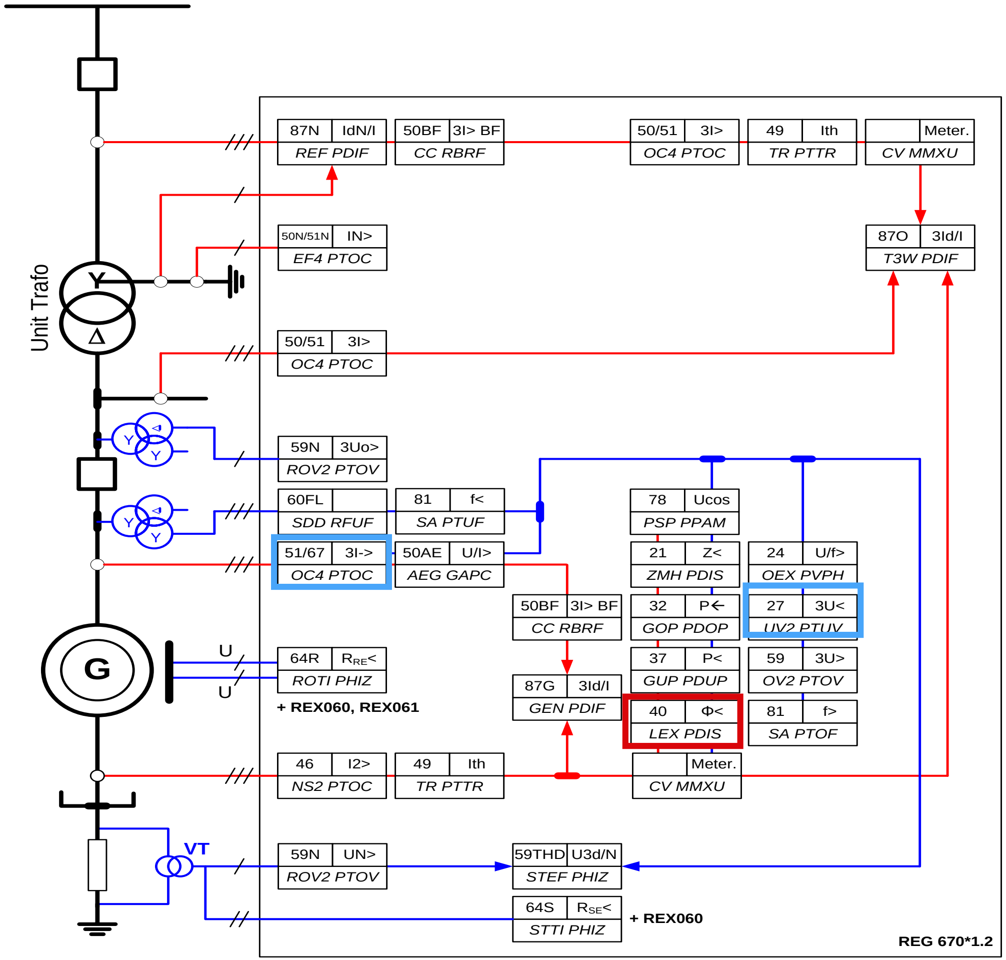


Loss of/Under excitation 40

- Endangering condition
  - Stator reactive current component
- Protected object
  - Rotor and stator winding
- Consequences
  - Thermal damage of rotor and stator end regions
  - Asynchronous machine operation
  - Voltage and current variations

Main Protection Function

Reserve Protection Function



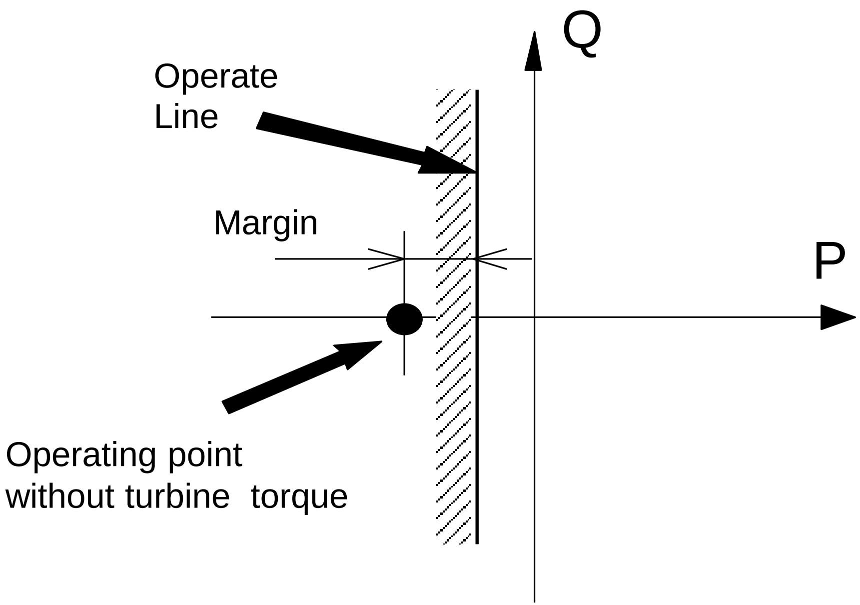
Generator motoring protection 32/37

- Generator shall produce active power (i.e. P>0)
- When it starts to receive the active power it acts as a motor (i.e. P<0)
- Not dangerous operating condition for machine but it may be dangerous for the turbine

Generator motoring protection 32/37

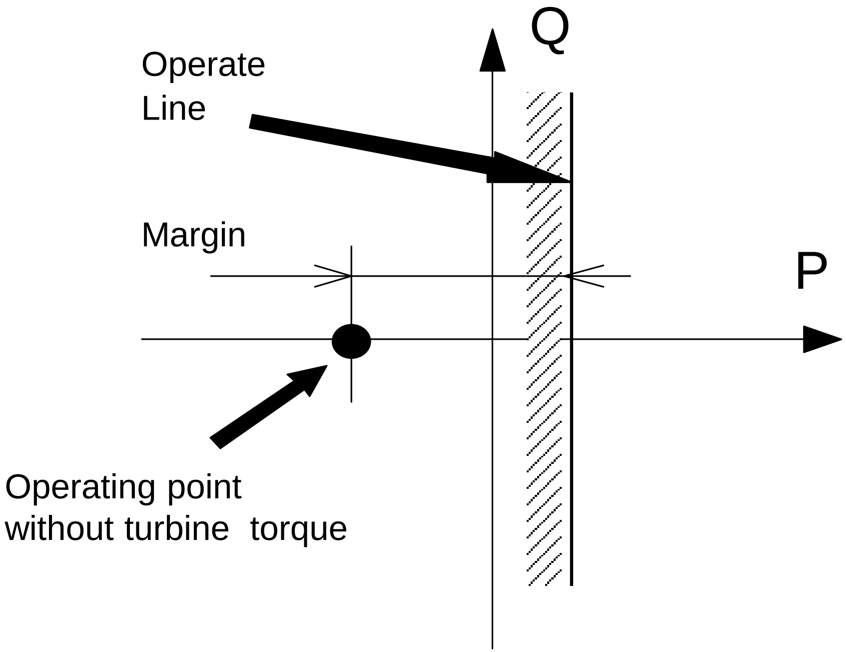
- Causes
  - loss of prime-mover
  - low water flow (hydro)
  - load variations / problems
- Effects
  - steam units → overheating of turbine and turbine blades
  - hydro units → cavitation of the blades
- Demands
  - accurate active power measurement (i.e. P~0 & Q=30-60%)

Reverse power protection



- Set desired pickup (0,5 to 3%)
- Set time delay 5-30 s
- Sequential tripping logic

Low forward power protection



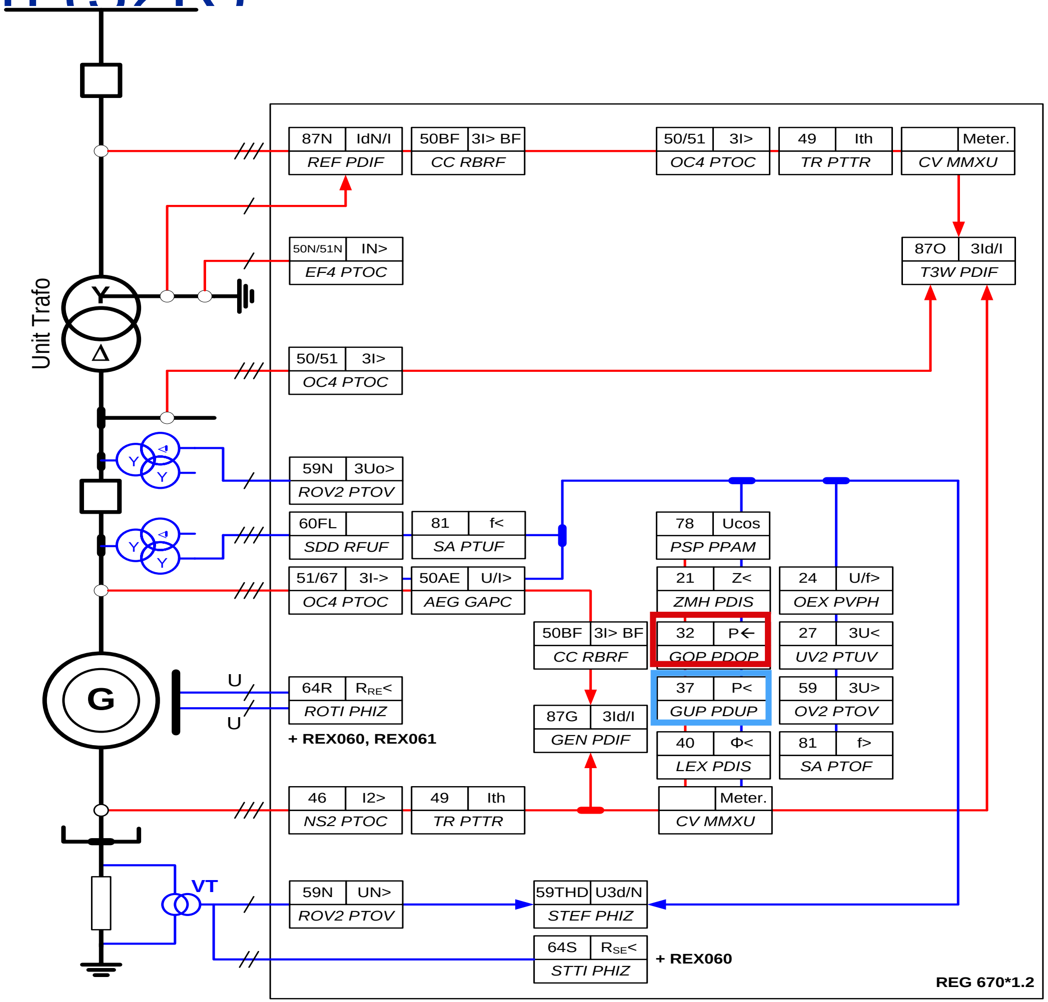
- Set desired pickup (1 to 10%)
- Set time delay 5-30 s
- Sequential tripping logic
- Blocked by external signal when generator is not loaded

Reverse Power Protection (32R)

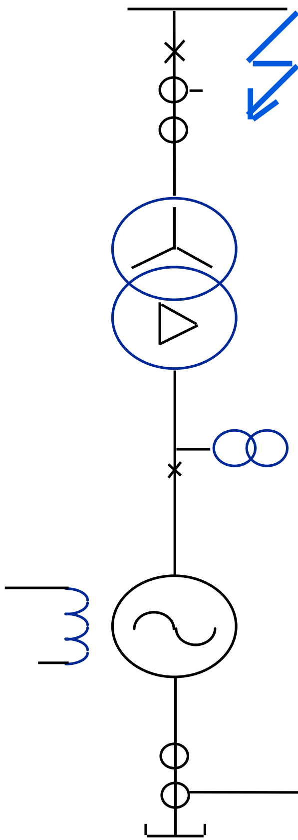
- Endangering condition
  - Motor operation
- Protected object
  - Turbine
- Consequences
  - Excessive heating of turbine blades (steam units)
  - Mechanical damages to thrust bearing (Francis turbines)
  - Explosion risk for diesel units

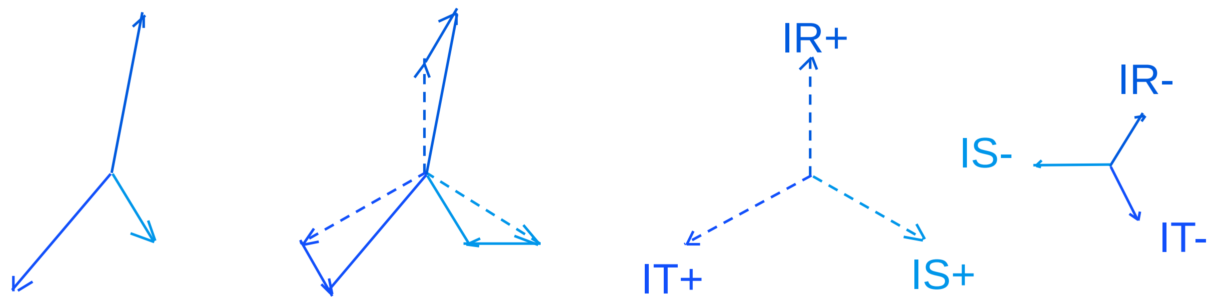
Main Protection Function

Reserve Protection Function



Negative sequence overcurrent (46)





From asymmetric currents, a negative sequence current component I_2, is filtered out.

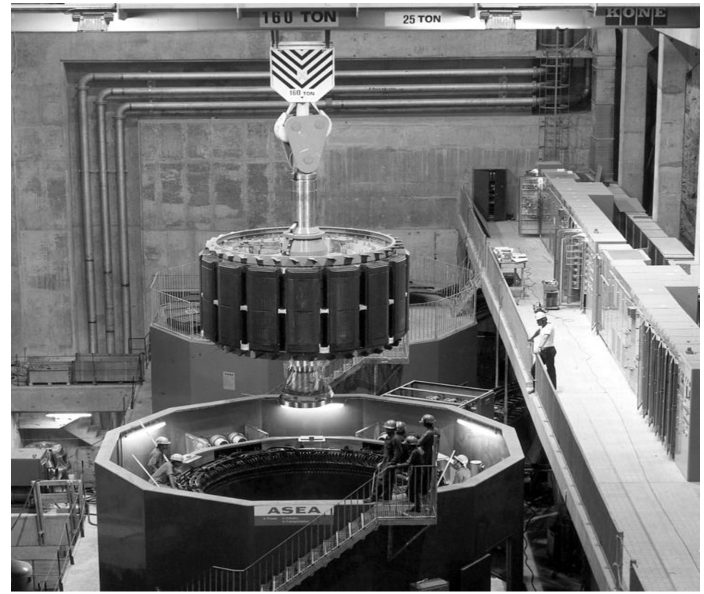
Negative sequence stator currents rotate in a opposite direction from the rotor and consequently induce a 120Hz current component into the rotor. As a consequence rotor ends can over-heat.

$$\mathbf{I_2^2 \times t = k}$$

Negative phase sequence (46)

Causes

- unbalanced loads
- untransposed transmission circuits
- unbalanced system faults
- series faults
- CB pole discrepancy
- open circuits



Features

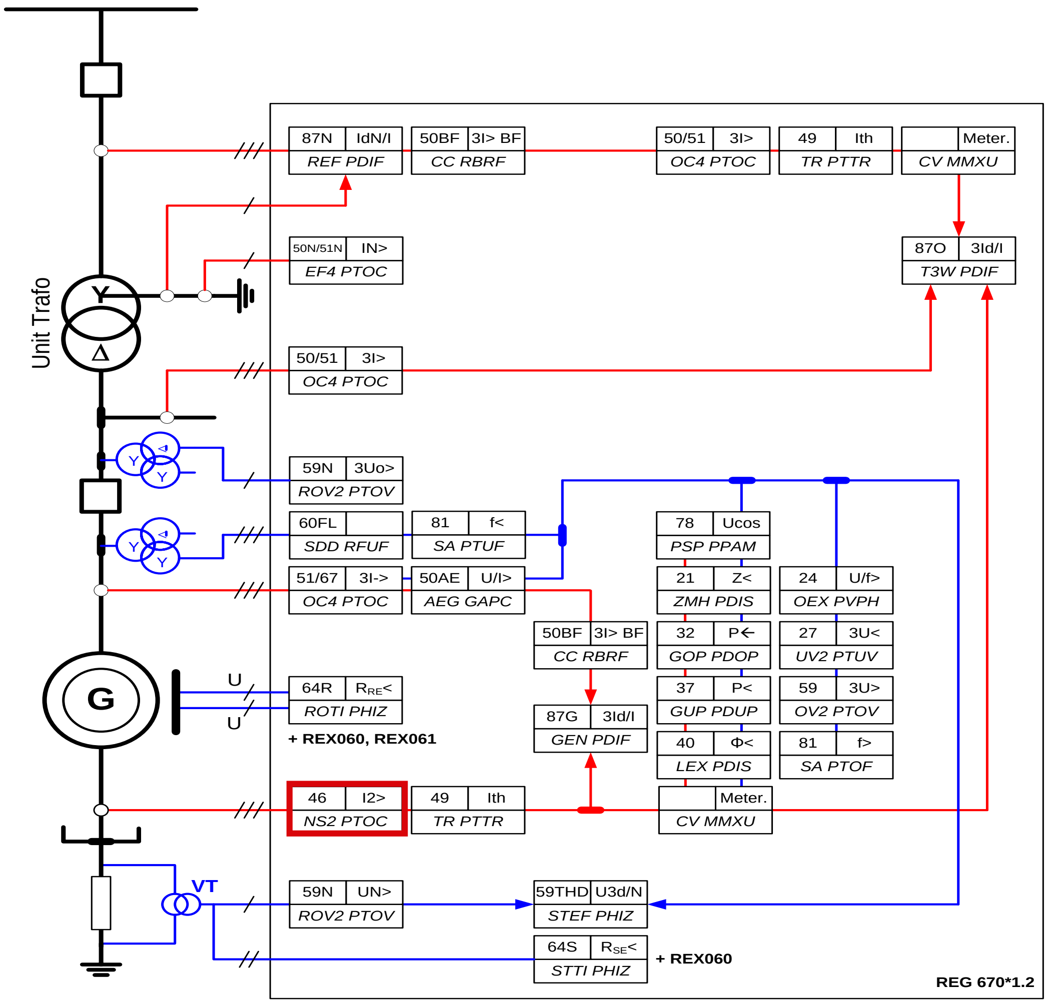
- Characteristic adjustable to $I_2^2\,t=k$

Broken stator winding

- Endangering condition
  - Unsymmetrical currents
- Protected object
  - Stator windings
  - Rotor
- Consequences
  - Rotor overheating
  - Vibrations

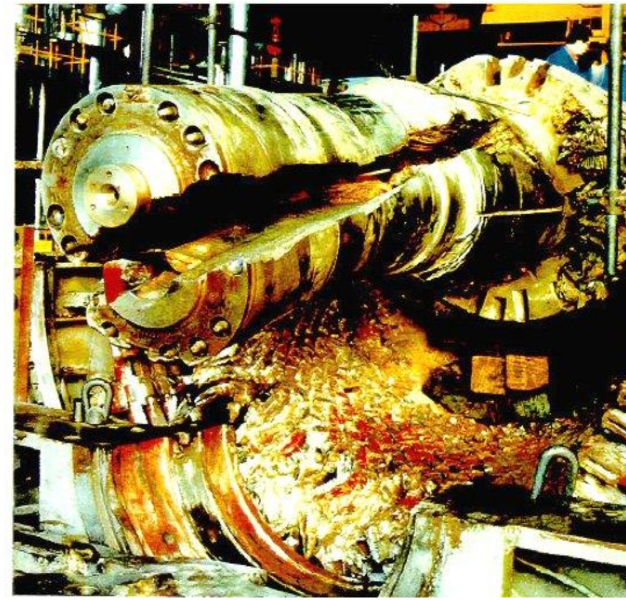
Main Protection Function

Reserve Protection Function

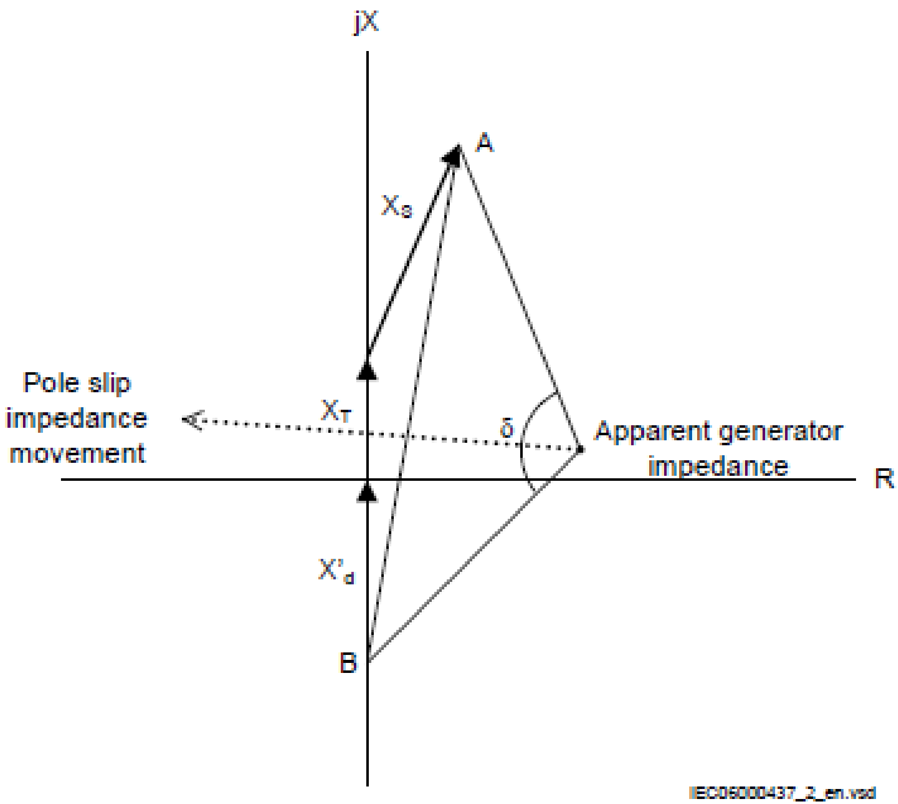


Pole slip / out of step protection (78)

- Asynchronous running of a synchronous machine with the rest of the system but **with excitation intact (opposed to loss of Field)**
- Characterized by power (P & Q) oscillation
- Manifests as impedance movement in R & X plane
- Big mechanical impact on turbine and shaft
- Pole Slip typically caused by:
  - Long fault clearance time (especially close by 3Ph faults are critical)
  - Inadvertent tripping of a transmission line (increase of transmission impedance between generator and load)
  - Loss of large generator unit



Pole slip / out of step protection (78)

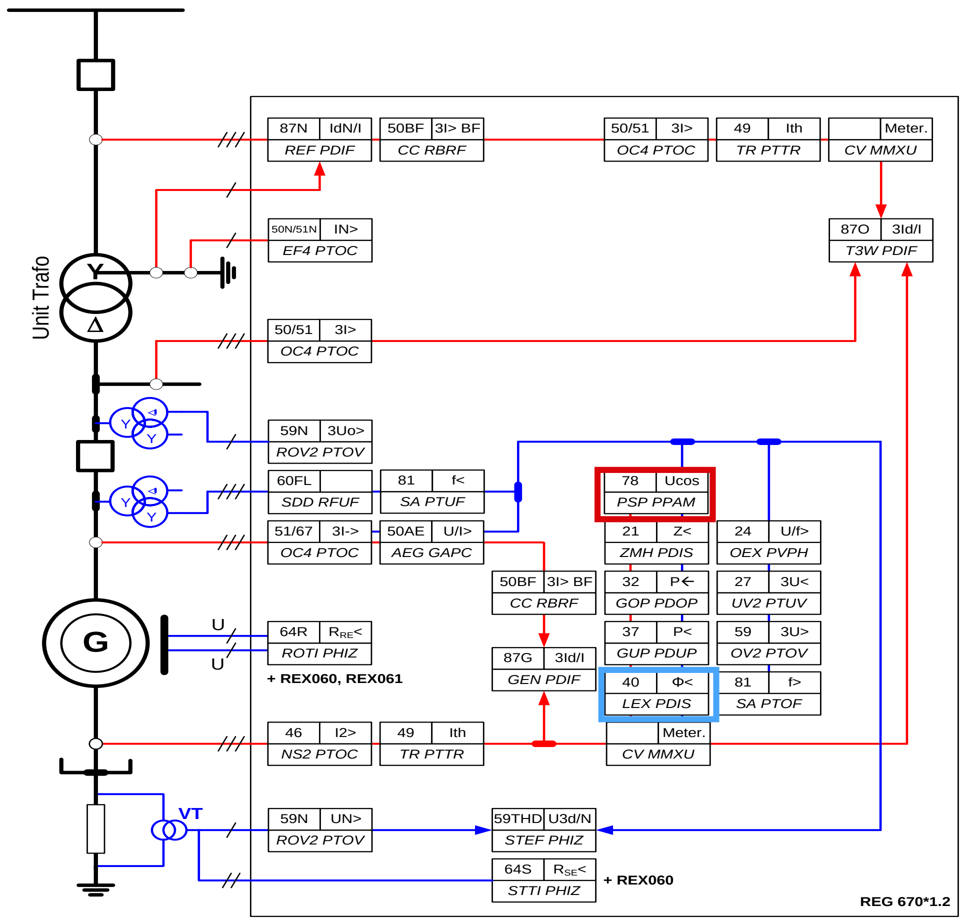


Pole slip / out of step protection (78)

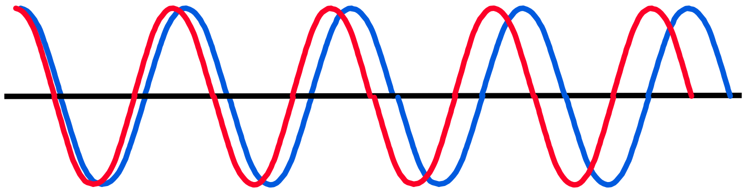
- Endangering condition
  - High stator current
  - Possible system blackout
- Protected object
  - Rotor shaft and stator winding
- Consequences
  - Mechanical damages to shaft
  - Asynchronous machine operation (with field intact)
  - Voltage and current variations

Main Protection Function

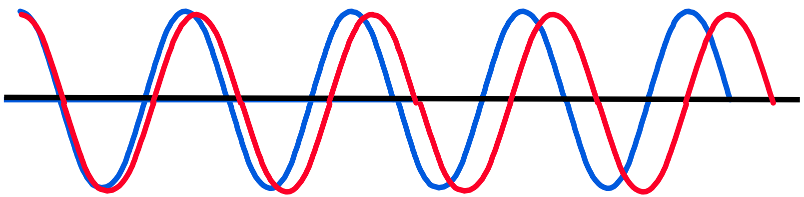
Reserve Protection Function



Frequency protection (81U/O)



- Over-frequency 81O: protects in case of turbine over-speed



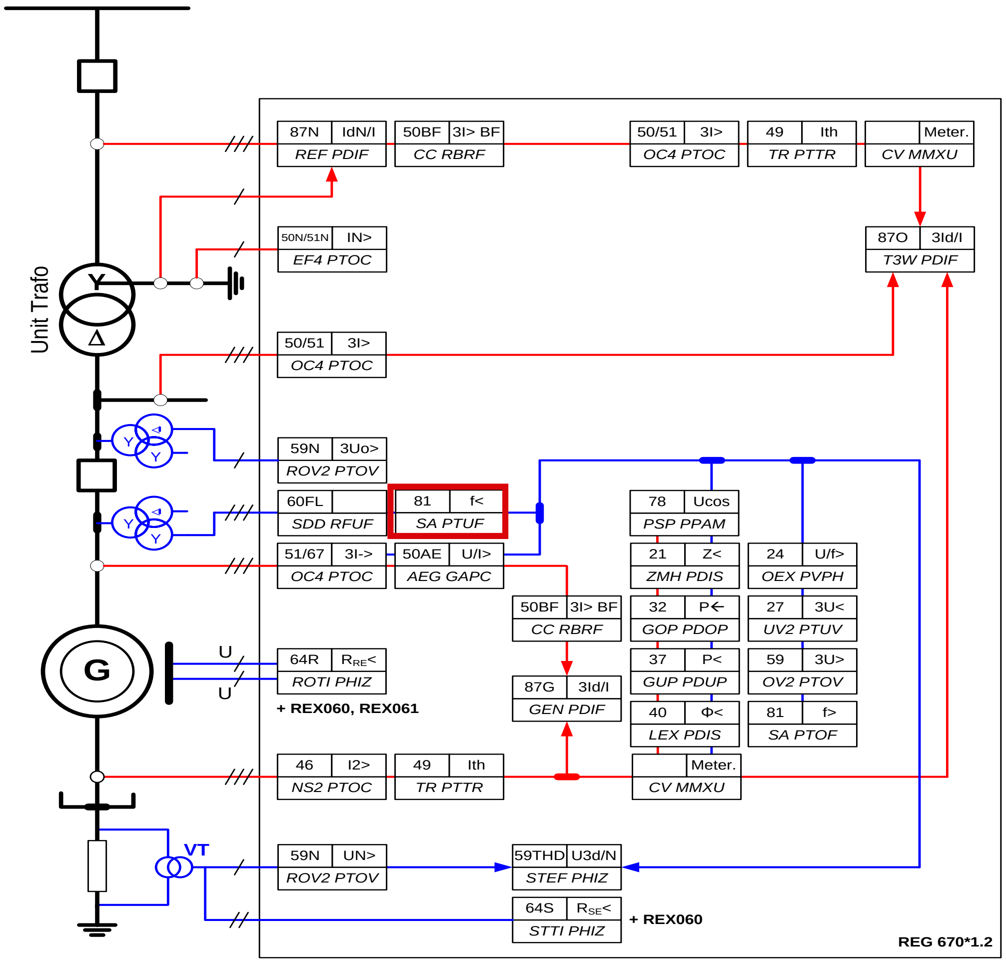
- Under-frequency 81U: protection of the steam turbine at the "critical speed"

Low network frequency (81U)

- Endangering condition
  - Under-frequency
- Protected object
  - Transformer
  - Steam turbine
- Consequences
  - Over-excitation
  - Steam turbine vibrations

Main Protection Function

Reserve Protection Function

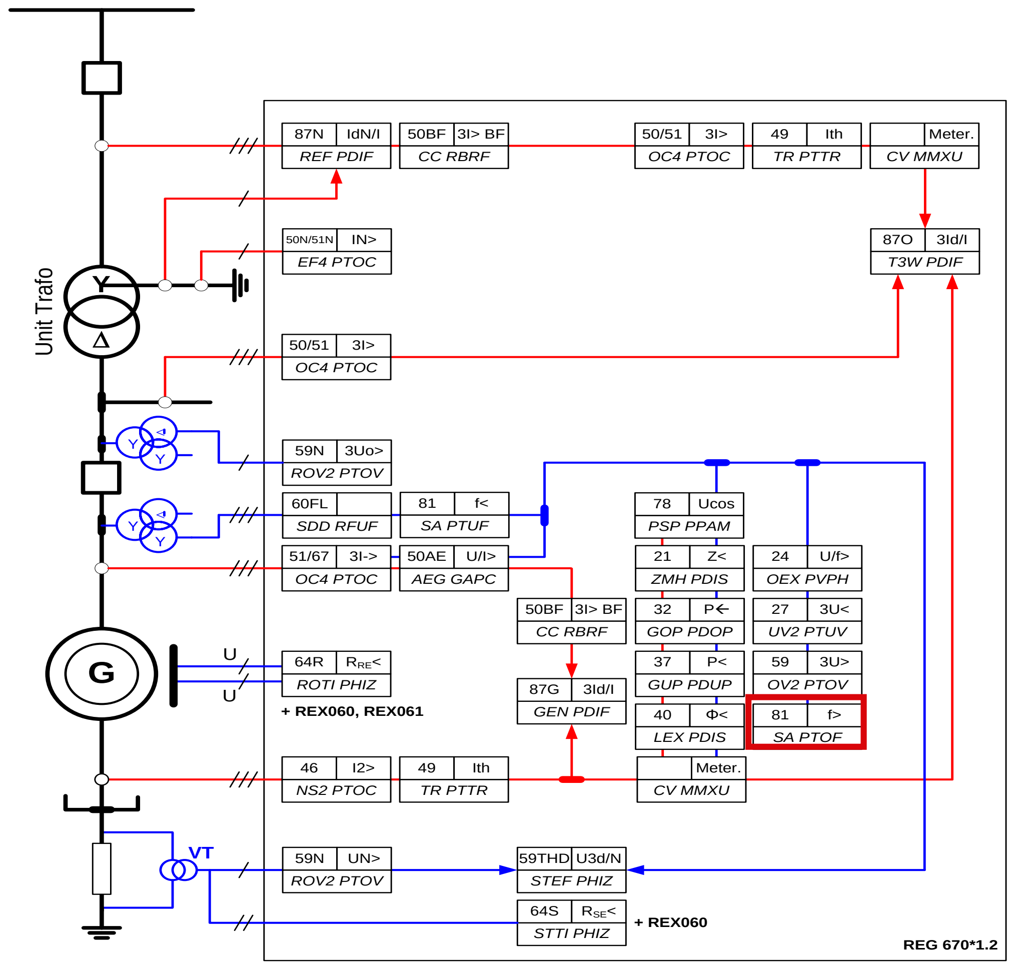


High Network Frequency (81O)

- Endangering condition
  - Over-frequency
- Protected object
  - Turbine
  - Rotor
- Consequences
  - Mechanical stresses
  - Turbine vibrations

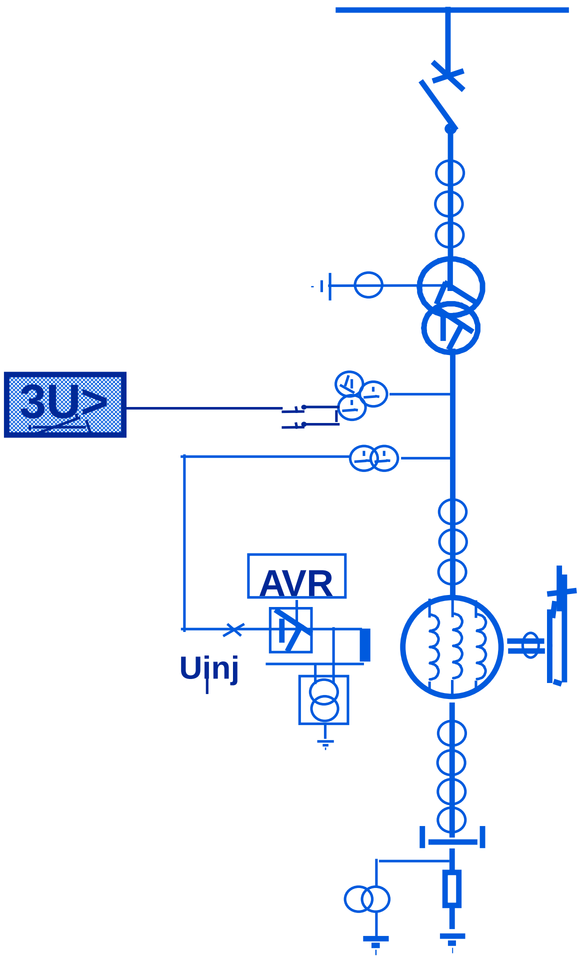
Main Protection Function

Reserve Protection Function



Over-voltage protection, 59

- With faulty AVR overvoltage can cause over excitation of the generator-transformer block
- V can sharply increase after load rejection followed by machine runaway

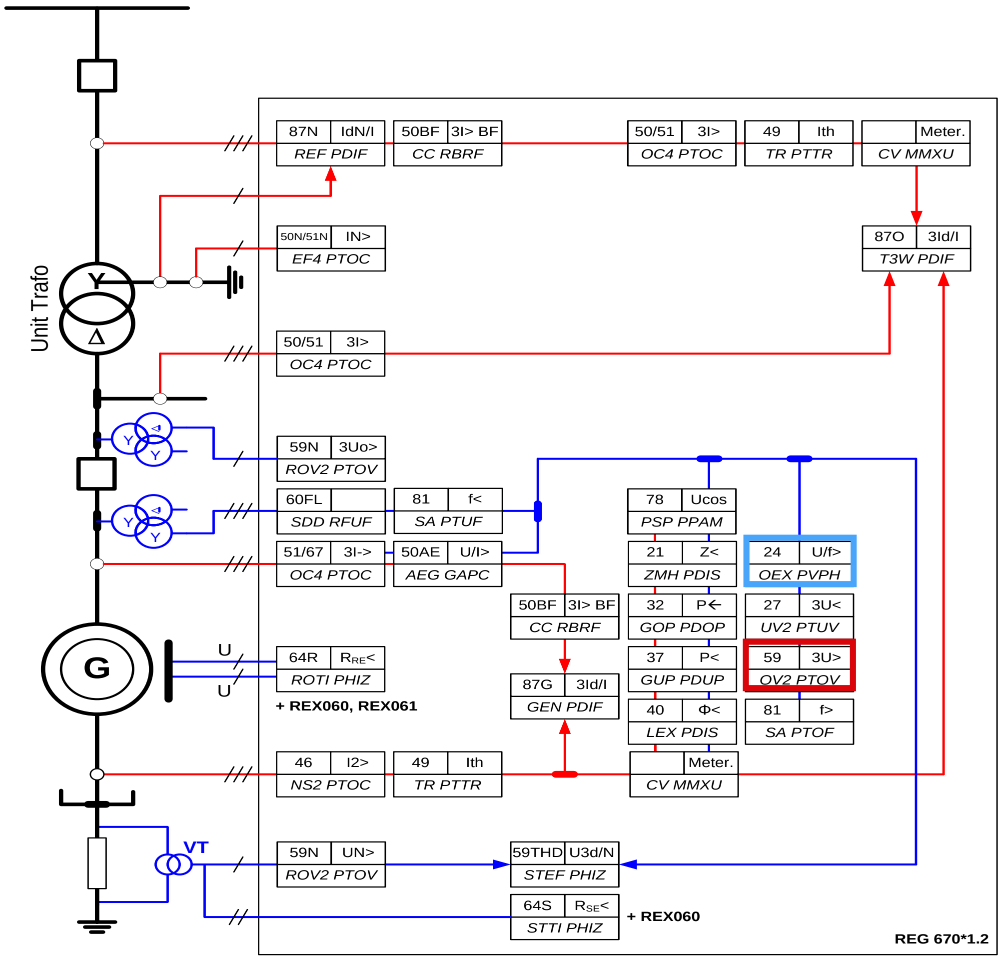


Over-voltage protection (59)

- Endangering condition
  - Over-voltage
  - Improper voltage regulation
- Protected object
  - Electrical circuits
- Consequences
  - Increased risk for earth-faults
  - Over-excitation

Main Protection Function

Reserve Protection Function



Over-fluxing (excessive V/Hz), 24

$$\Phi \; or B = const \cdot \frac{E}{f} \approx const \cdot \frac{U}{f}$$

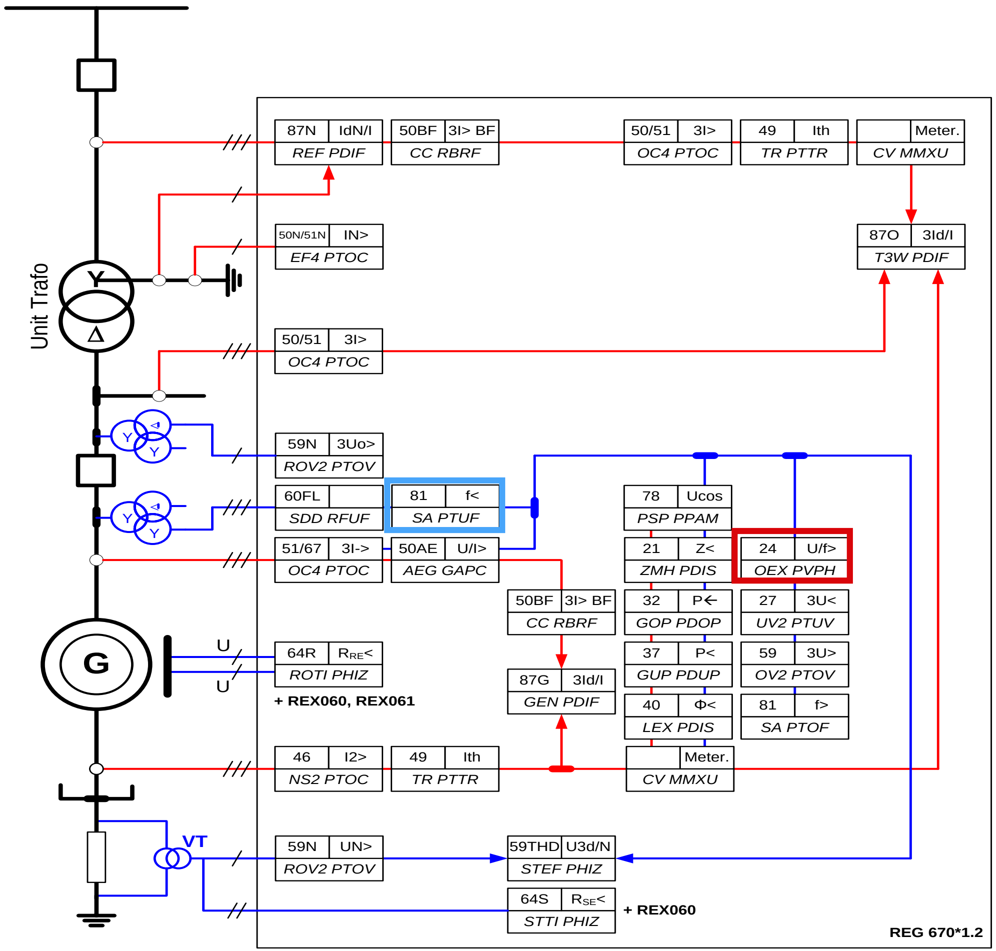
- Overfluxing protects generator and transformer magnetic core against overheating
- Specially critical during start-up and shut-down
- Wide frequency operation of the relay important for generator protection

Incorrect turbine control (24, 81O/U)

- Endangering condition
  - Under-frequency
- Protected object
  - Transformer
- Consequences
  - Over-excitation

Main Protection Function

Reserve Protection Function

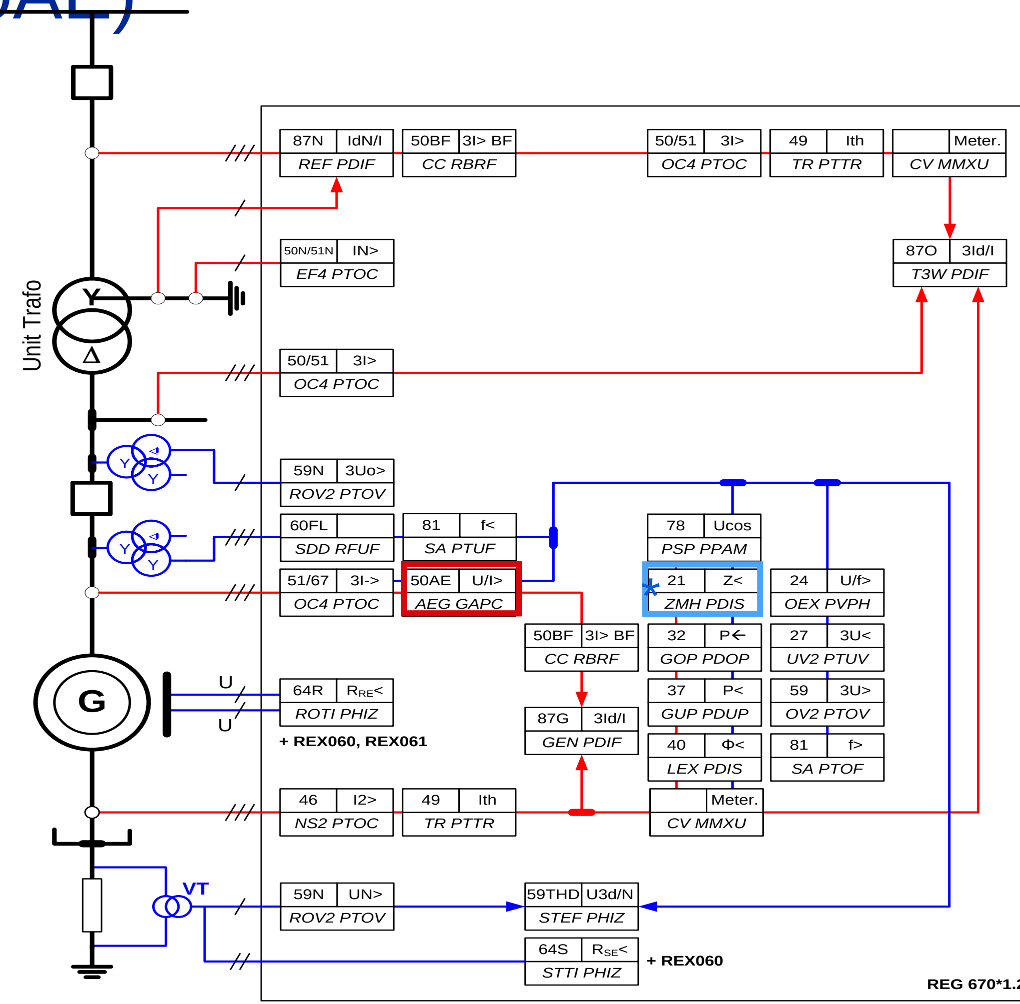


Accidental energizing, 50AE

- Operates when generator is energized while offline
- Behaved a induction motor
- Significant damages to rotor
- Operating errors, CB flash-over
- voltage controlled OC most commonly used

Accidental energizing (50AE)

- Endangering condition
  - Stator overcurrent or unsymmetrical currents
- Protected object
  - Bearings
  - Rotor
- Consequences
  - Bearing damages due to low oil pressure
  - Rotor overheating
  - Stator overheating



Main Protection Function

Reserve Protection Function

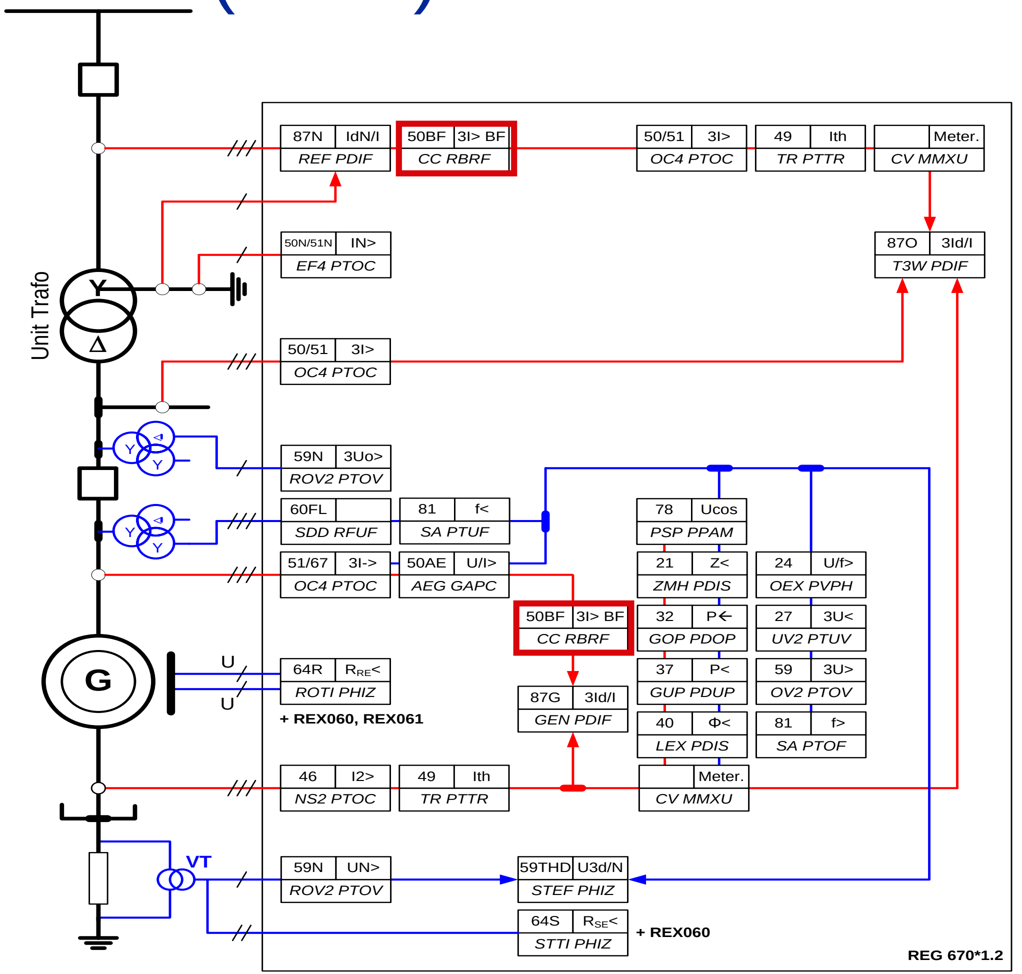
*** 3Z< is a delayed reserve protection**

Breaker-failure protection (50BF)

- Issues a back-up trip of adjacent breaker in case of failure of the circuit breaker of the protected object to open (i.e. to interrupt the primary circuit)
- Its operation in most cases trips only local breakers
- Commonly uses the bus bar protection disconnector replica logic to route its tripping command to adjacent breakers
- Re-trip (t1), Backup trip / bus-strip (t2), Second back-up trip timer (t3)
- Short reset time (15ms)
- Known CB faulty (bypass t2)
- Operating mode
  - Current / Contact / Current & Contact

Breaker fails to open the circuit (50BF)

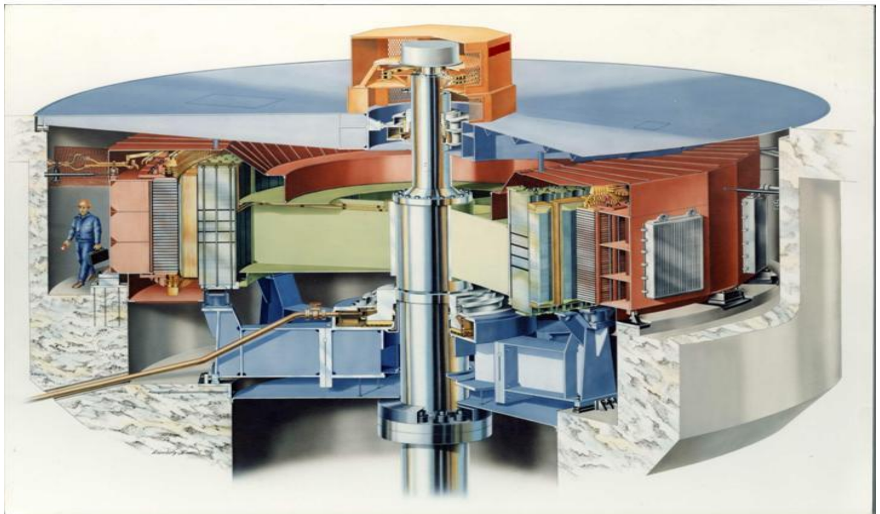
- Endangering condition
  - Stator overcurrent or unsymmetrical currents
- Protected object
  - Electrical circuits
  - Rotor
- Consequences
  - Rotor overheating
  - Stator overheating
  - Prolonged damages caused by the fault current



Main Protection Function

Reserve Protection Function

Conclusion



- Stator earth faults
- Rotor earth faults
- Stator short circuits
- Stator/rotor interturn faults
- External faults
- Abnormal operation

Thank you for your participation

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