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ABB Protective Relay School Webinar Series
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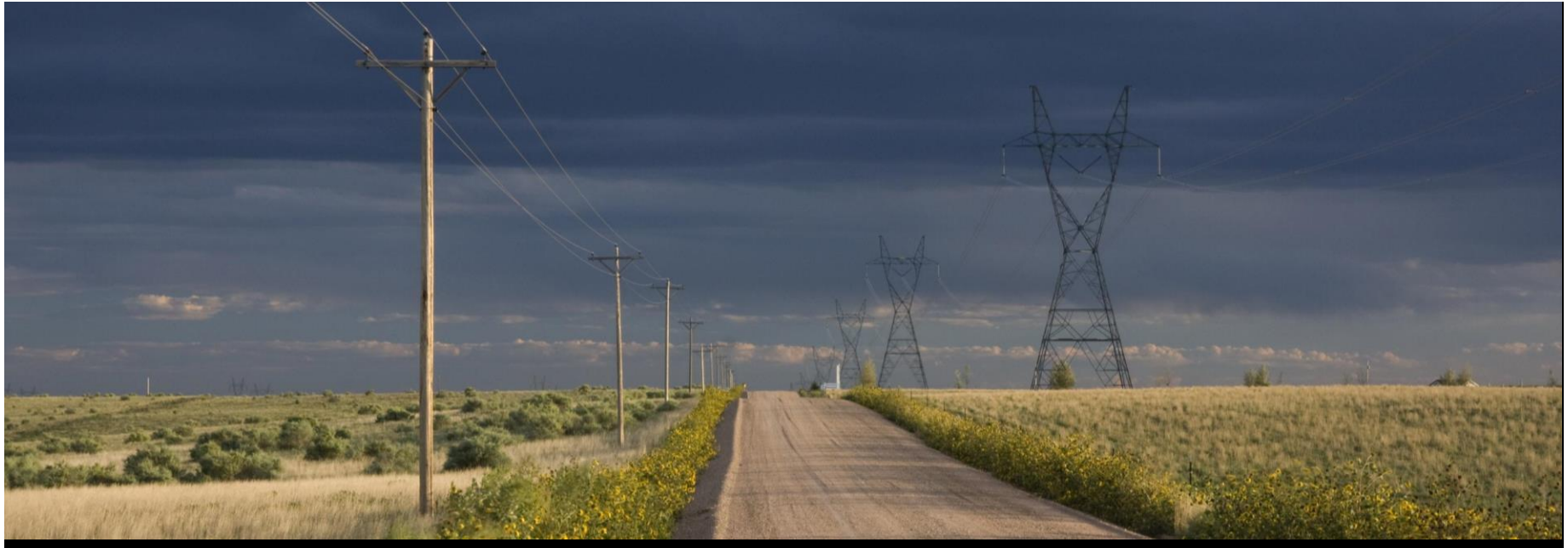


ABB Protective Relay School Webinar Series

Generator Protection Fundamentals

Jack Chang

June 18 , 2015

Presenter

Jack Chang

Jack Chang is the regional technical manager for ABB Inc. in the Substation Automation business serving customers in Canada and northern regions. He provides engineering, commissioning and troubleshooting support to customers applying ABB's high-voltage protective and automation devices. Prior to joining ABB, Jack worked as a substation P&C project engineer in two specialized consulting firms (now ABB and Quanta Services, respectively) and also as an engineering consultant to a public owned utility in their transmission expansion and upgrade projects. Jack is a registered professional engineer in the province of Alberta, Canada.

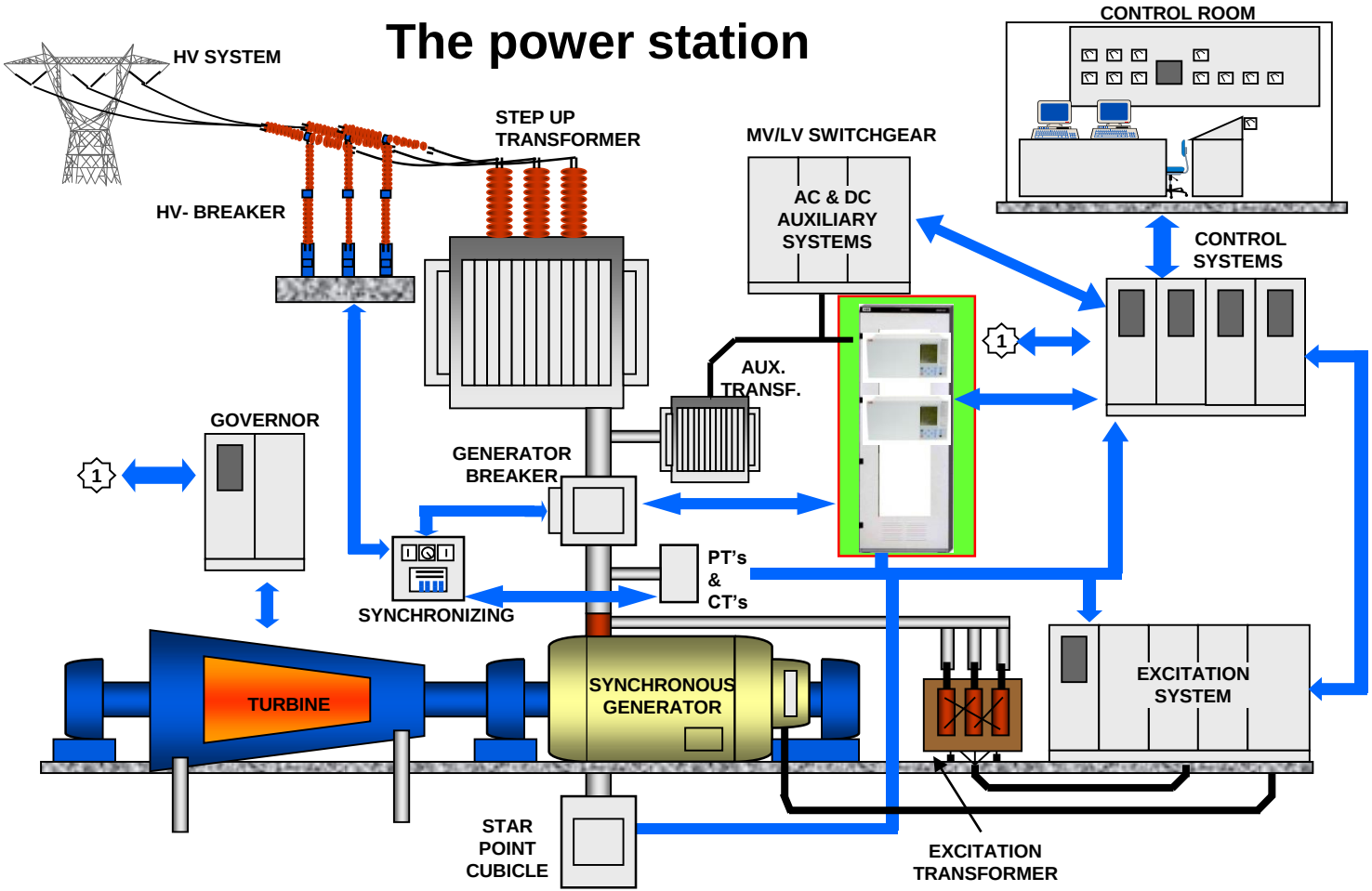
Learning objectives

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

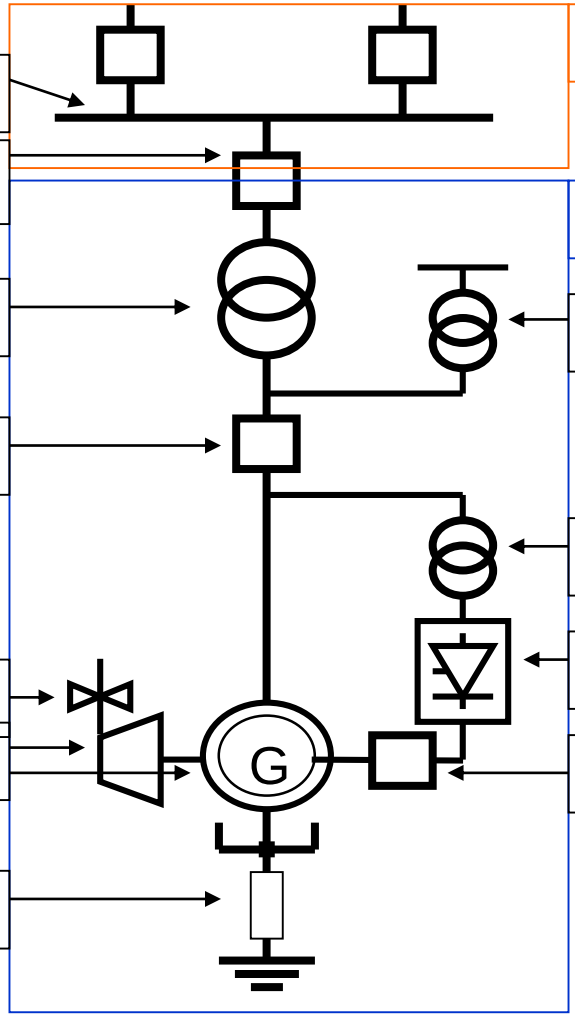
Standards

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

Typical Power Plant Components



Typical Parts of a Power Plant



Busbar in HV Substation

HV - Breaker

Main Transformer

Generator Breaker

Turbine valve

Turbine - Generator

Earthing System

HV Substation

Power plant

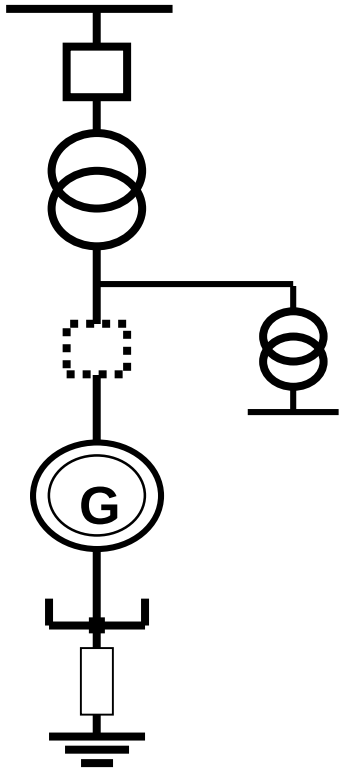
Auxiliary Transformer

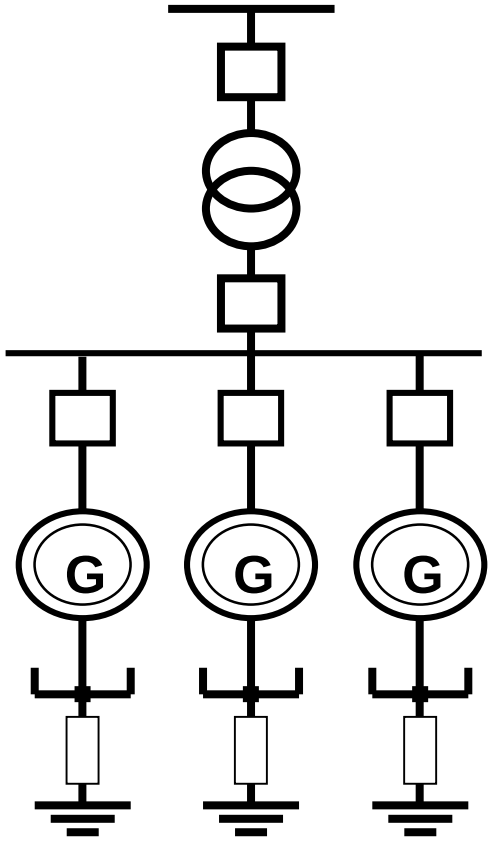
Excitation Transformer

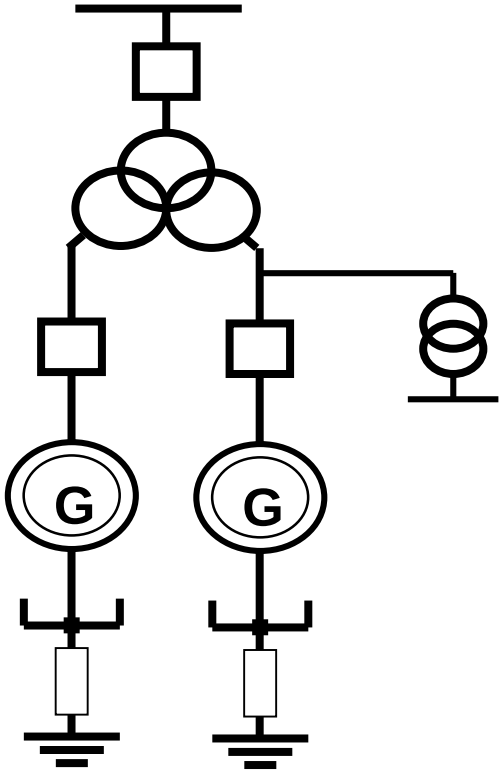
Excitation System

Field Circuit Breaker

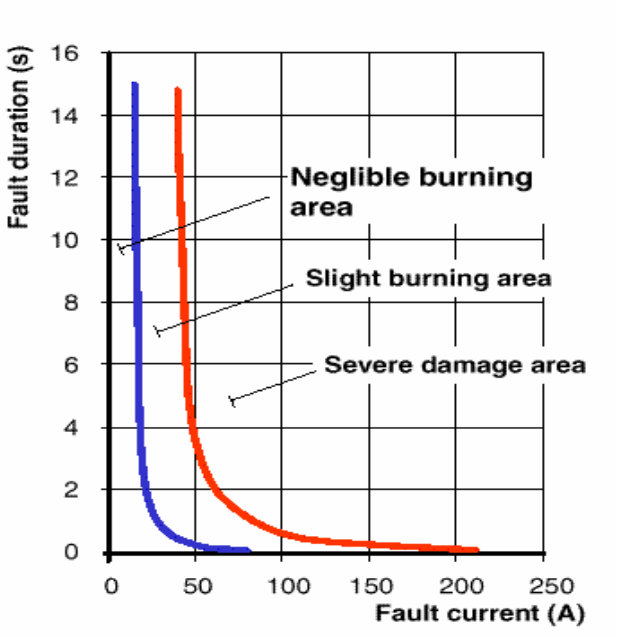
Different power plants electrical equipment layouts





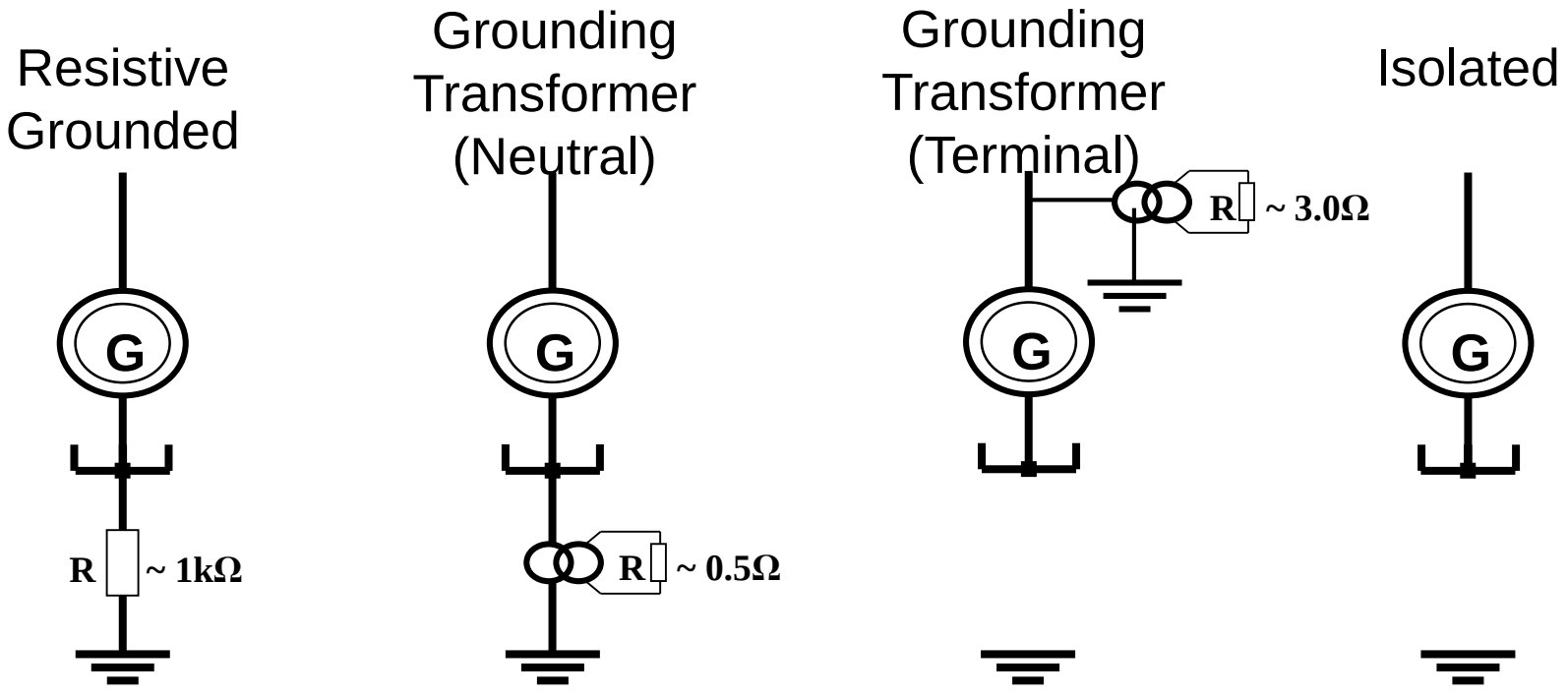


Damage to the stator core in case of earth-fault

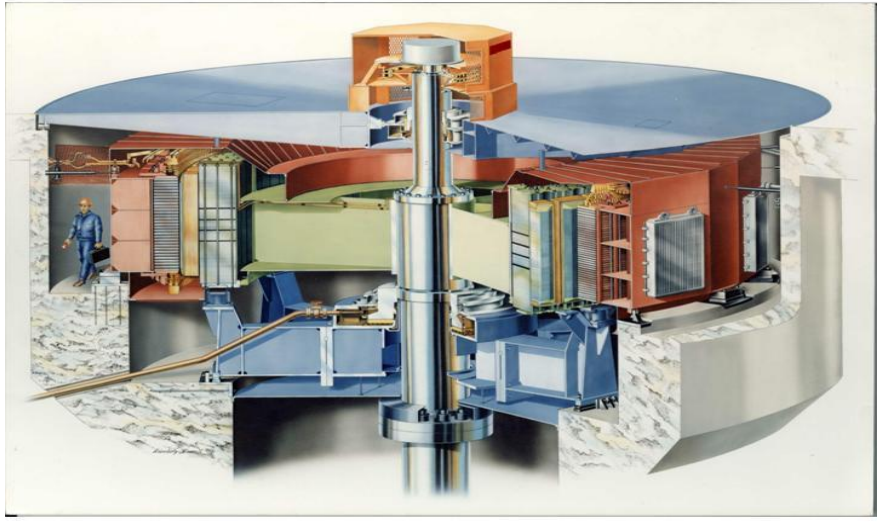


- Practically all unit connected generators are high-impedance earthed
- Only industrial generators may be low-impedance earthed

Stator winding earthing practices



Possible faults

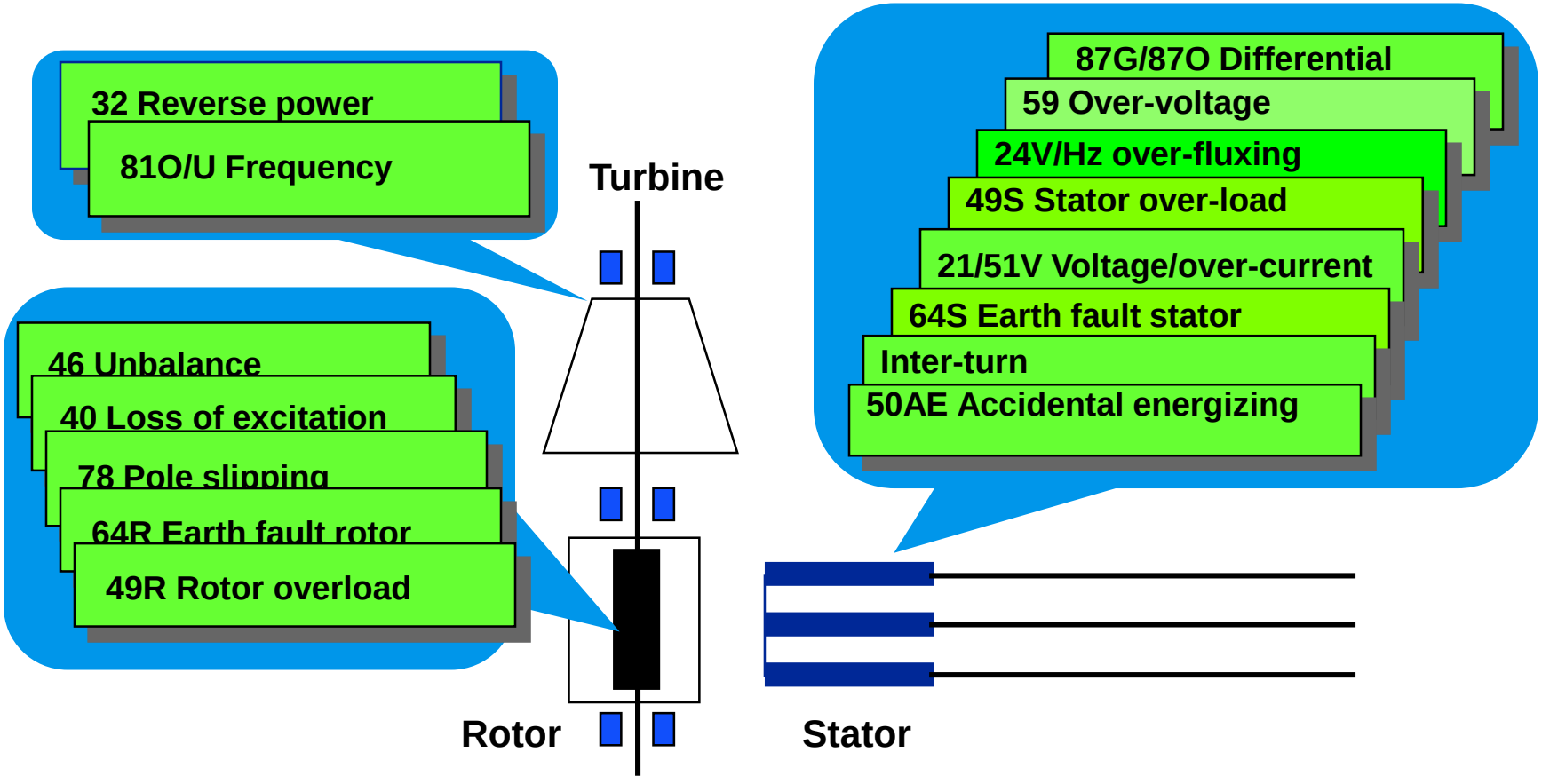


- Stator Earth Faults
- Rotor Earth Faults
- Stator Short Circuits
- Stator/Rotor Interturn faults
- Unit transformer faults
- External faults

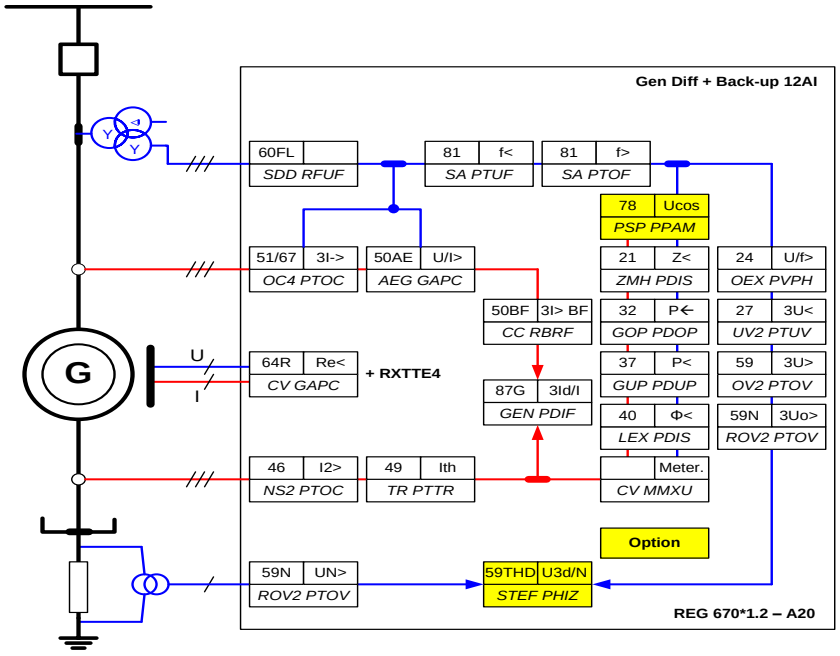
Abnormal operating condition

- 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



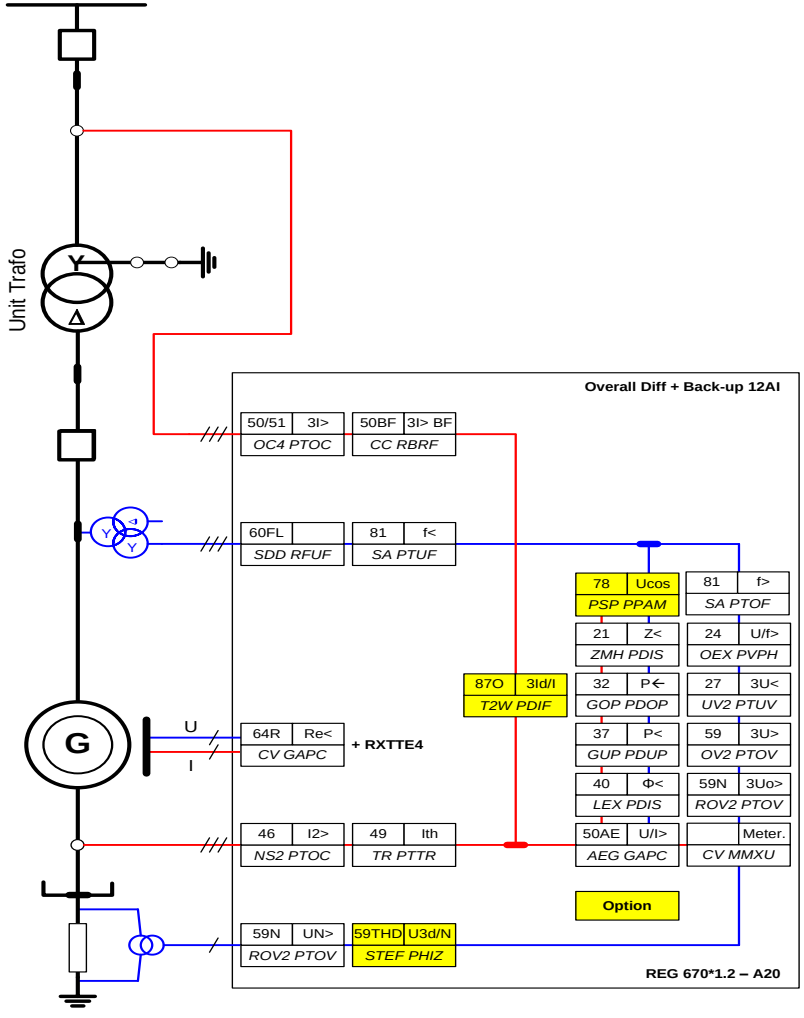
Other functions available from the function library

25 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

Function alternatives for 87G/GEN PDIF

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

Generator protection with 87T (87O)



Function allocations with older generation relays

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

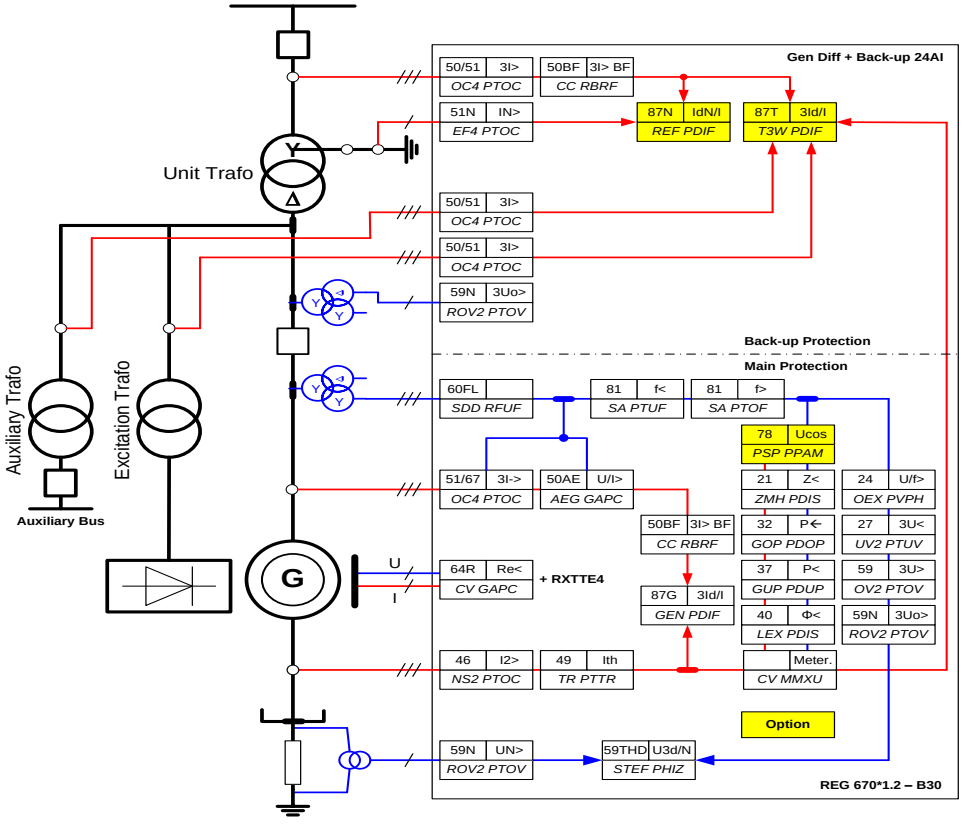
Table 3: Example on relay functions divided into two function groups

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

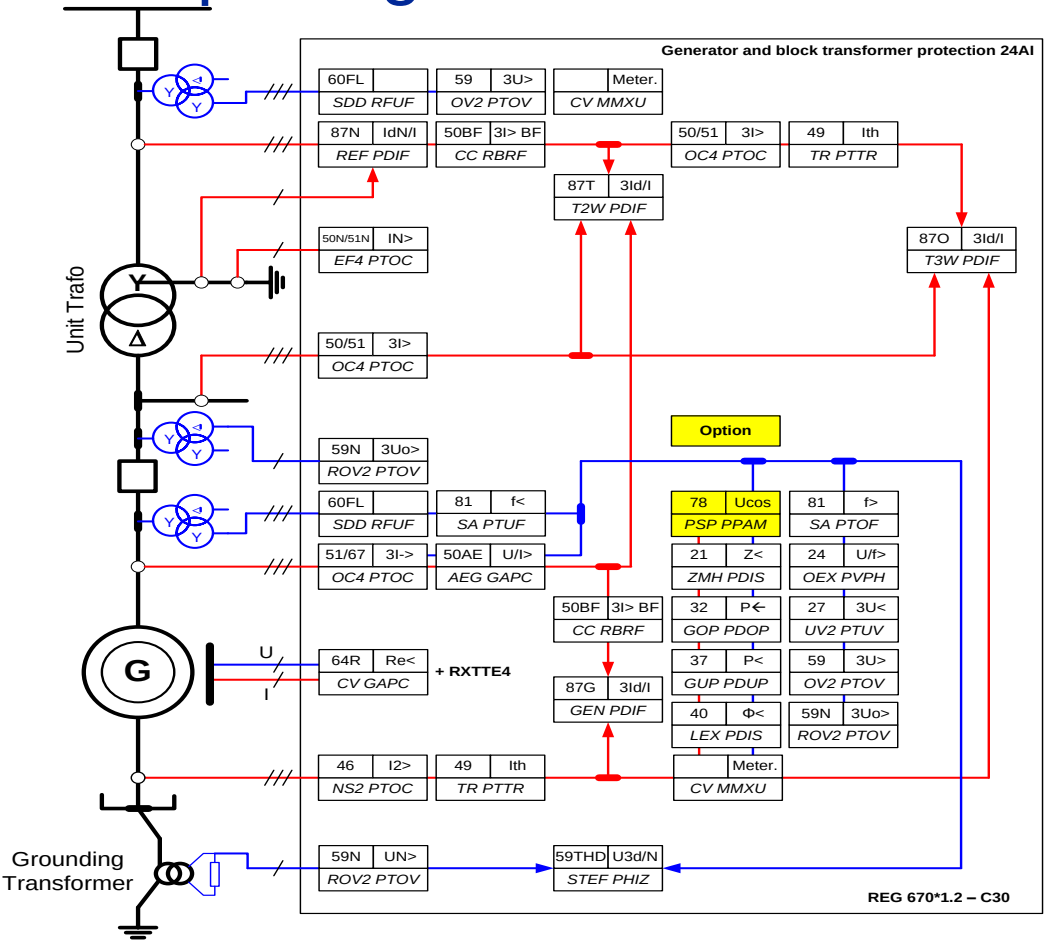
Generator protection & optional transformer protection



Other functions available from the function library

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

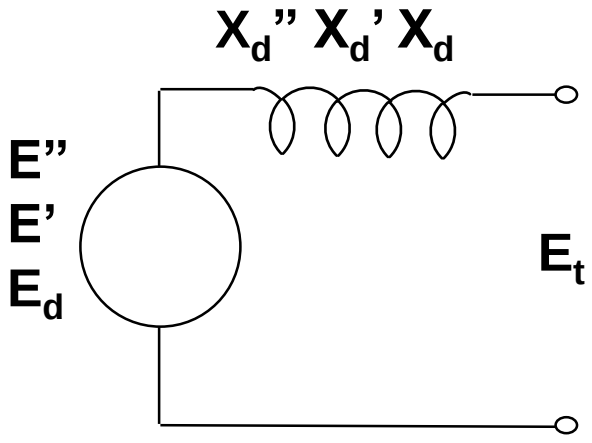
Complete generator-transformer unit protection



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

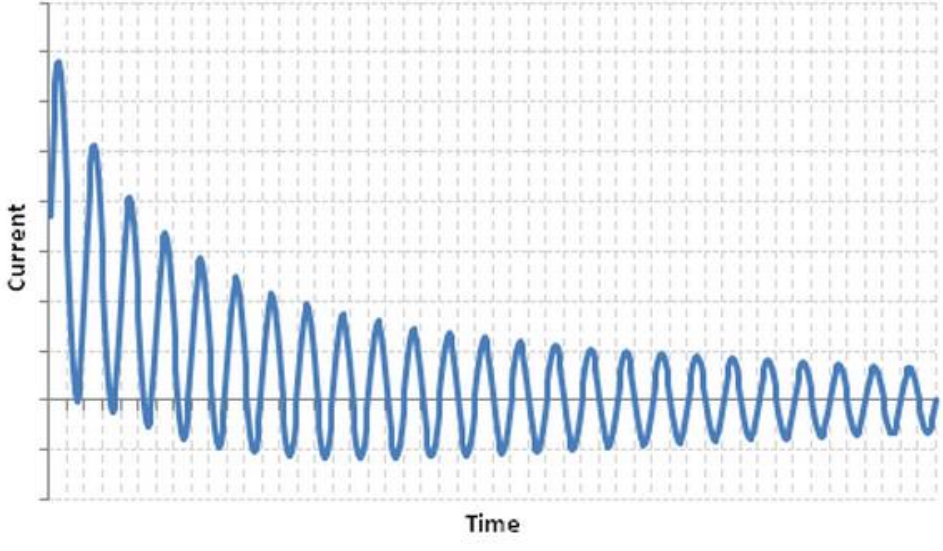
Generator terminal short circuit



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

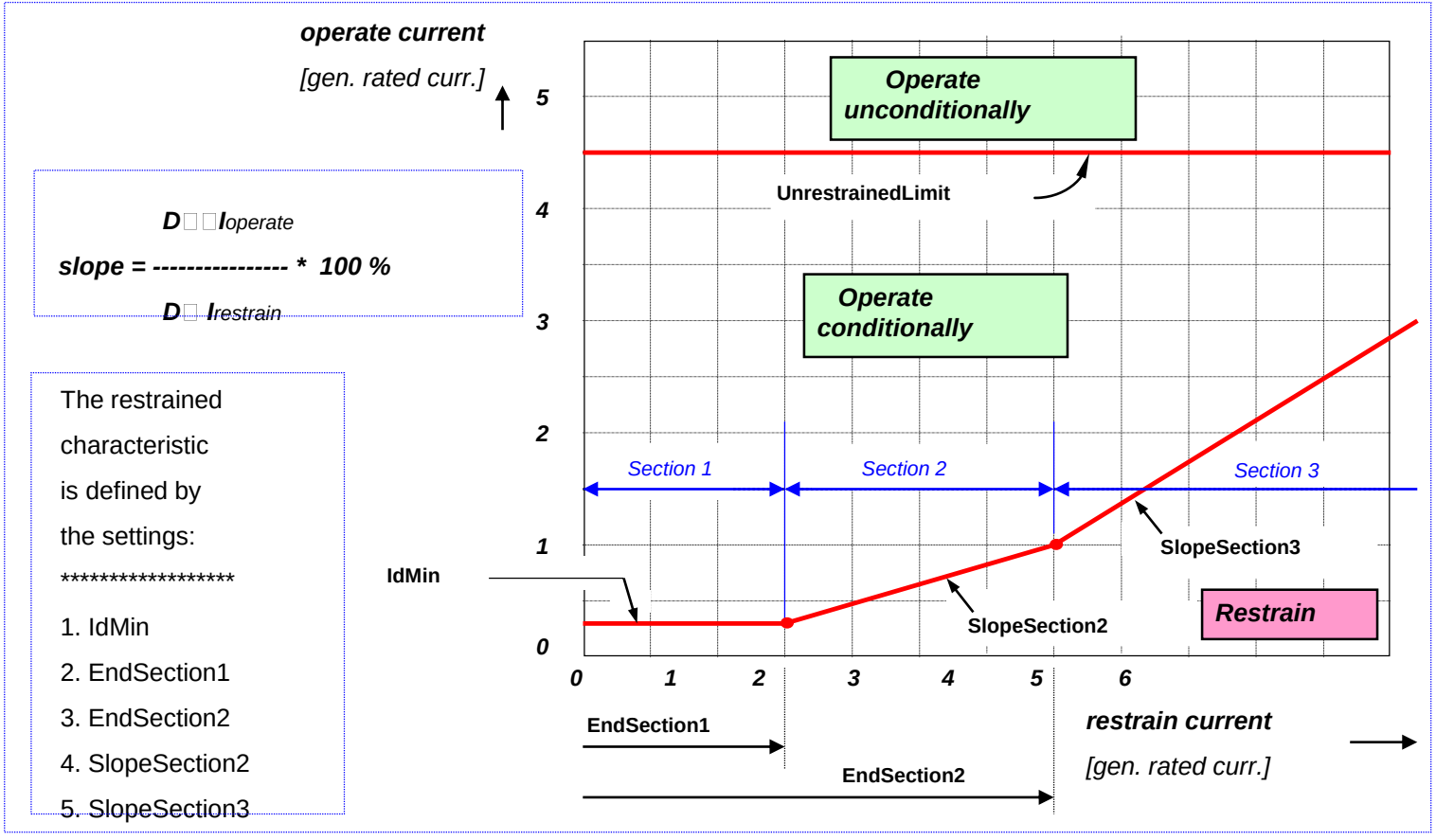
Detection of stator short circuits

- 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



Generator unit (overall) differential protection

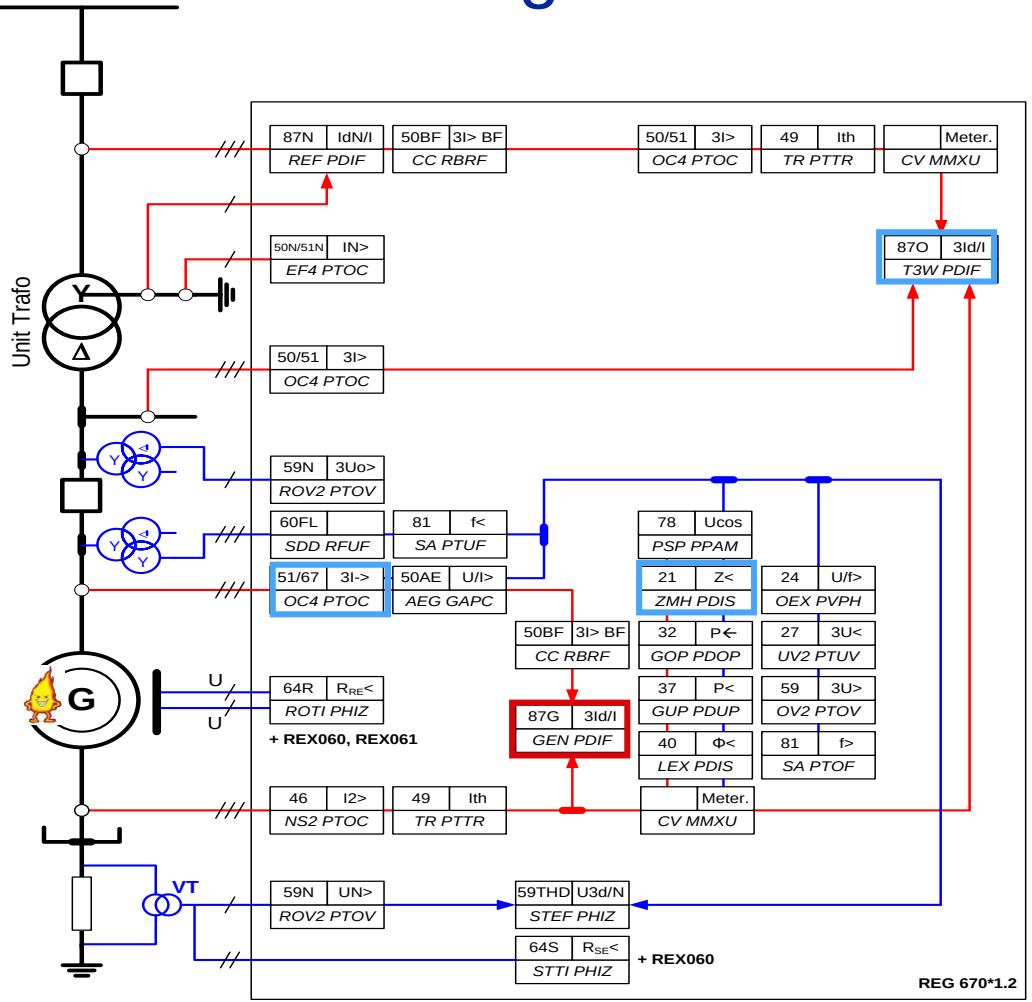
- Identical to transformer differential protection
  - Zero sequence current elimination
  - Vector group compensation
  - Transformer ratio compensation
  - Unstabilized differential protection
  - Stabilized differential protection
    - Harmonic blocking
    - Waveform blocking
  - Negative sequence 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

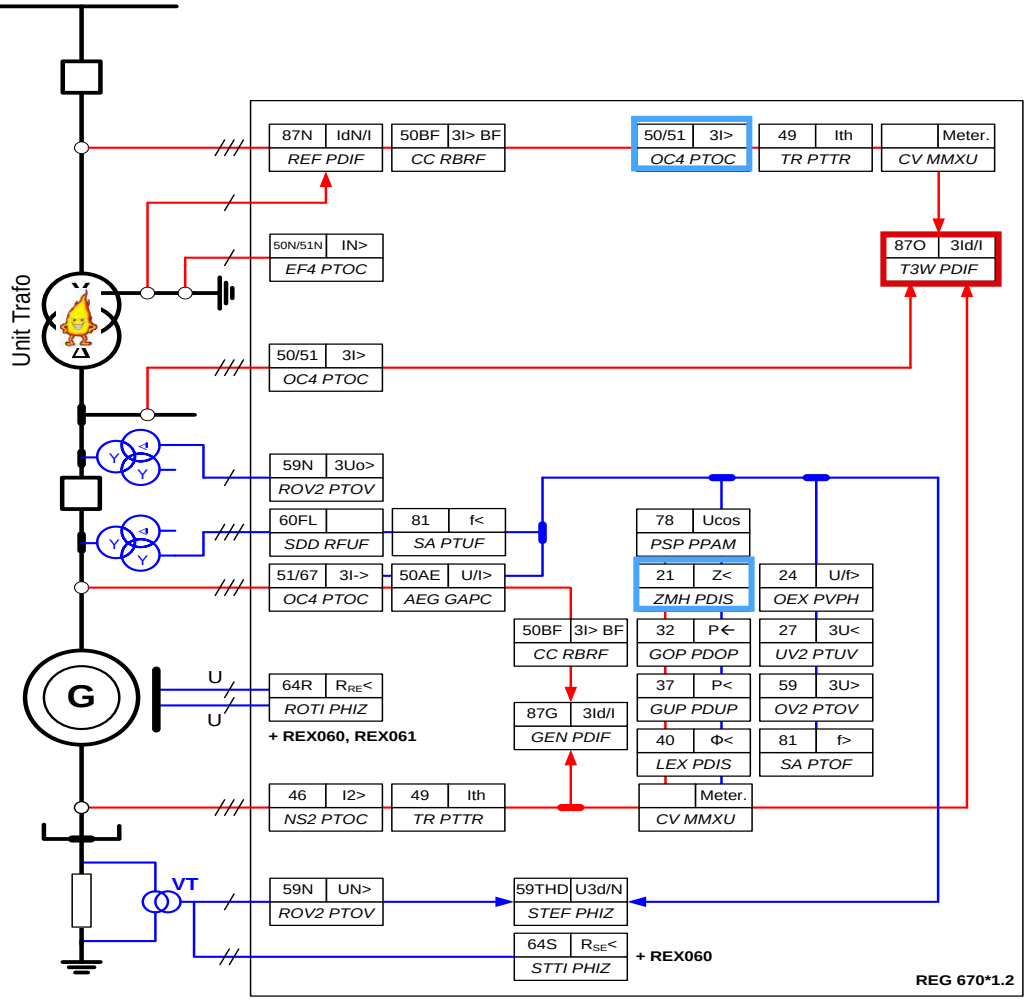


Phase to phase fault in the XFMR, and bus work

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

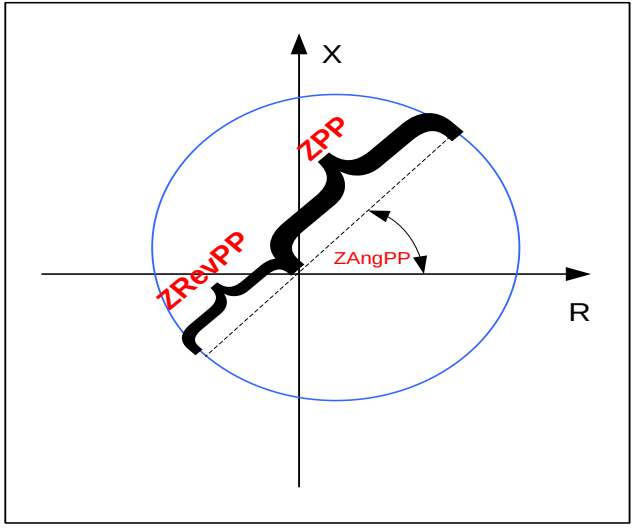
Main Protection Function

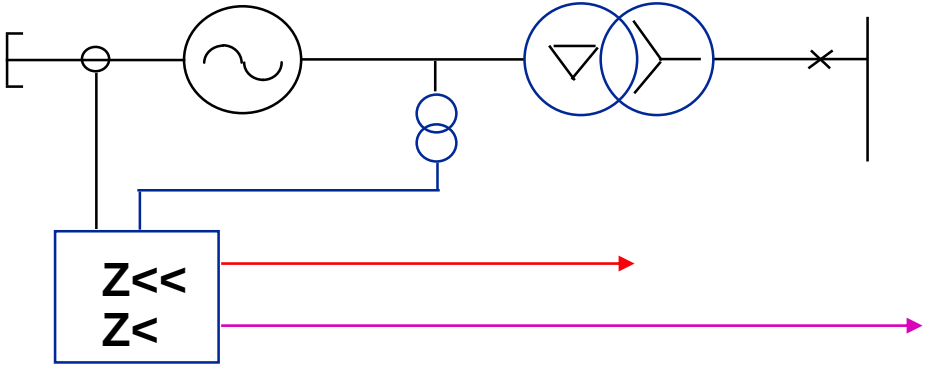
Reserve Protection Function



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

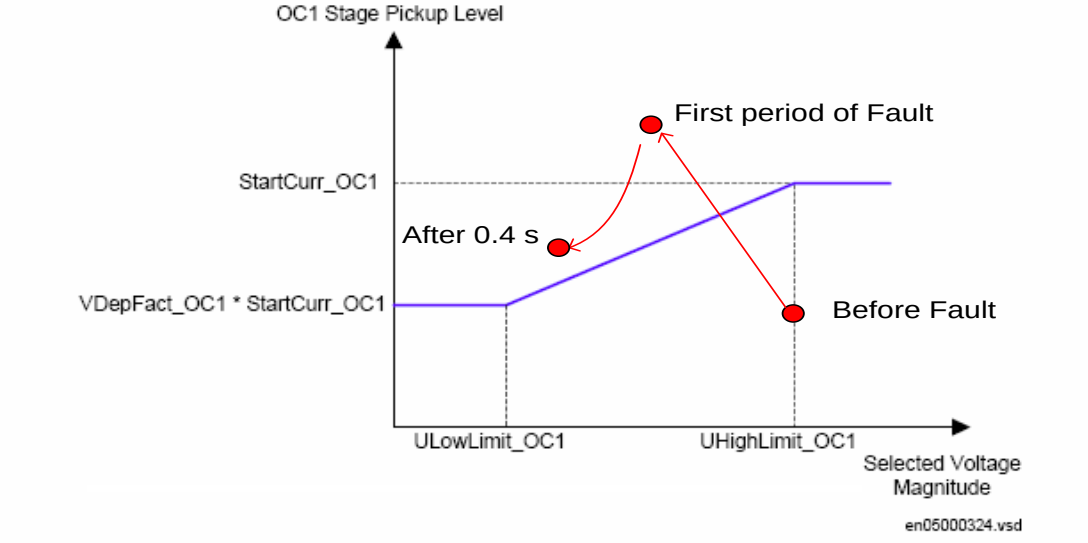


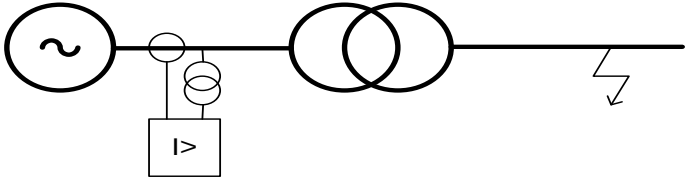


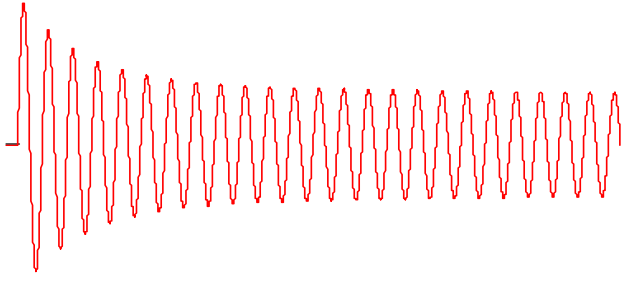
Phase overcurrent protection

- 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
- 21 functions is easier to apply in order to coordinate with outgoing line protective relays

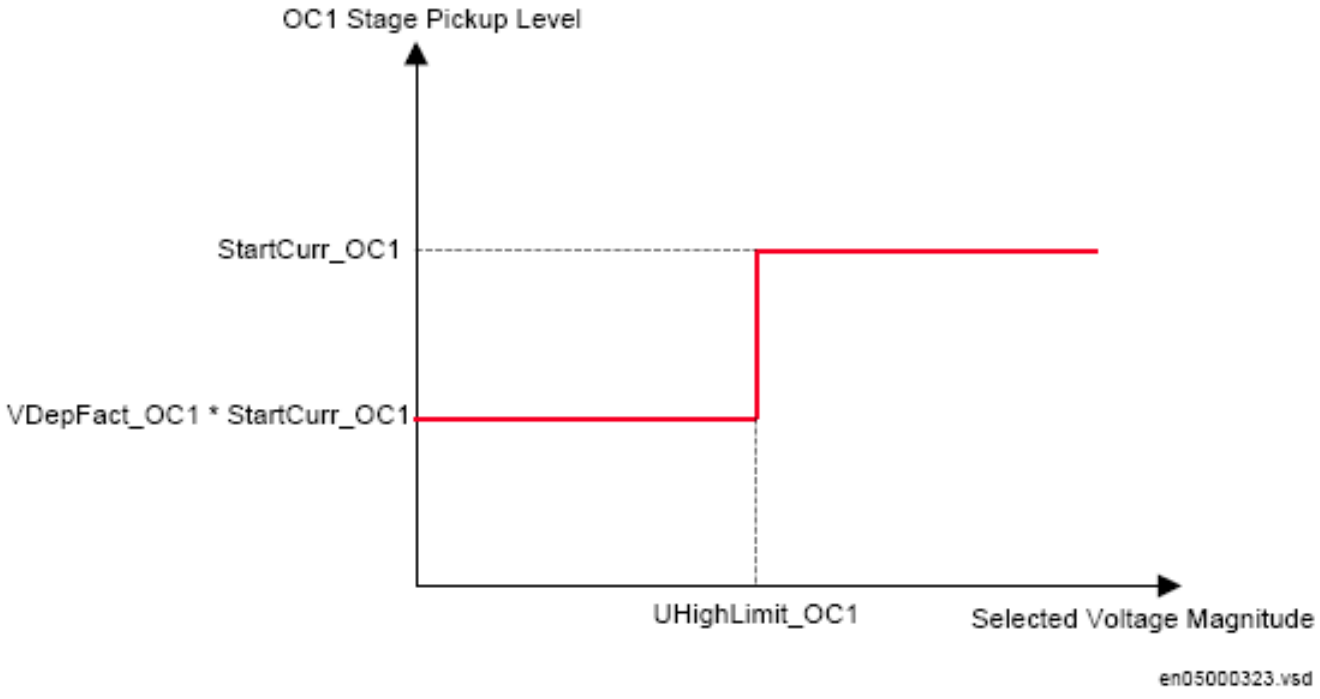
External short circuit







Voltage controlled phase overcurrent protection

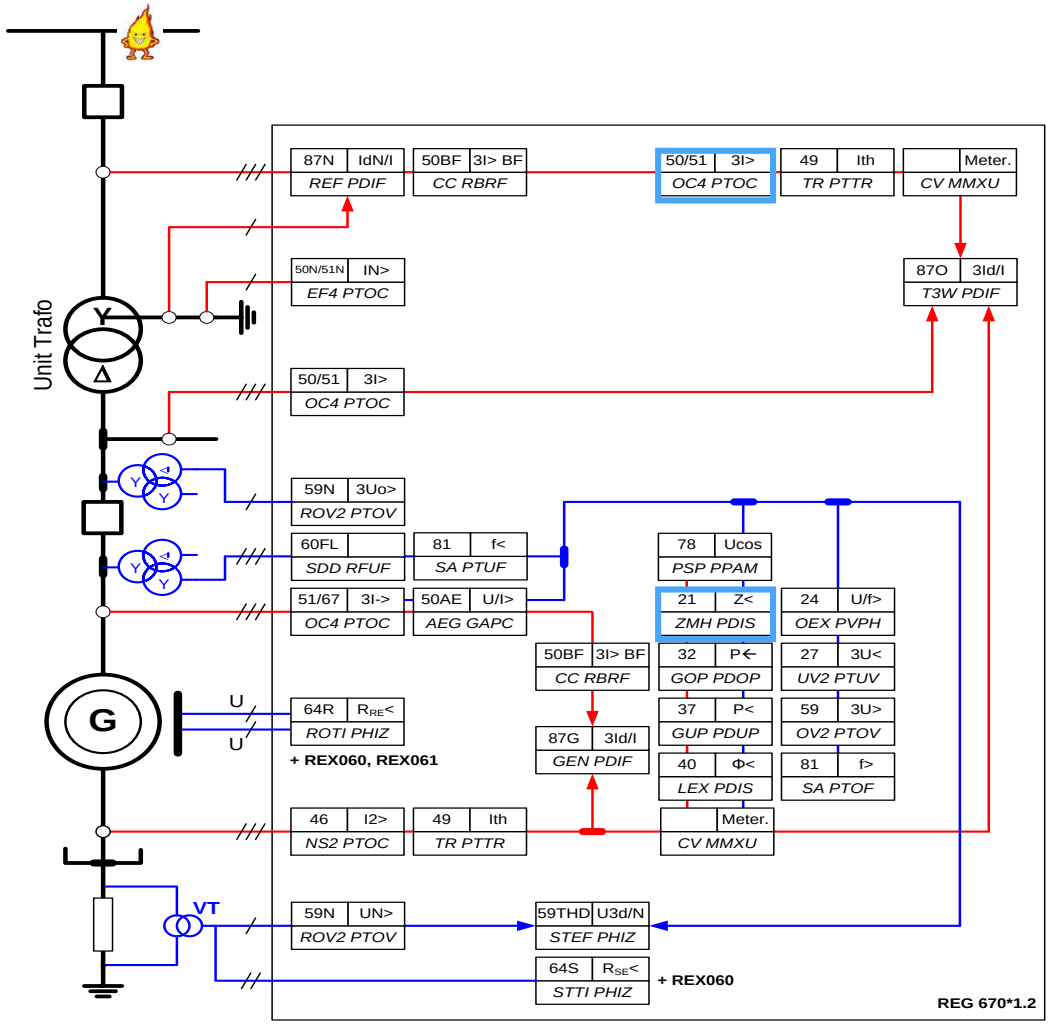


External faults

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

Main Protection Function

Reserve Protection Function

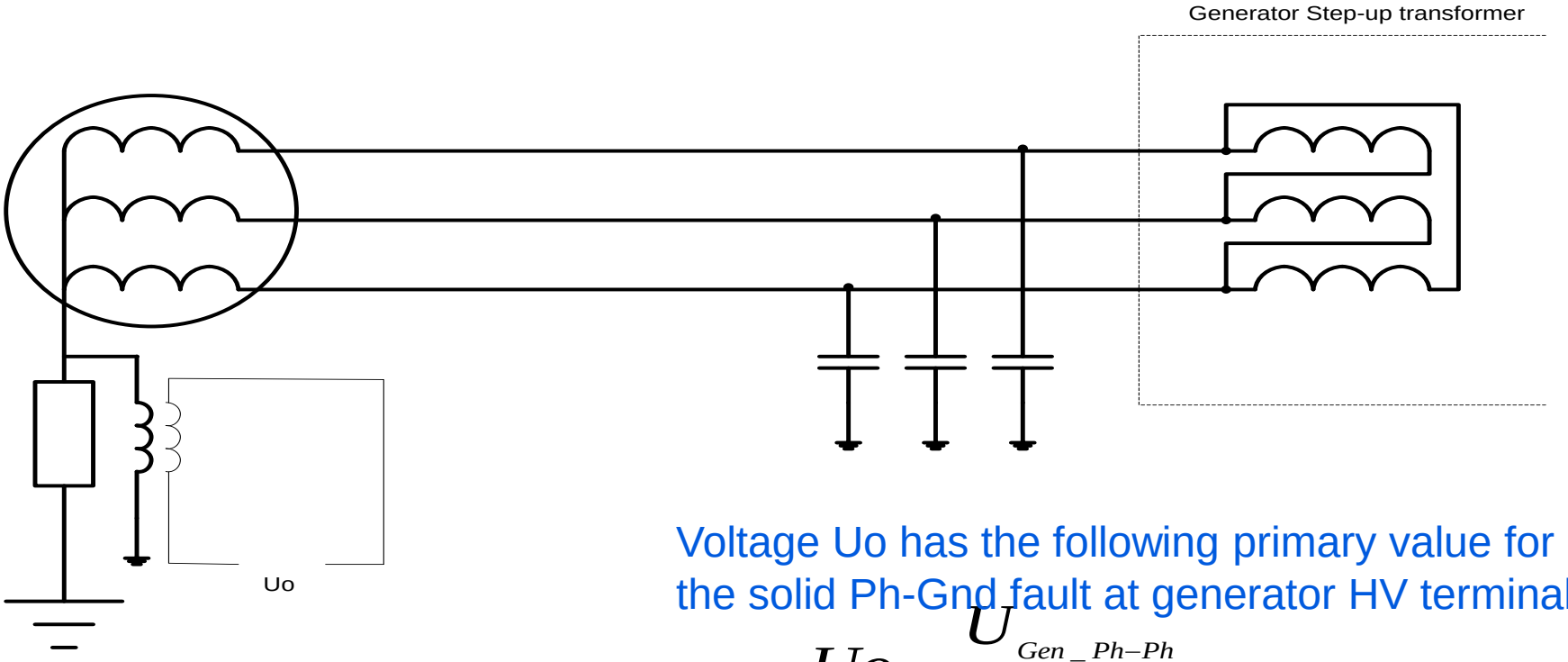


Stator earth fault

- 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

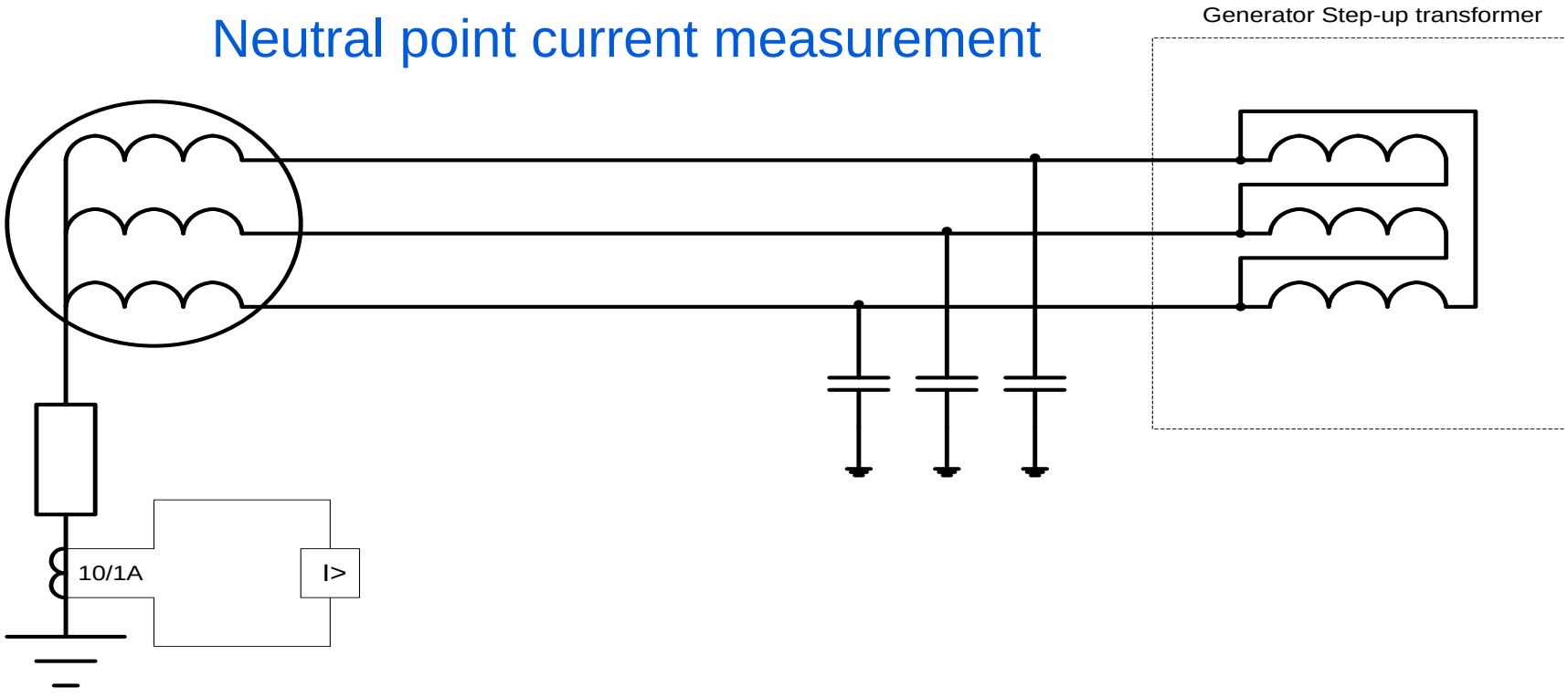


Voltage Uo has the following primary value for the solid Ph-Gnd fault at generator HV terminals

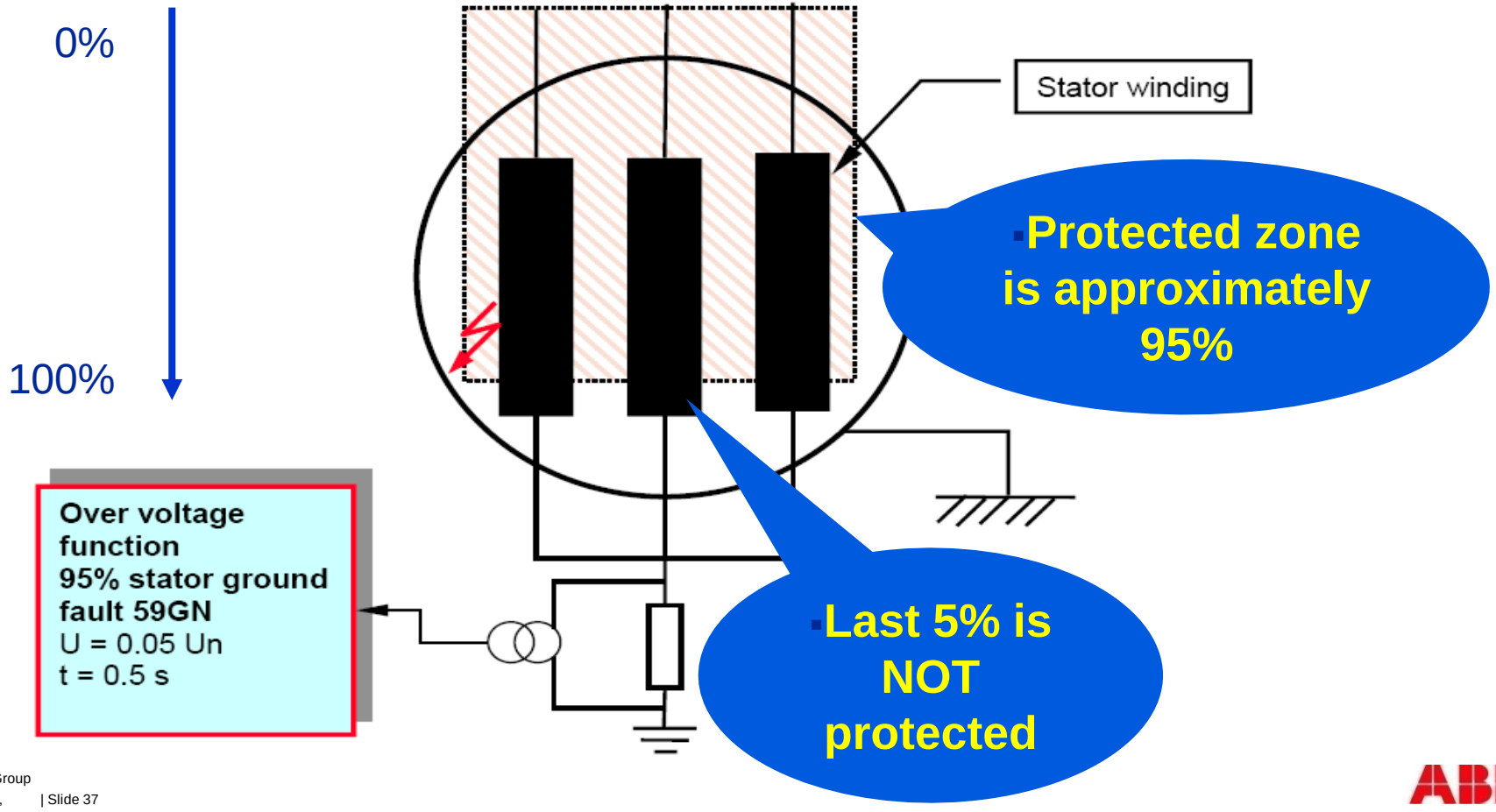
$$Uo = \frac{U_{Gen\_Ph-Ph}}{\sqrt{3}}$$

Current based 95 % stator earth fault protection

Neutral point current measurement



Why 95 % and 100% stator ground fault protection?

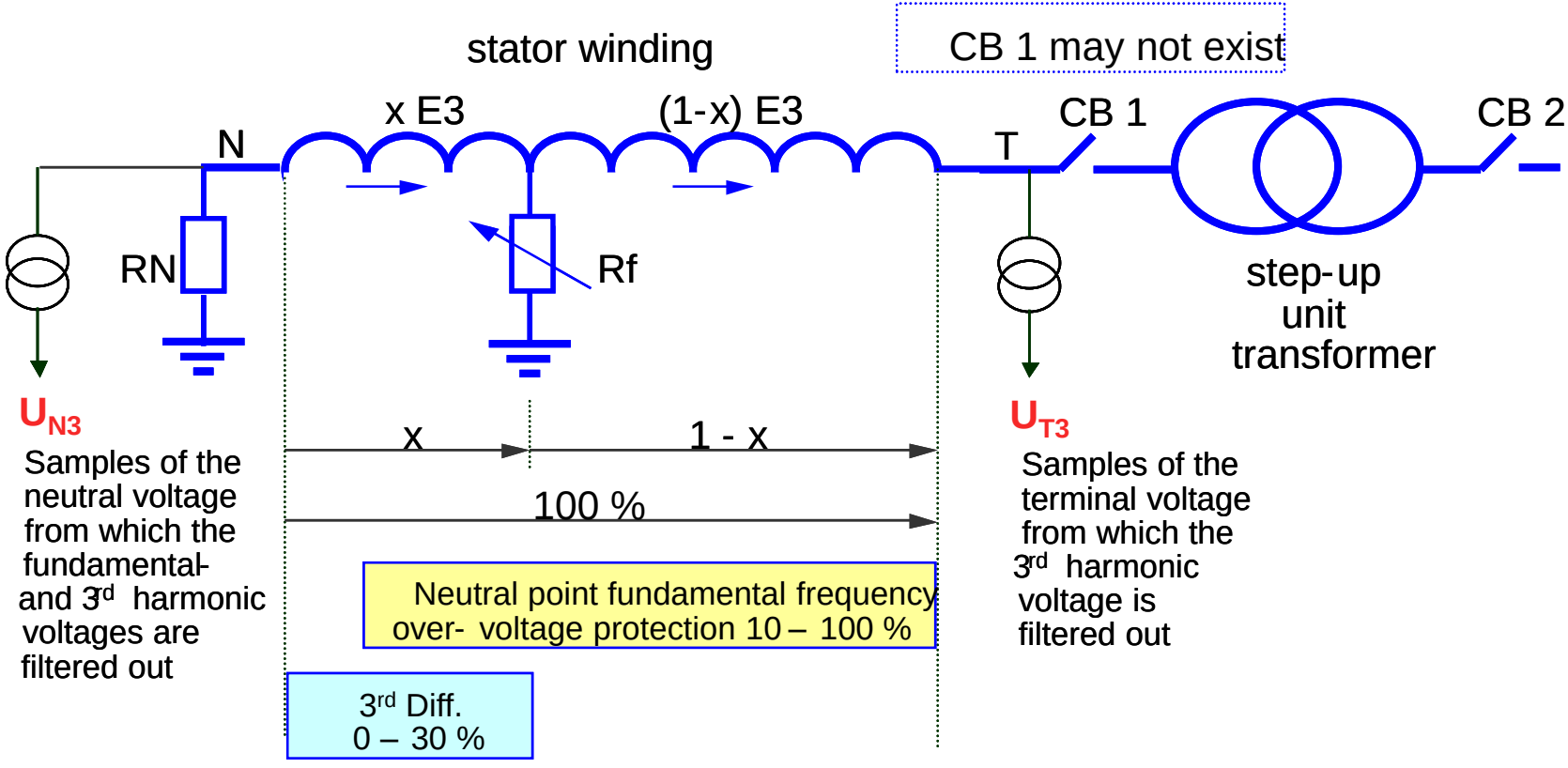


Possible 100 % stator earth fault protection solutions

- 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 based 100% stator earth-fault

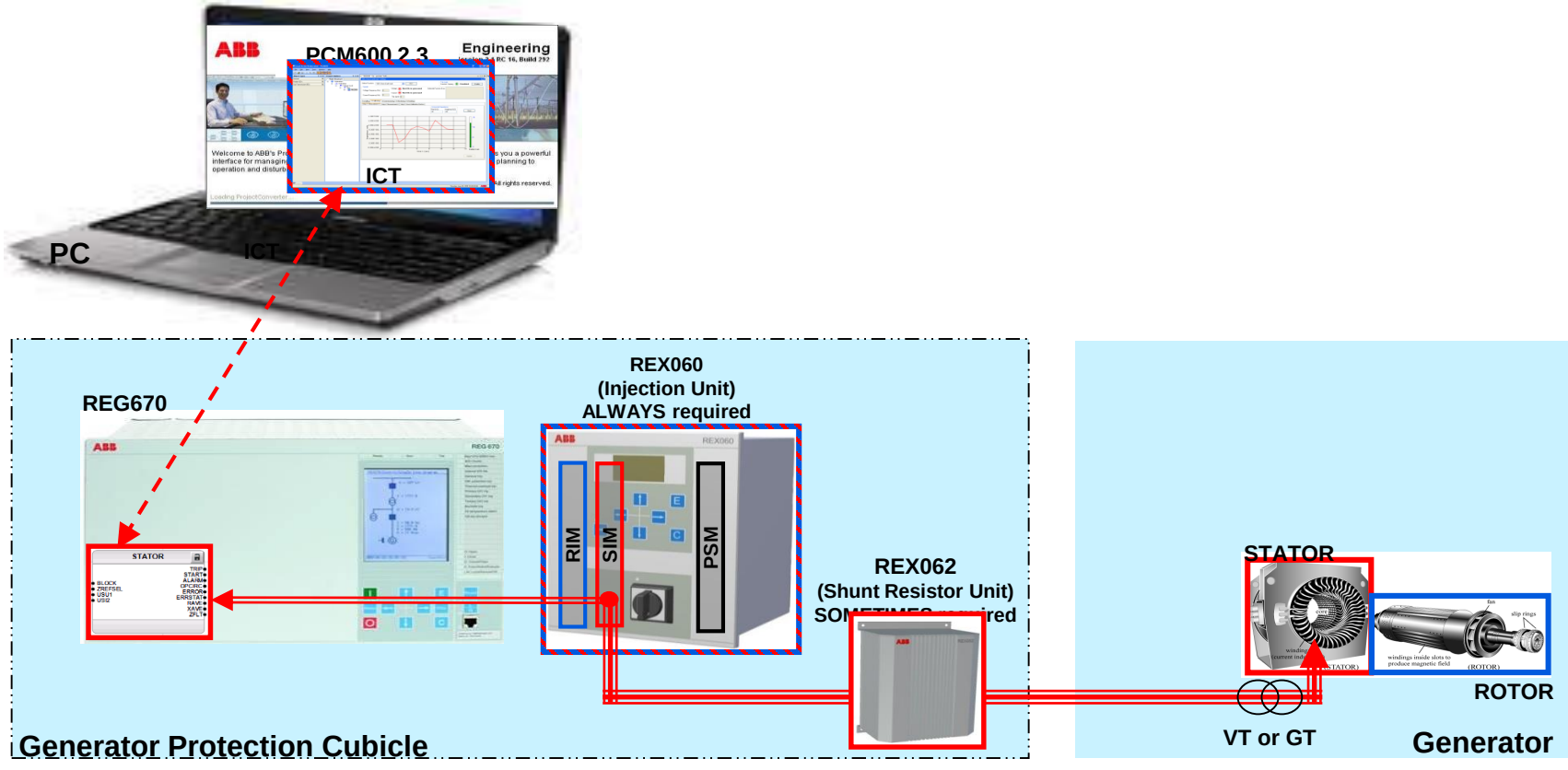


3rd harmonic 100% stator ground fault

- 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

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

Stator injection

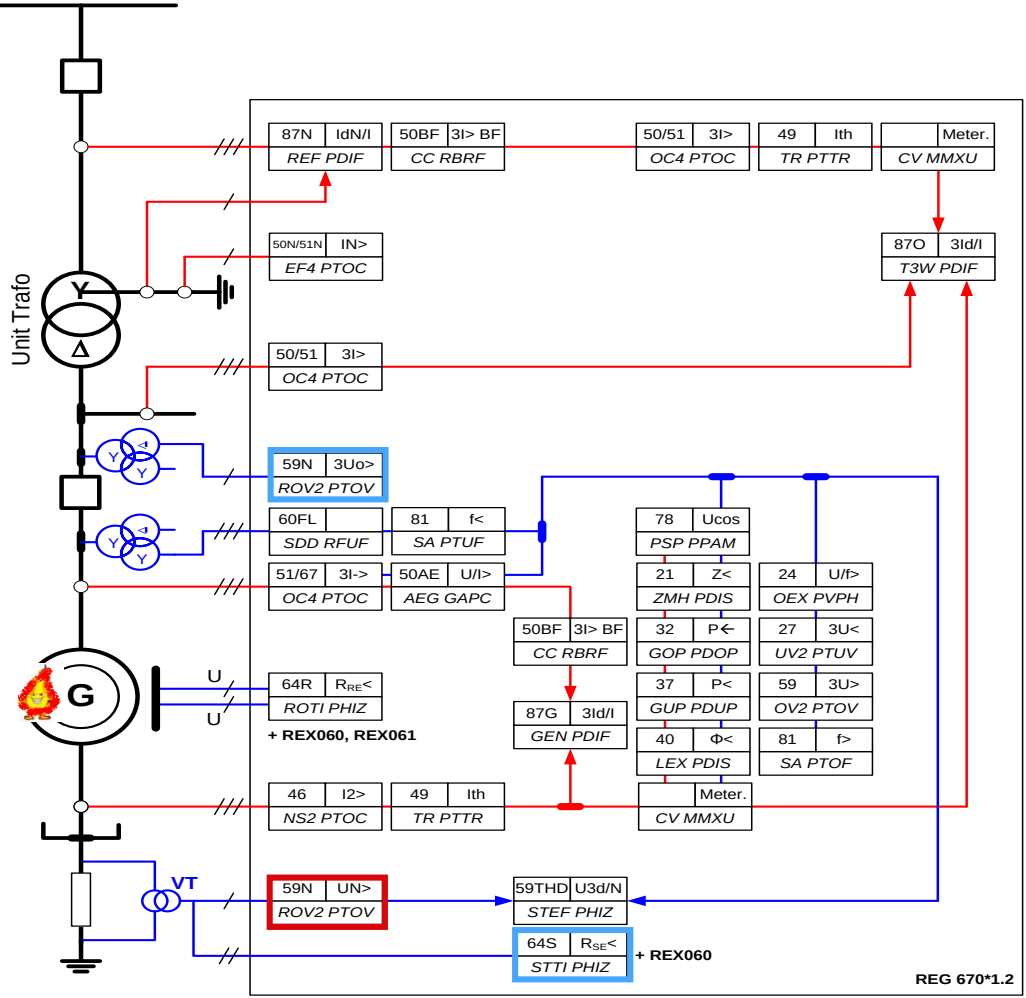


Earth fault in the stator winding

- 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

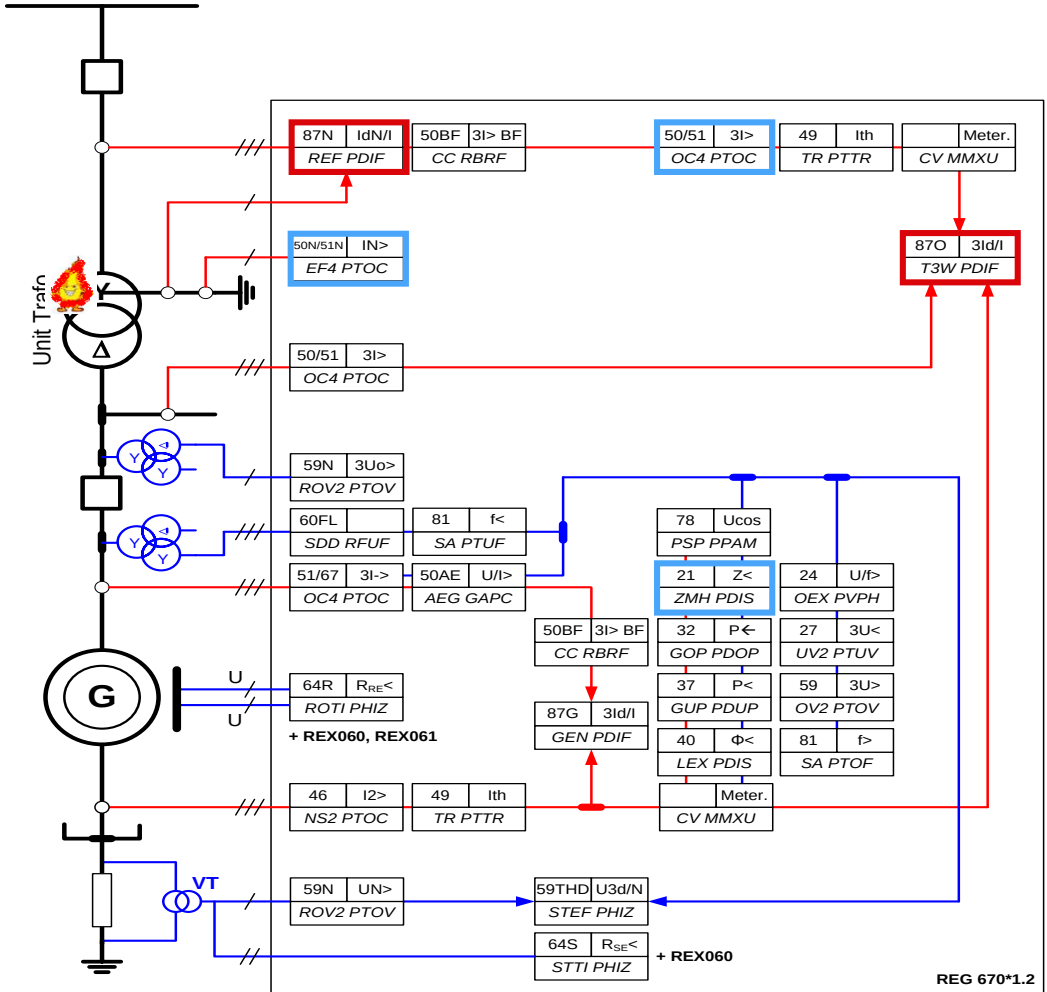


Earth fault in transformer HV winding

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

Main Protection Function

Reserve Protection Function

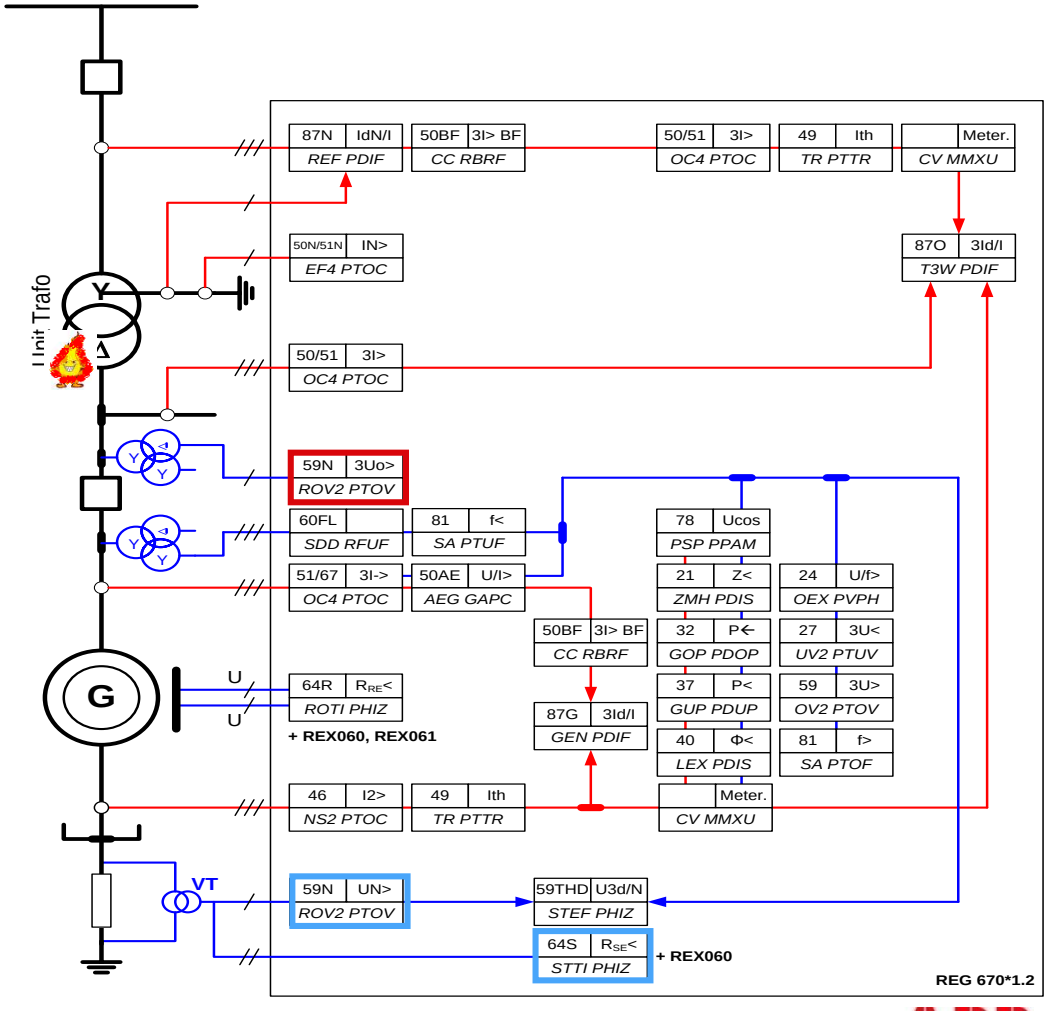


Earth fault in transformer LV winding

- 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



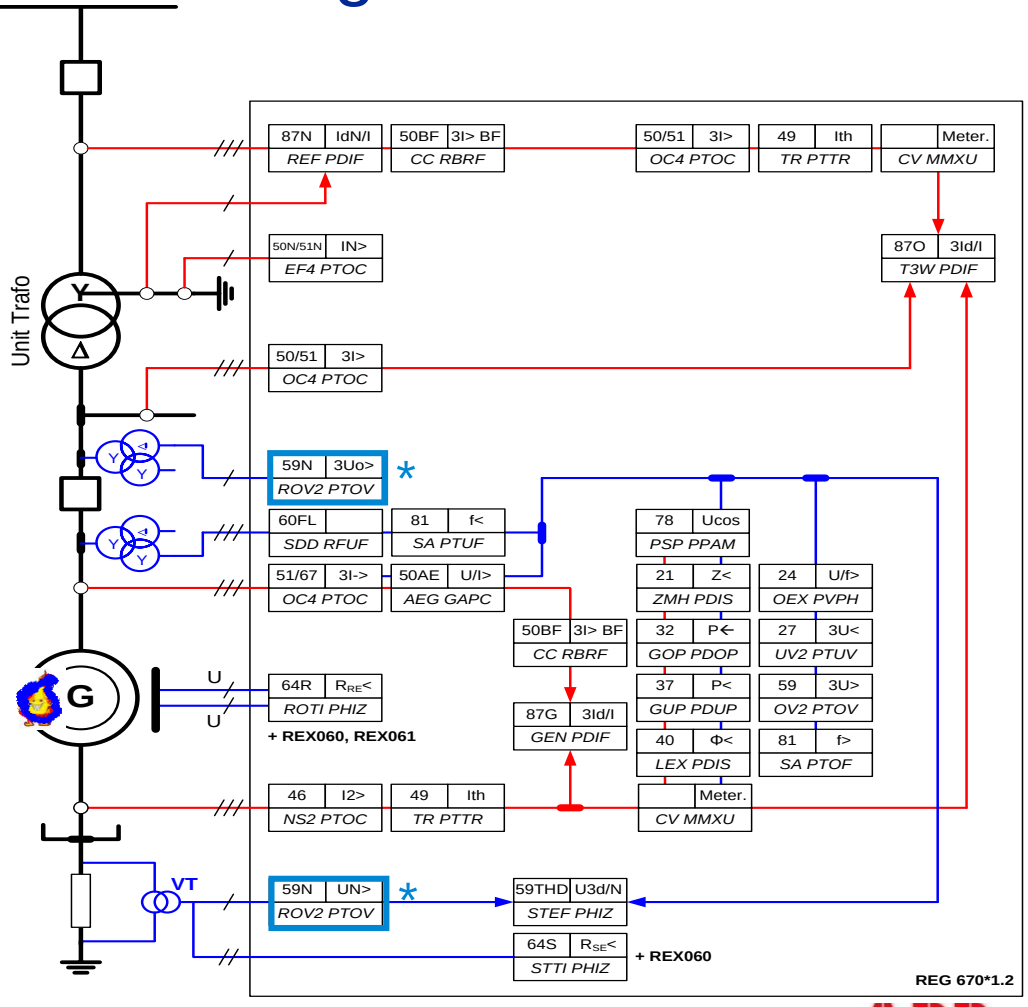
Turn to turn fault in the stator winding

- 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

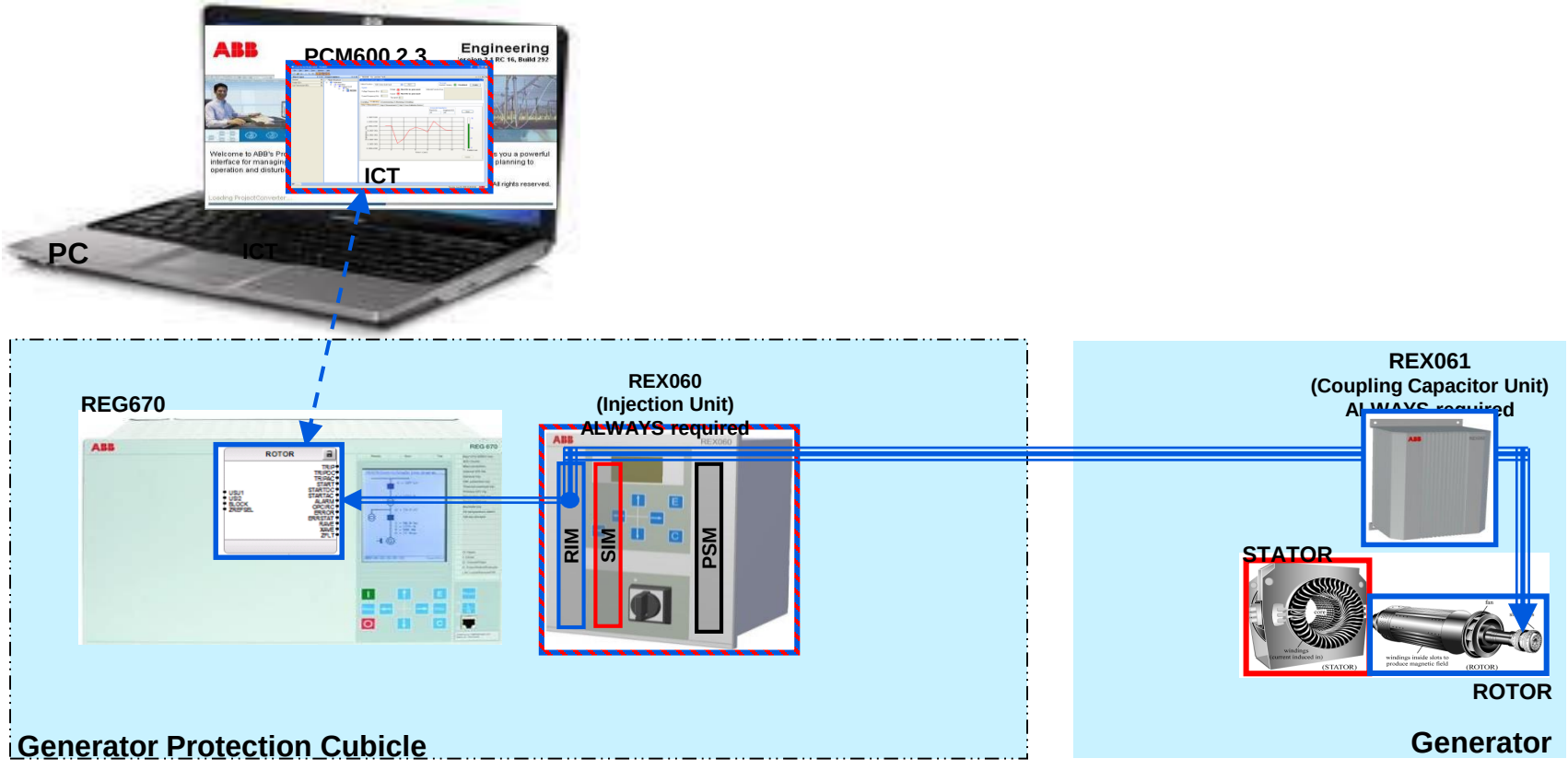
Reserve Protection Function



Rotor earth fault

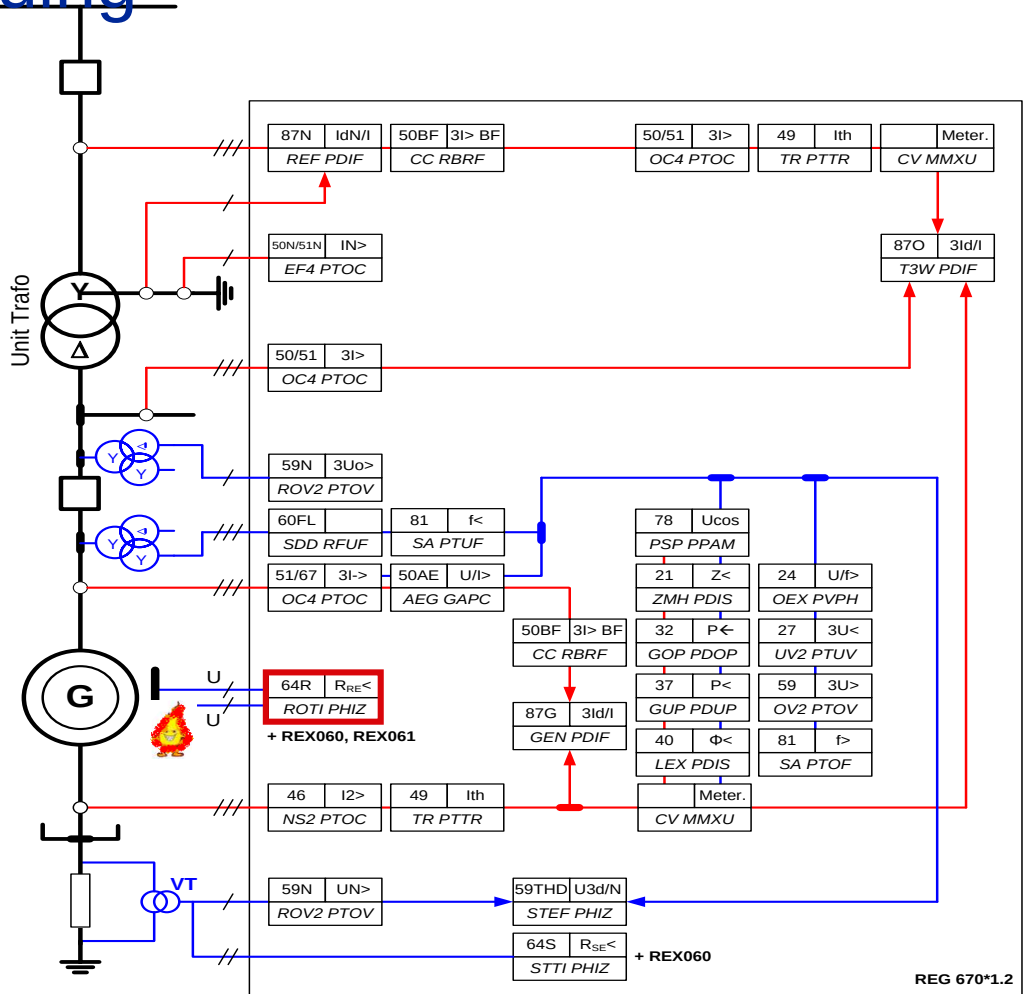
- The field circuit of the generator is normally isolated from earth
- With a single earth fault in the rotor circuit it is possible to have continuous operation without generator damages
- There however creates an increased risk of a second rotor earth fault. In such a case there will be large current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

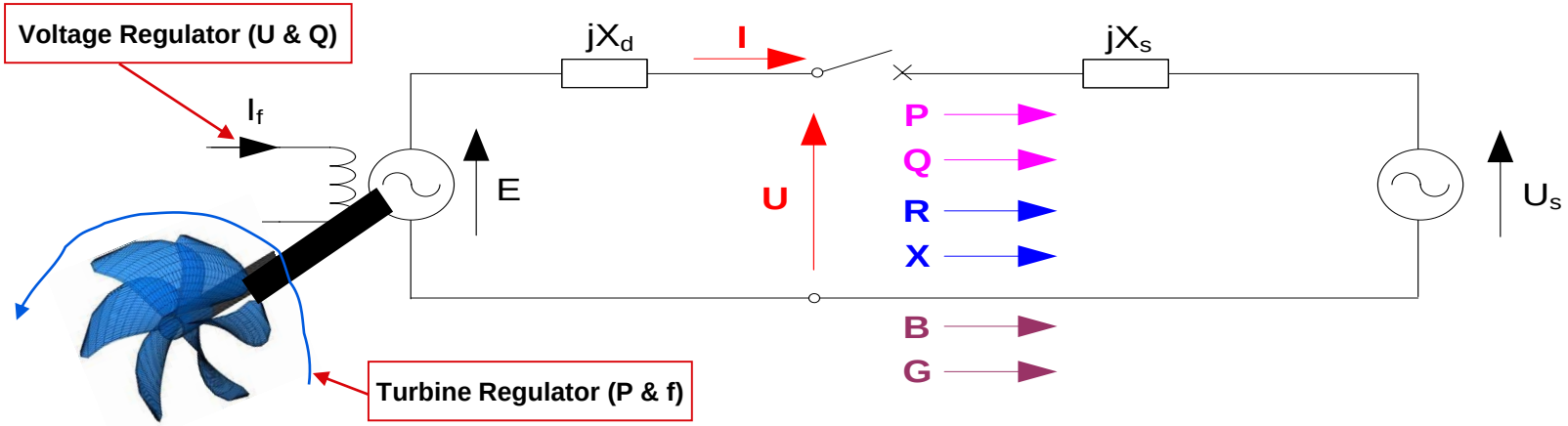
- Endangering condition
  - None
- Protected object
  - Rotor winding
- Consequences
  - Risk of evolving into double earth fault



Main Protection Function

Reserve Protection Function

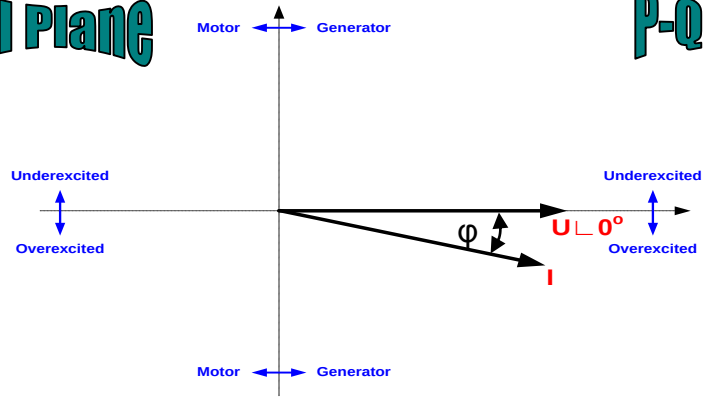
Performance of synchronous machine



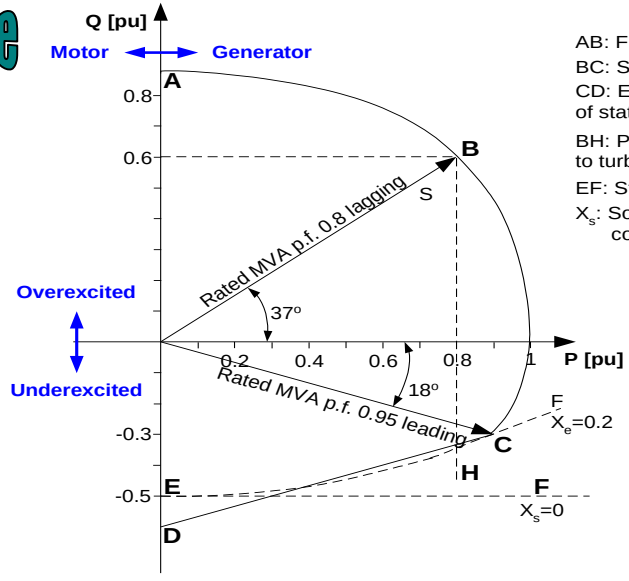
- Synchronous machine operating in a parallel with a large power system can:
  - supply active power to the system (operates as generator)
  - receive active power from the system (operates as motor)
  - supply reactive power to the system
    (overexcited machine; operates as shunt capacitor)
  - receive 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

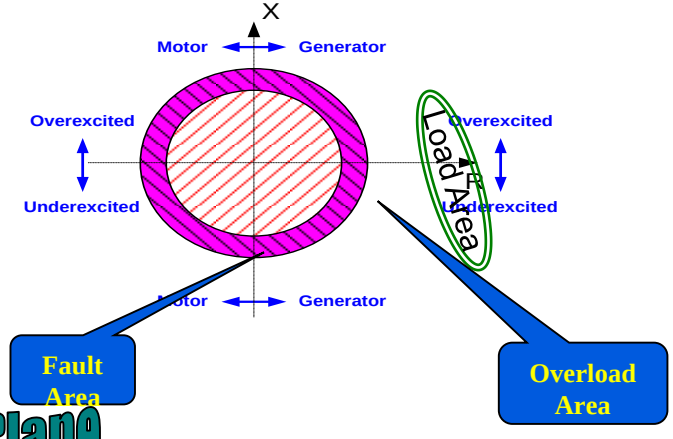


P-Q plane



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



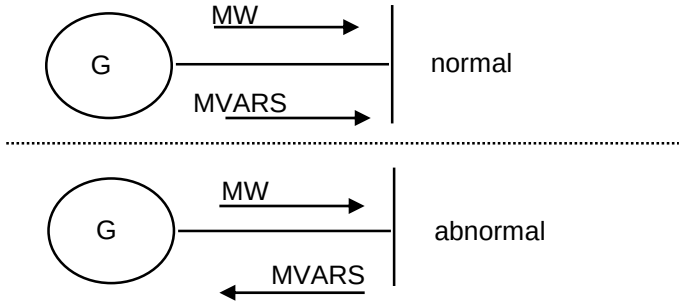
Loss of/under excitation 40

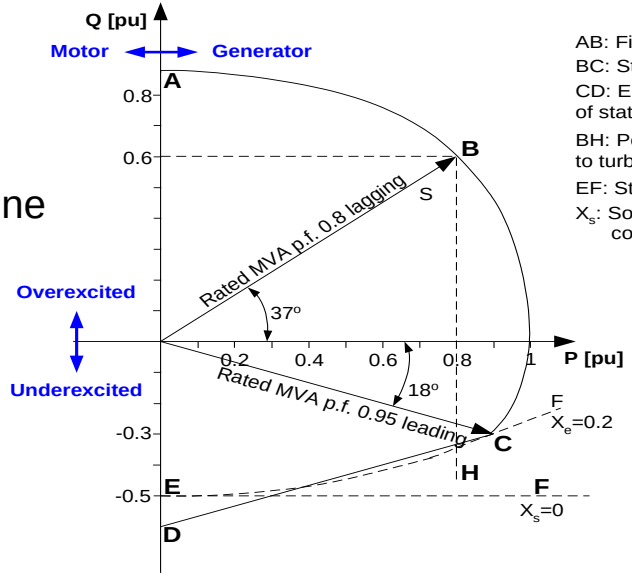
Causes

- 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





AB: Field current limit
BC: Stator current limit
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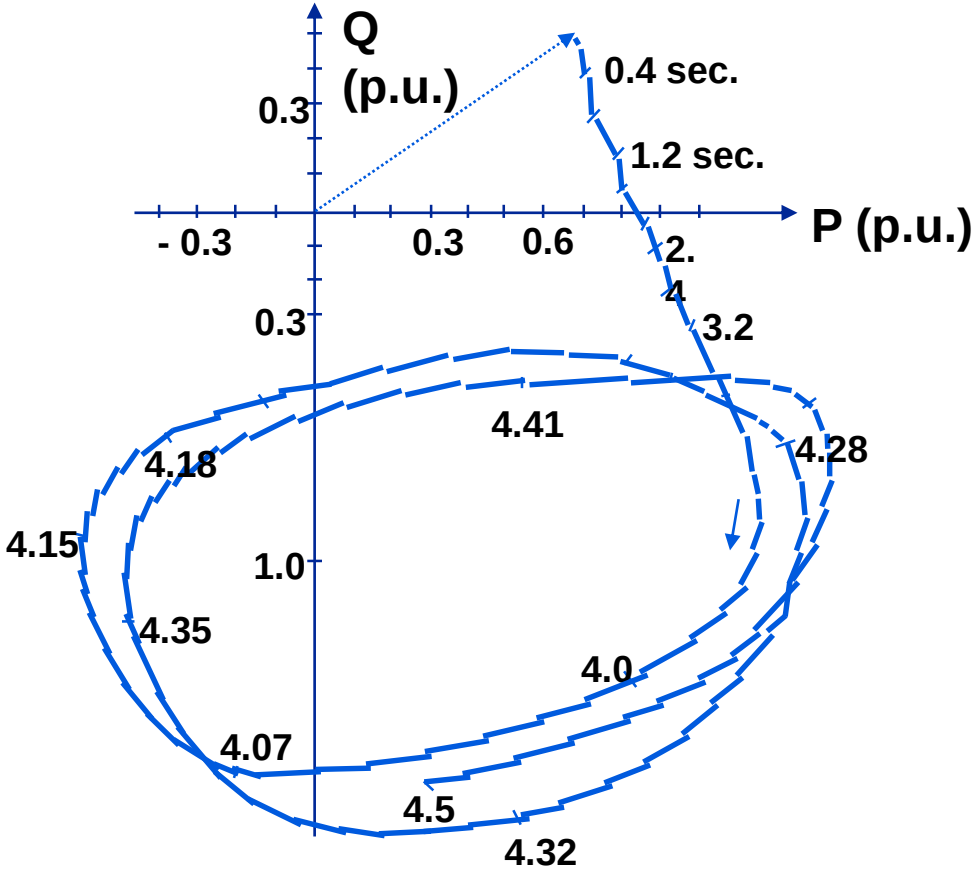
EF: Steady-state limit without AVR
X_s: Source impedance of connected power system

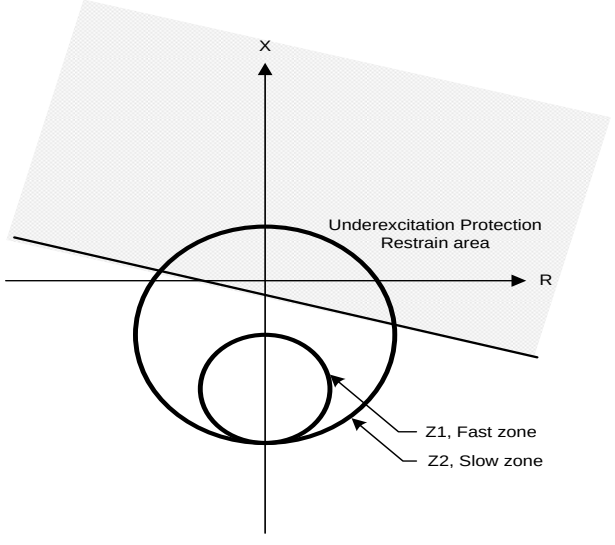
Loss of/under excitation 40

Generator apparent power S during loss of excitation

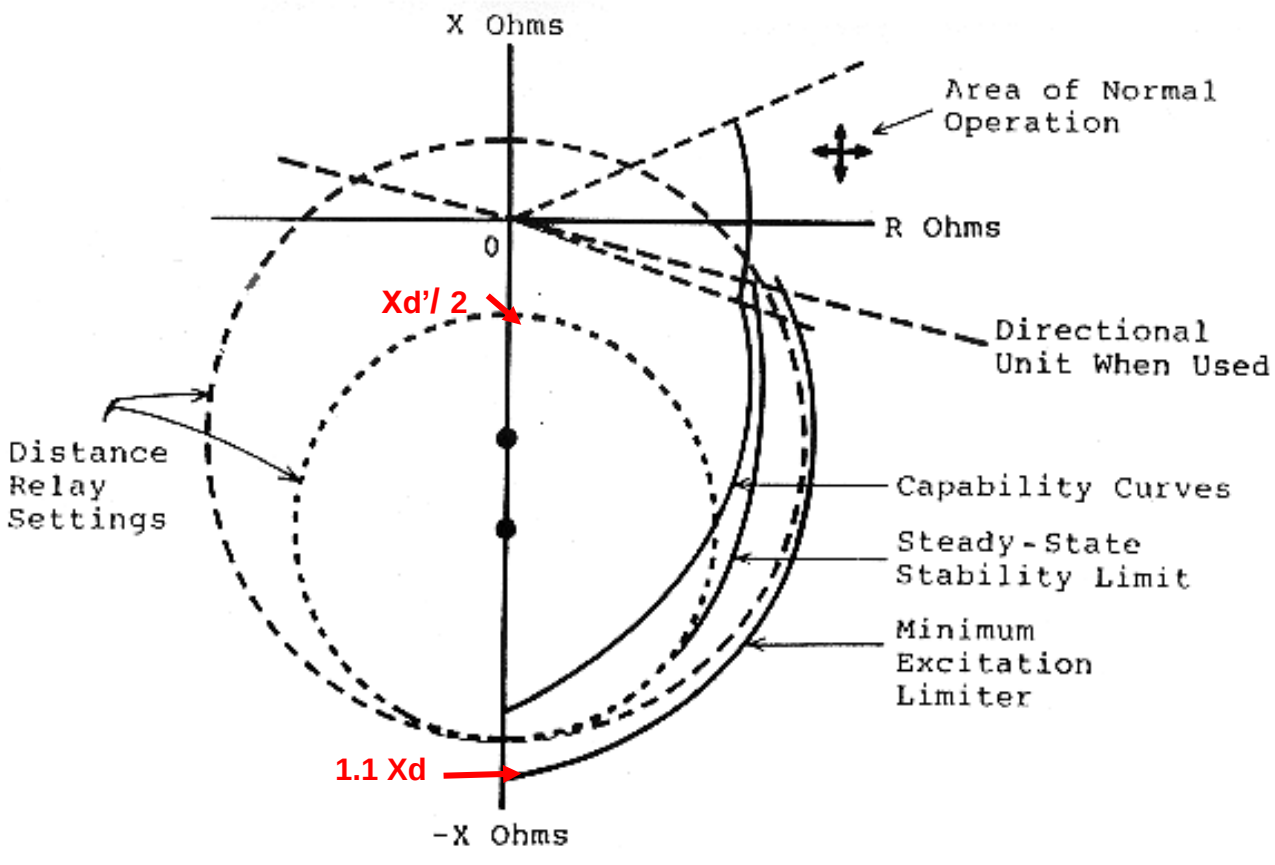


Loss of/under excitation 40

- 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

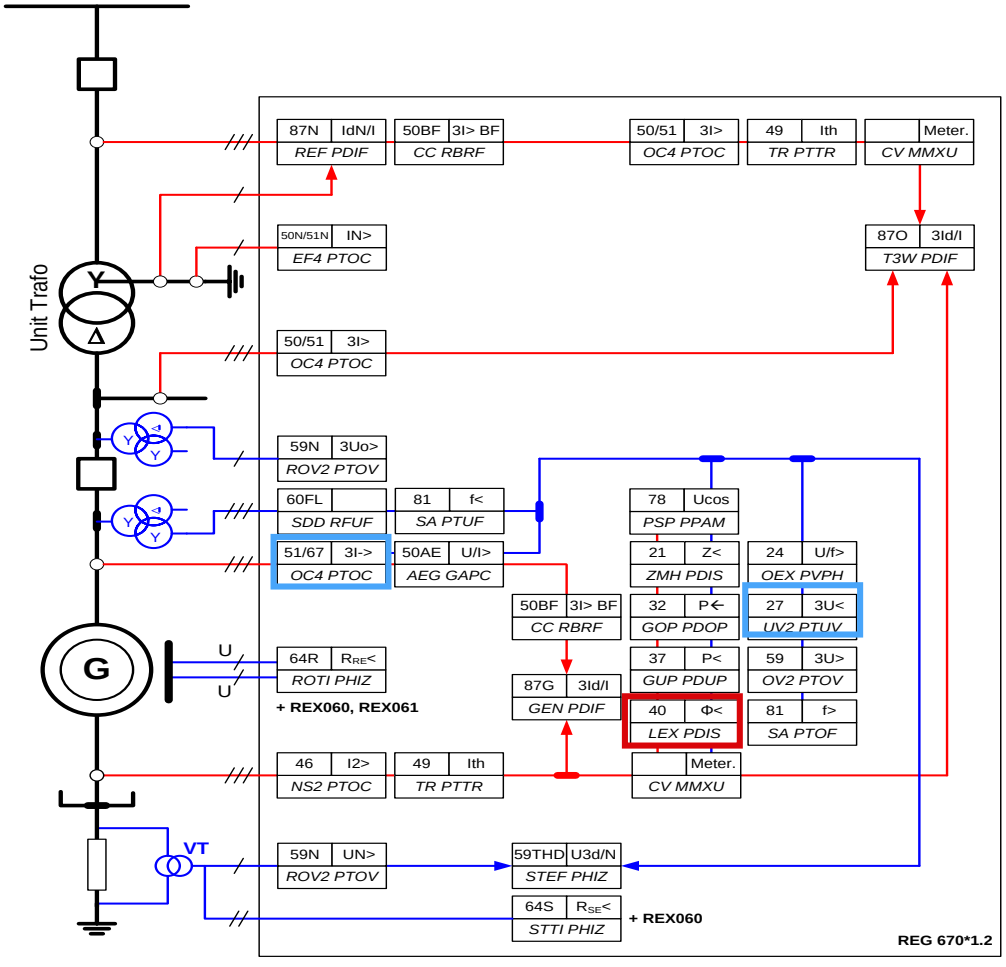


Loss of/Under excitation 40

- 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



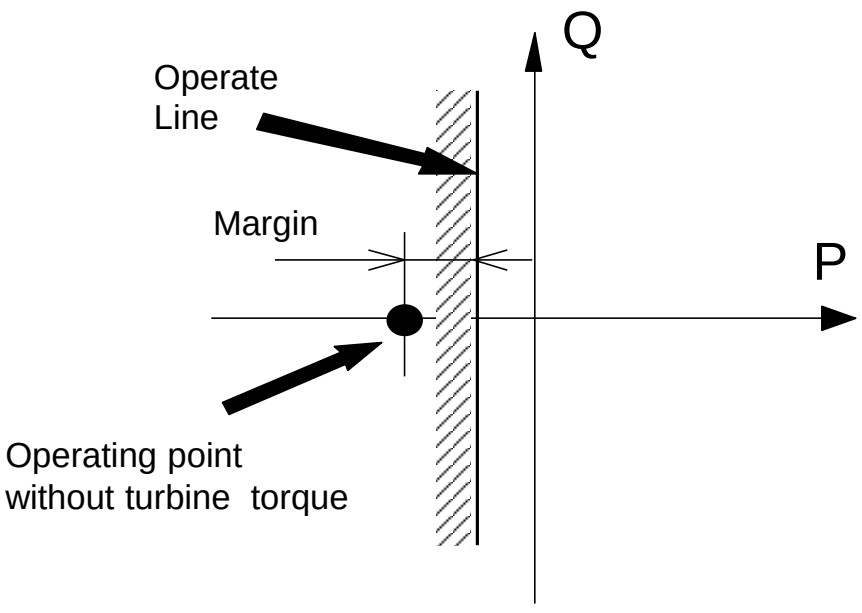
Generator motoring protection 32/37

- 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

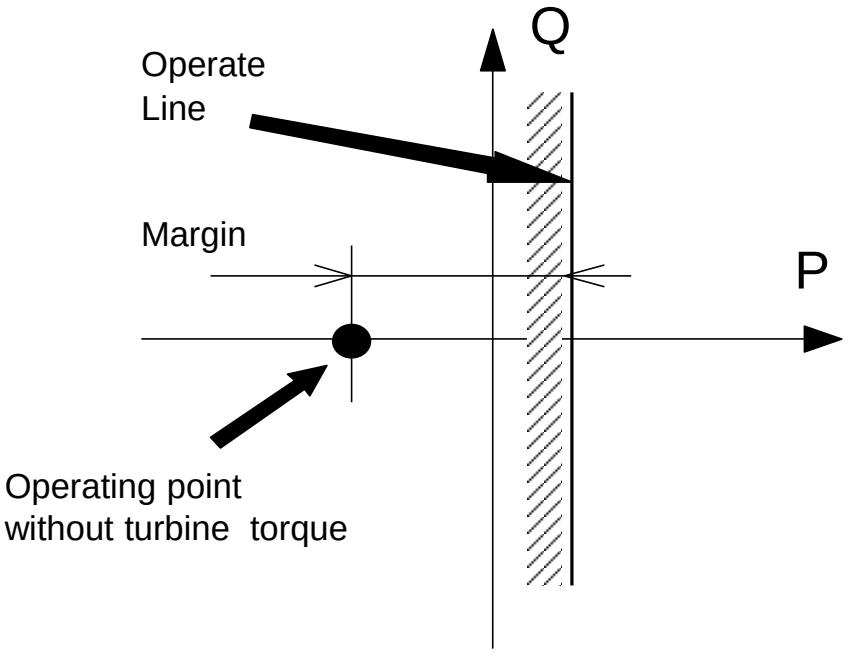
- Causes
  - loss of prime-mover
  - low water flow (hydro)
  - load variations / problems
- Effects
  - steam units → overheating of turbine and turbine blades
  - hydro units → cavitation of the blades
- Demands
  - accurate active power measurement (i.e. P~0 & Q=30-60%)

Reverse power protection



- Set desired pickup (0,5 to 3%)
- Angle to 180 deg
- Set time delay 5-30 s
- Sequential tripping logic (allowed to operate only when steam valve is closed)

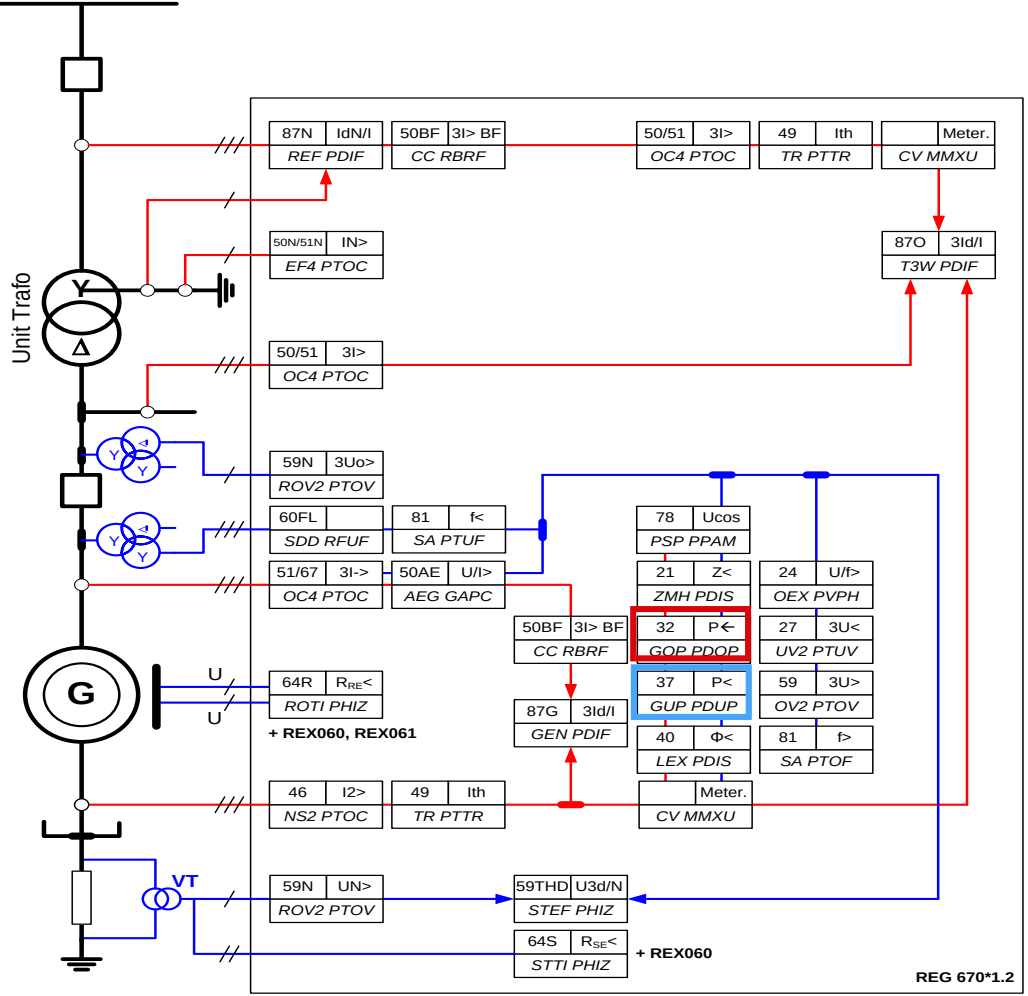
Low forward power protection



- Set desired pickup (1 to 10%)
- Angle to 0 deg
- Set time delay 5-30 s
- Sequential tripping logic
- Blocked by external signal when generator is not loaded
- Sequential tripping (allowed to operate only when steam valve is closed)

Reverse Power Protection (32R)

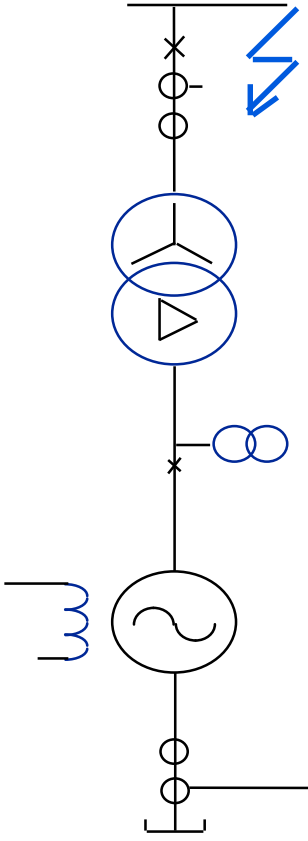
- Endangering condition
  - Motor operation
- Protected object
  - Turbine
- Consequences
  - Excessive heating of turbine blades (steam units)
  - Mechanical damages to thrust bearing (Francis turbines)
  - Explosion risk for diesel units

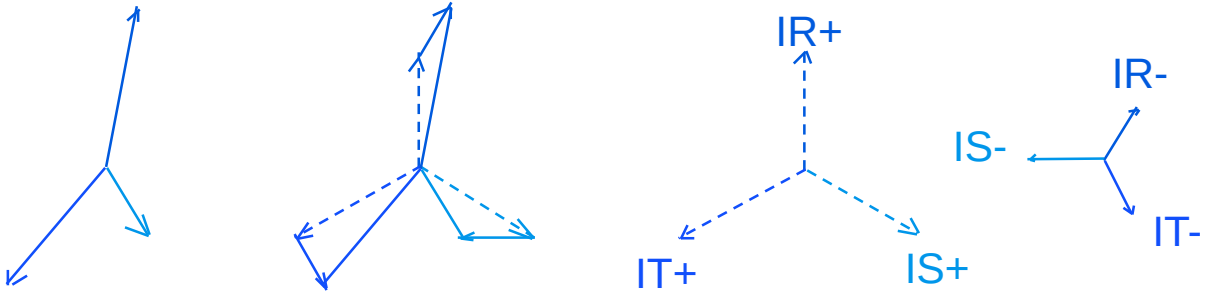


Main Protection Function

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.

I- , I nsc

46

$$I_2^2 \times t = k$$

Negative phase sequence (46)

Causes

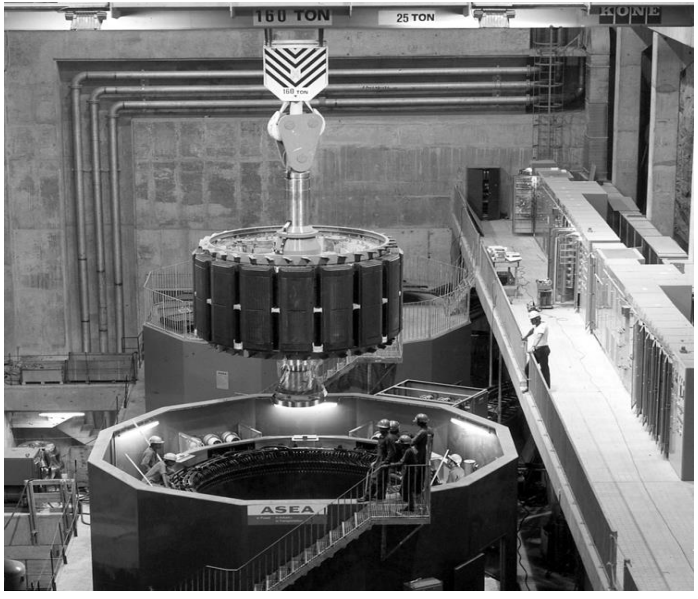
- unbalanced loads
- untransposed transmission circuits
- unbalanced system faults
- series faults
- CB pole discrepancy
- open circuits

Features

- Machine damage curve follows $I_2^2\,t=k$

K can be obtained from machine manufacturer

- I2 inverse time OC element should also follow $I_2^2\,t=k$

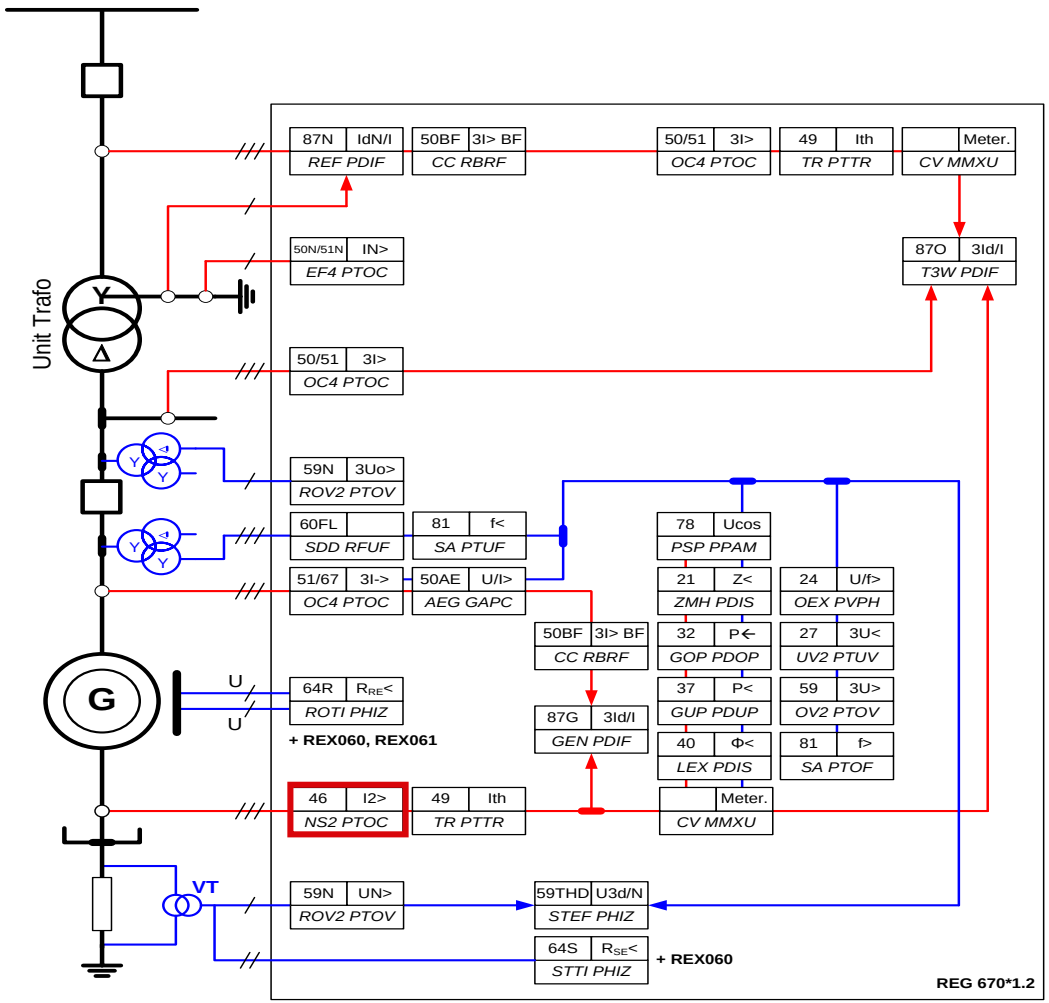


Broken stator winding

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

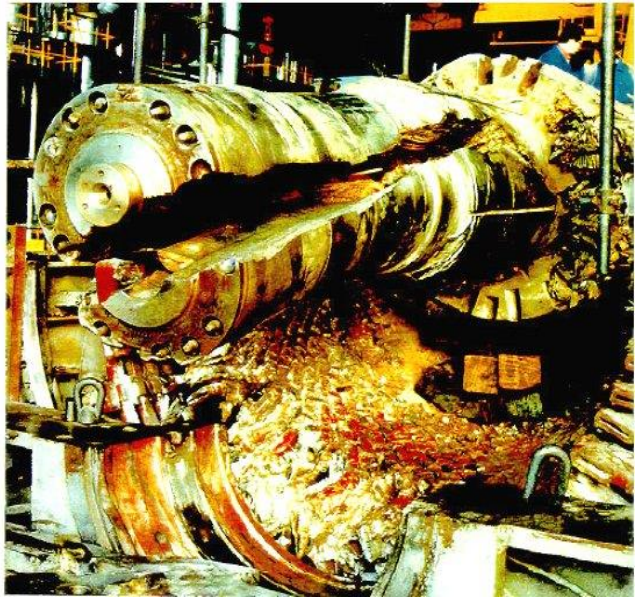
Main Protection Function

Reserve Protection Function

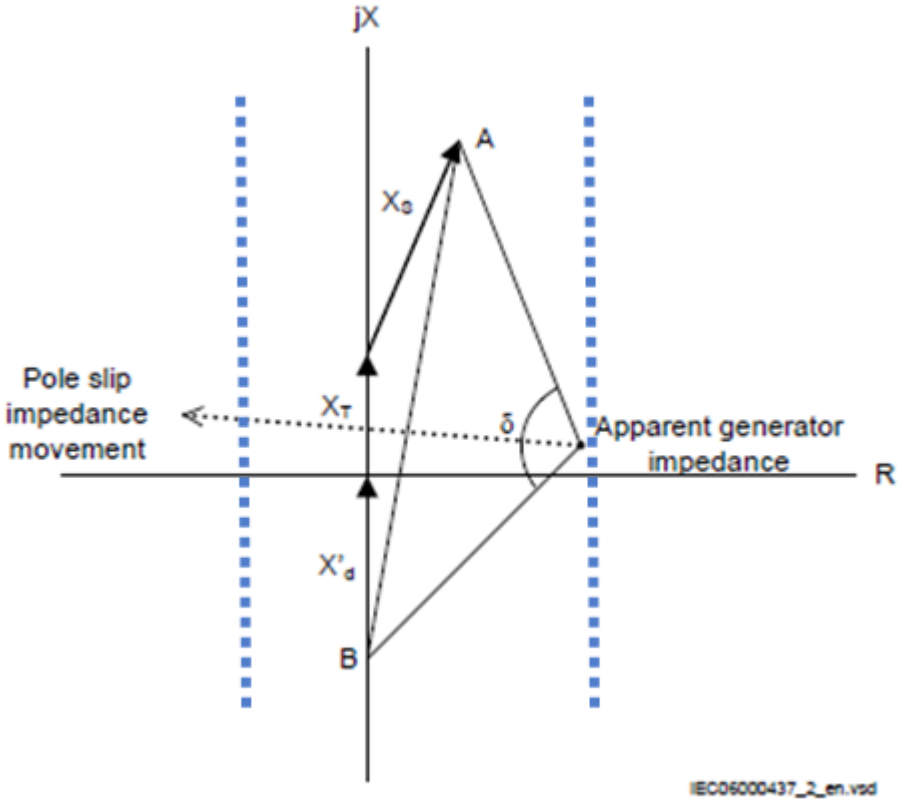


Pole slip / out of step protection (78)

- 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
- destructive 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)



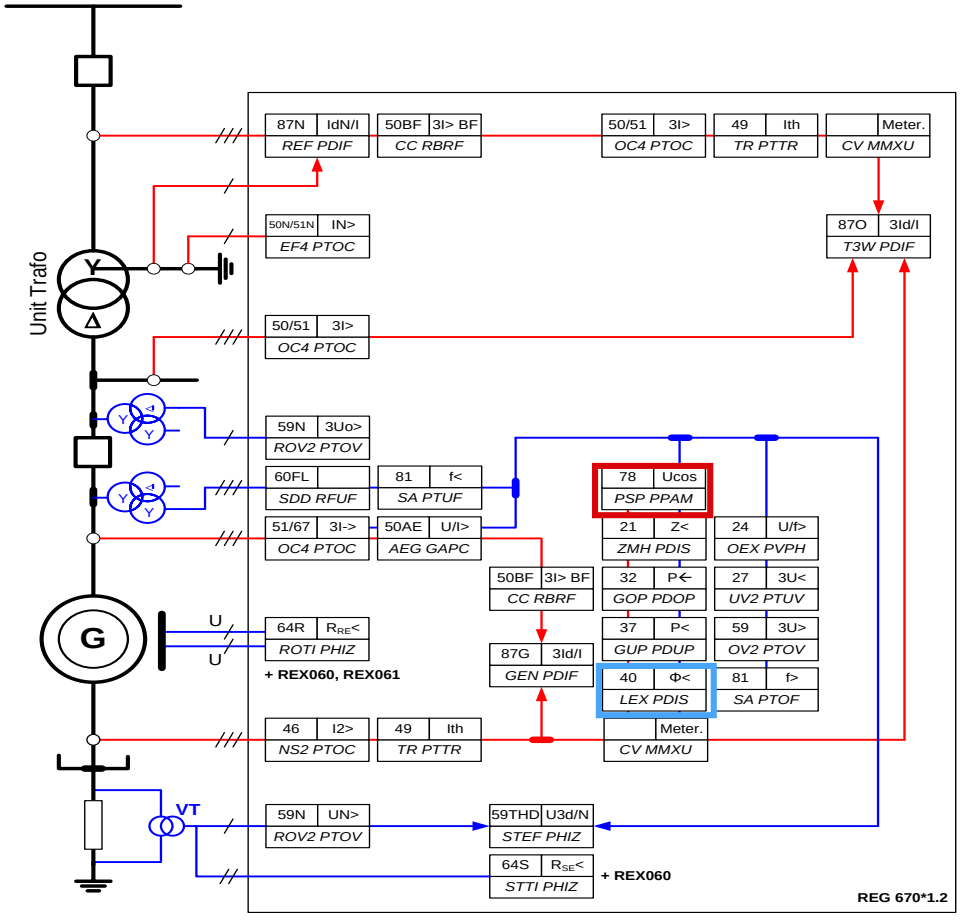
- Monitor the swing impedance loci across the generator unit R-X plane
- 78 function typically locates at the gen terminal (PT/CT location)
- Single or double lens characteristic typically are employed with mho supervision
- Must be secure against generator unit faults or stable power swing
- Double lens (binder) scheme is more secure
- The delta rotor angle can be controlled (thru binder impedance settings) to allow a more favorable phase shift across breaker poles when tripping the breaker
- System transient stability studies to decide who should trip (line or Gen)

Pole slip / out of step protection (78)

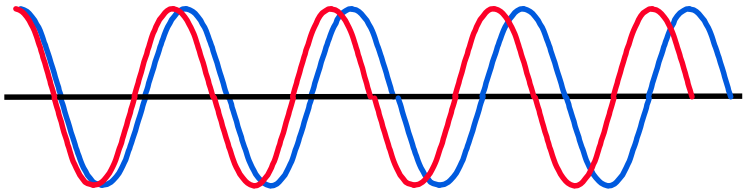
- Endangering condition
  - High stator current
  - Possible system blackout
- Protected object
  - Rotor shaft and stator winding
- Consequences
  - Mechanical damages to shaft
  - Asynchronous machine operation (with field intact)
  - Voltage and current variations

Main Protection Function

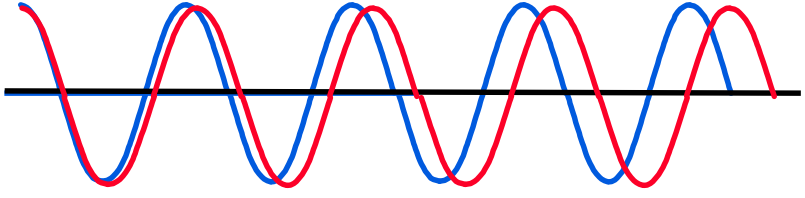
Reserve Protection Function



Frequency protection (81U/O)



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



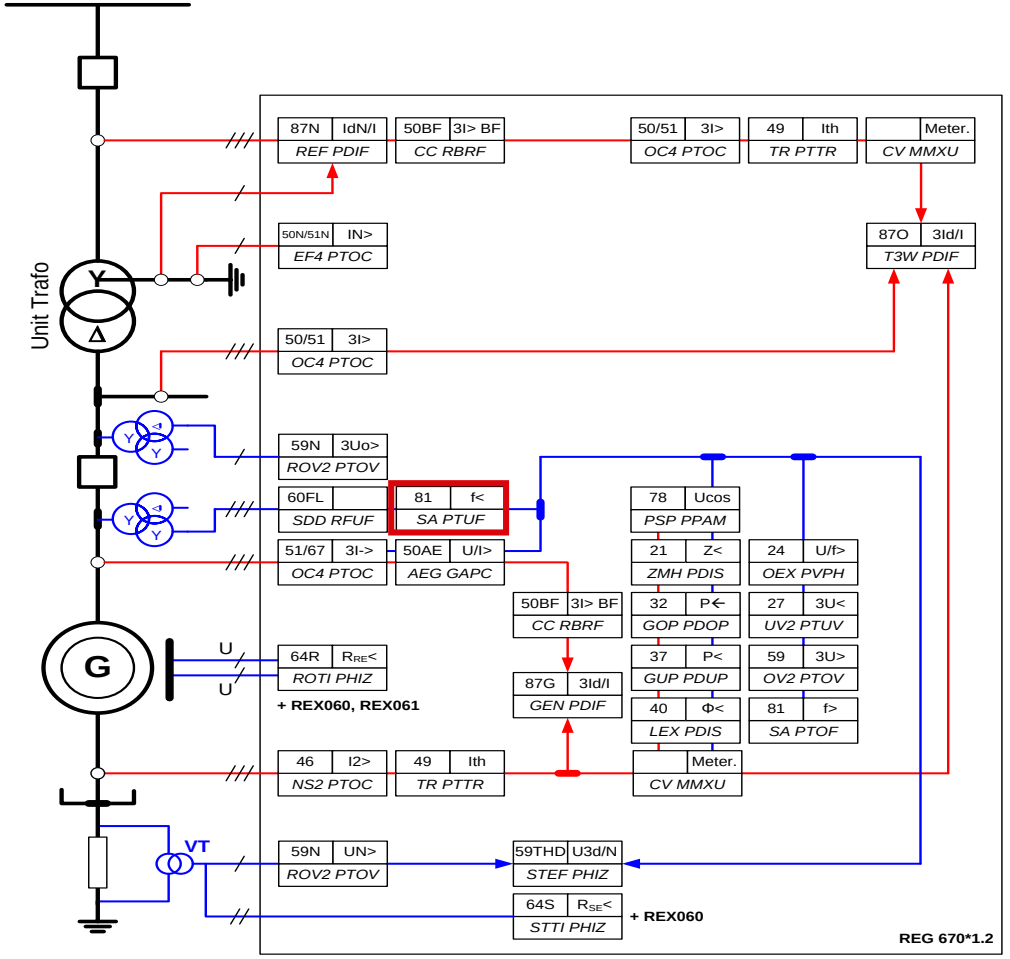
- Under-frequency 81U: protection of the steam turbine at the "critical speed"

Low network frequency (81U)

- Endangering condition
  - Under-frequency
- Protected object
  - Stator end core
  - Steam turbine
- Consequences
  - Over-excitation
  - Steam turbine vibrations

Main Protection Function

Reserve Protection Function

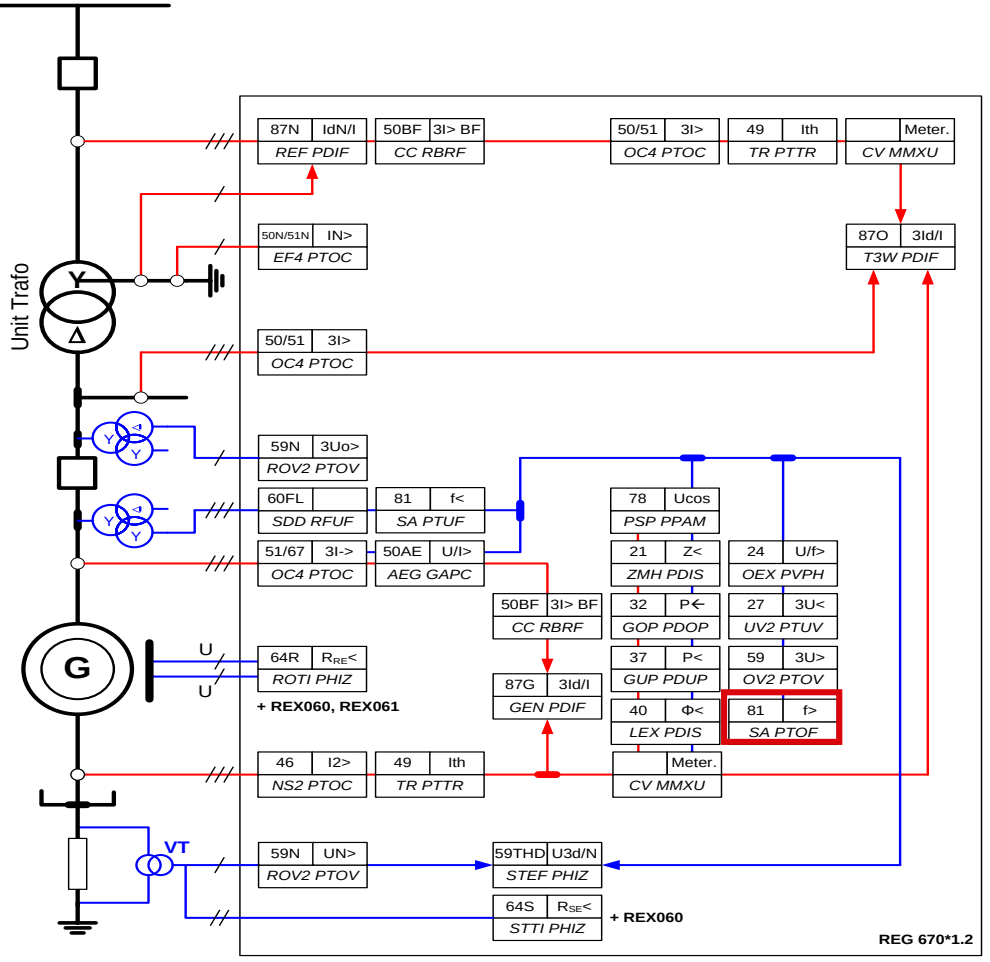


High Network Frequency (81O)

- Endangering condition
  - Over-frequency (load rejection)
- Protected object
  - Turbine (no load rejection capability)
  - Rotor
- Consequences
  - Mechanical stresses
  - Turbine vibrations

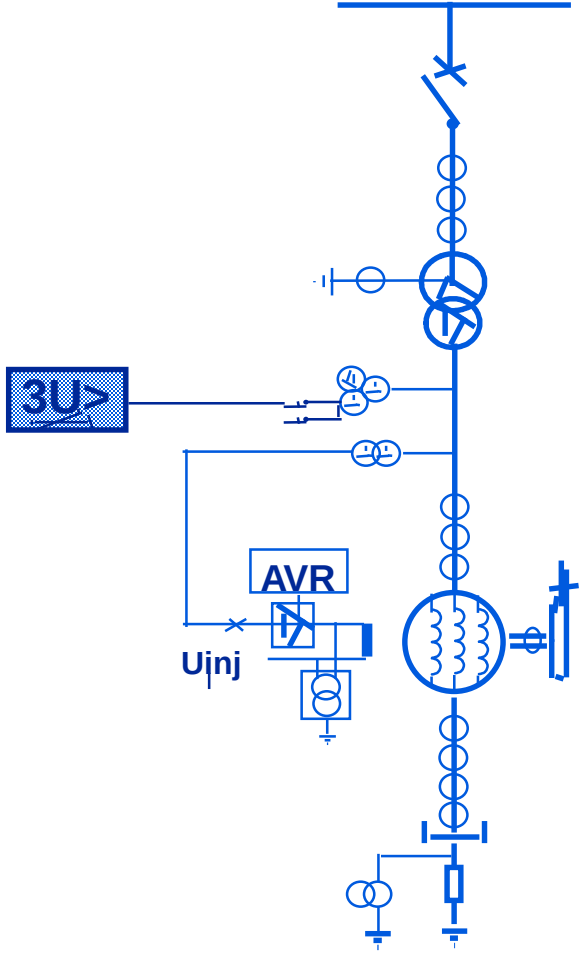
Main Protection Function

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

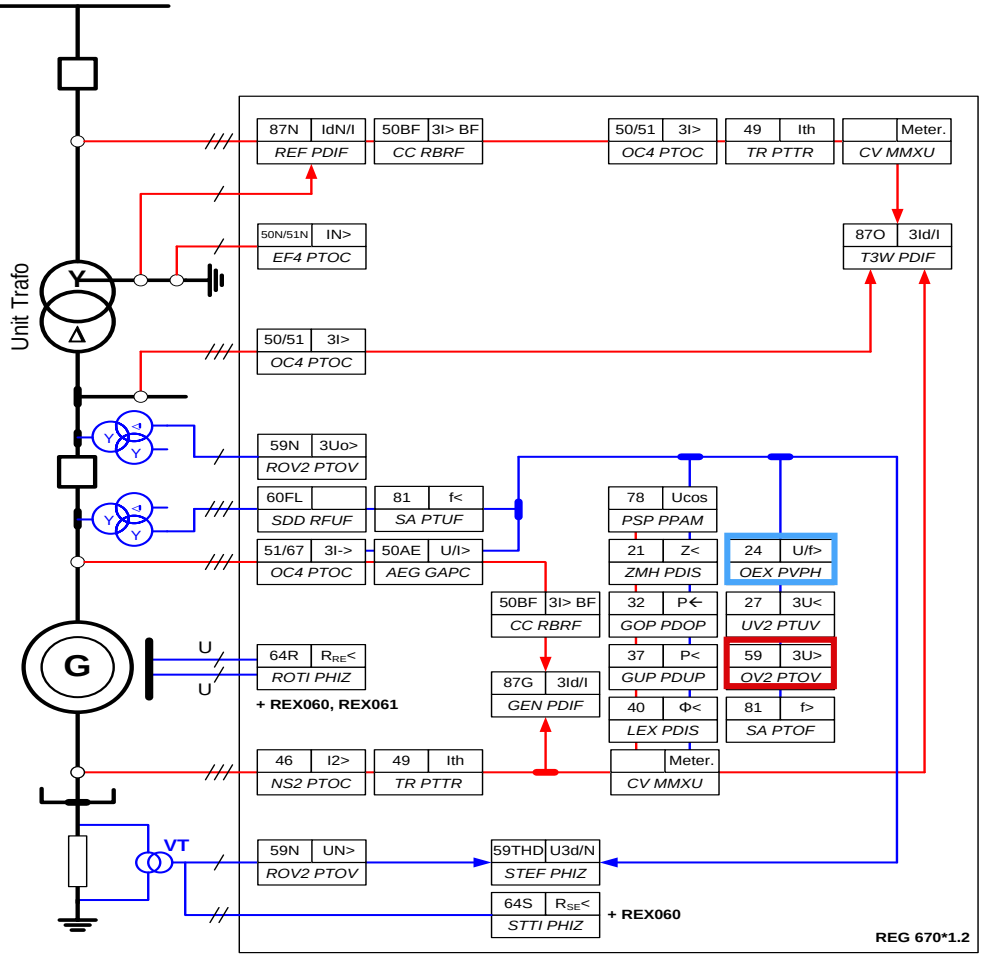


Over-voltage protection (59)

- 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



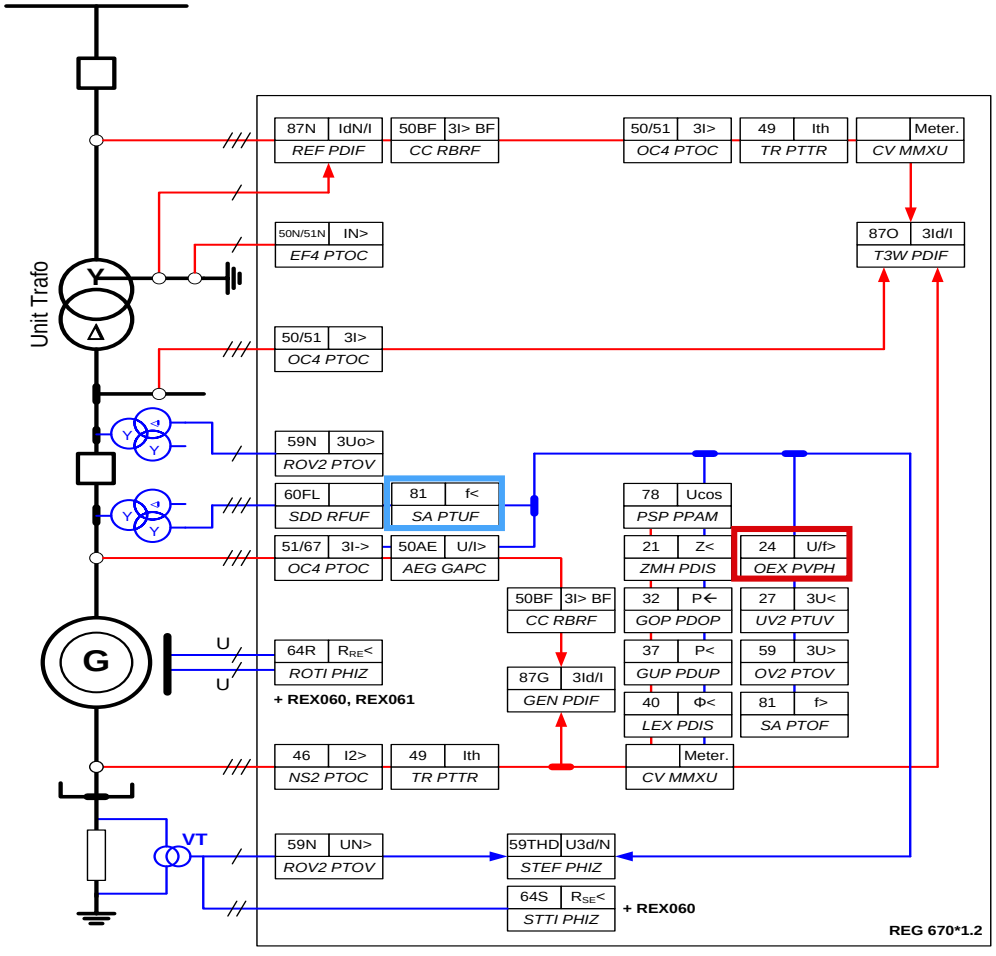
Over-fluxing (excessive V/Hz), 24

- 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

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

Incorrect voltage control (24,)

- Endangering condition
  - Under-frequency/over-voltage
  - Manual synchronization
  - VT failure, AVR failure
- Protected object
  - Transformer/Gen stator core
- Consequences
  - Over-excitation



Main Protection Function

Reserve Protection Function

Accidental energizing, 50AE

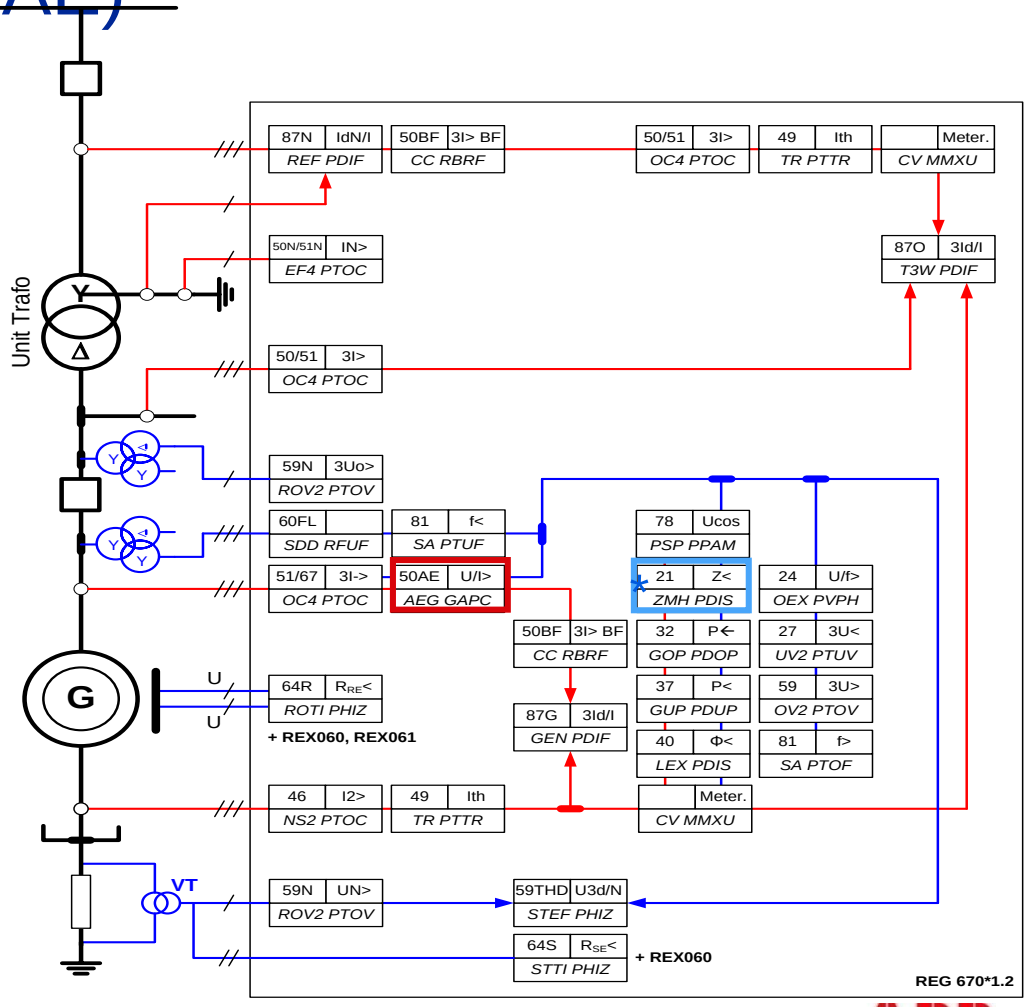
- Operates when generator is energized while offline (field is off)
- Behaved a induction motor
- Significant localized heating damages to rotor surface (I_2 based)
- Operating errors, CB flash-over
- Some relays (functions) usually taken out of service when the Gen is offline (40) or not appropriate
- Dedicated voltage controlled OC most efficient

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)

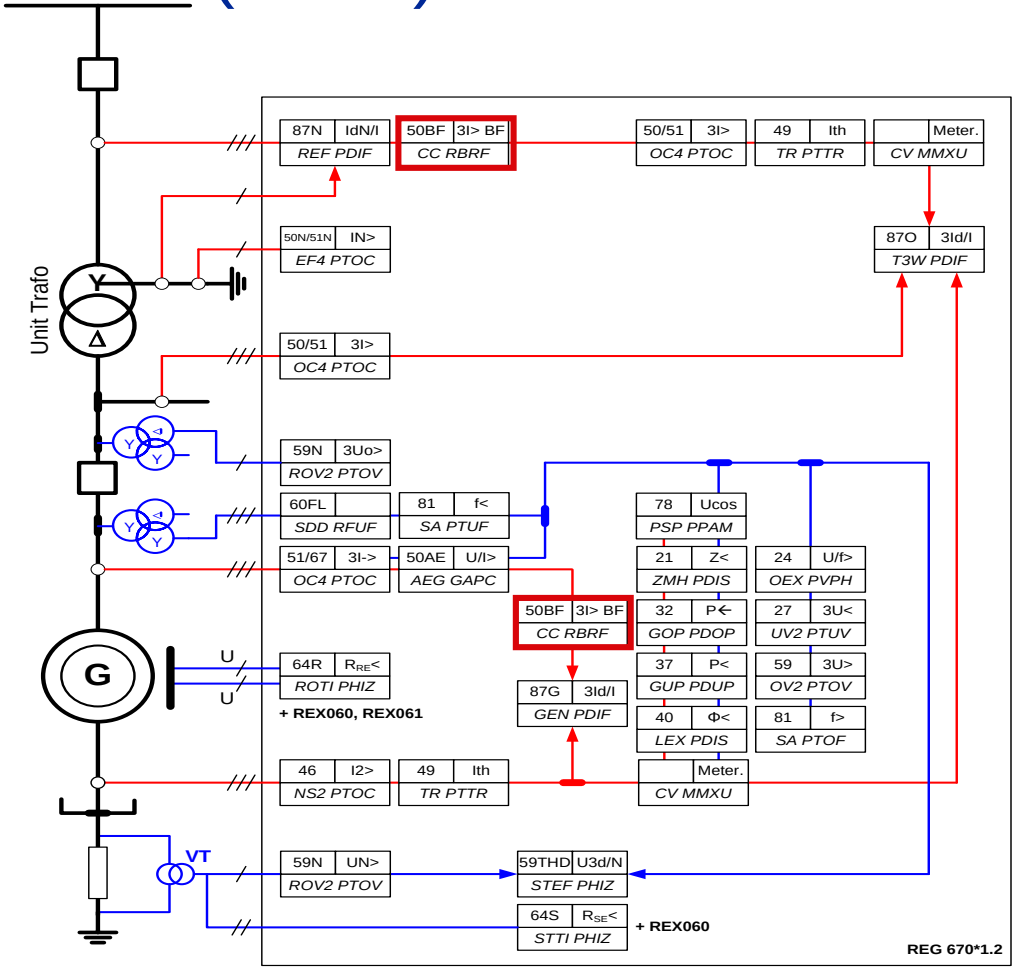
- Issues a back-up trip of adjacent breaker in case of failure of the circuit breaker of the protected object to open (i.e. to interrupt the primary circuit)
- Its operation in most cases trips only local breakers (Gen breaker)
- Commonly uses the bus bar protection disconnector replica logic to route its tripping command to adjacent breakers
- On units without Gen breaker, same BF considerations apply as in the HV breakers (transient stability, DTT requirement)
- Re-trip (t1), Backup trip / bus-strip (t2), Second back-up trip timer (t3)
- Operating mode
  - Current / Contact / Current & Contact

Breaker fails to open the circuit (50BF)

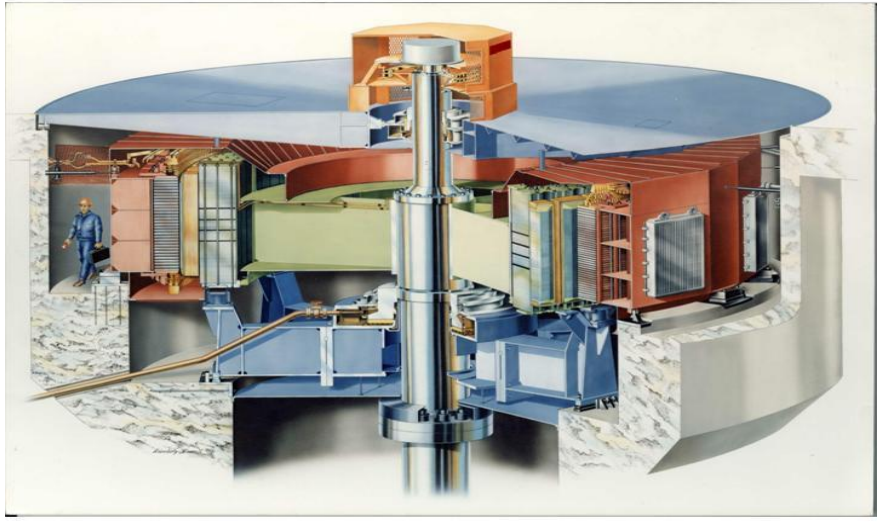
- Endangering condition
  - Stator overcurrent or unsymmetrical currents
- Protected object
  - Electrical circuits
  - Rotor
- Consequences
  - Rotor overheating
  - Stator overheating
  - Prolonged damages caused by the fault current

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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