Protection of Medium-Sized and Large Generators with SIPROTEC 7UM6

1. Introduction

Medium-sized and large generators make a major contribution to power generation. They carry the basic load and ensure the stability of an energy system.

The task of electrical protection in these systems is to detect deviations from the normal condition and to react according to the protection concept and the setting. Based on experience with larger power station units, cost-effective protection concepts can also be implemented with SIPROTEC relays for medium-sized generators.

The scope of protection must be in reasonable relation to the total system costs and the importance of the system.

2. Basic connections

In medium-sized and large power stations the generators are operated exclusively in unit connection.

In the unit connection the generator is linked to the busbar of the higher voltage level via a transformer. In the case of several parallel units, the generators are electrically isolated by the transformers. A circuit-breaker can be connected between the generator and the transformer (see Figs. 2 and 3).

Fig. 1 SIPROTEC generator protection

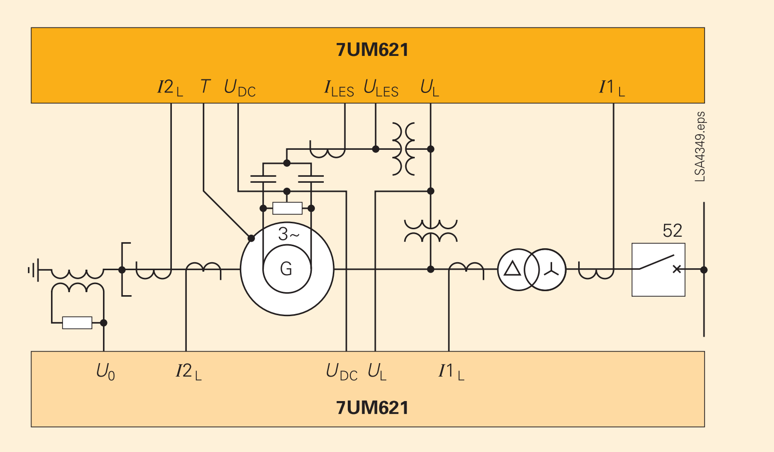

Fig. 2 Block diagram of generator protection

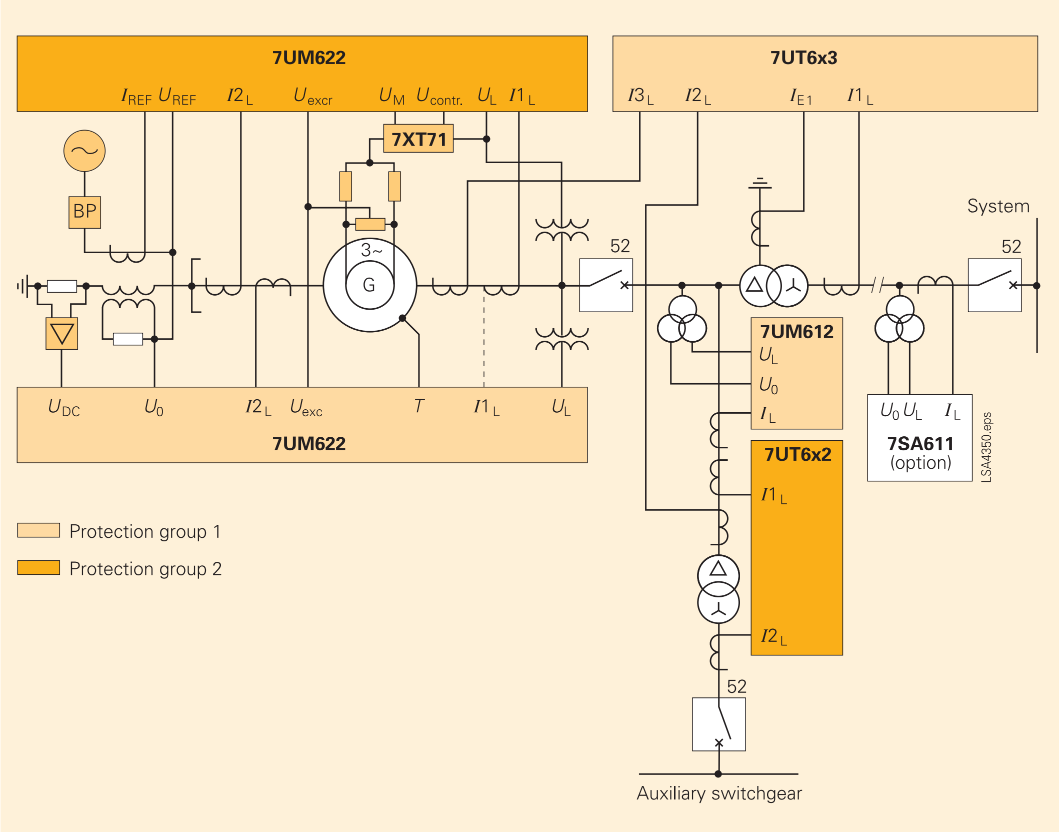

Fig. 3 Redundant protection concept for large generators

3. Protection concept

Components of the protection concept are:

- The redundancy concept
- The tripping concept
- Protection function scope

3.1 Redundancy concept

The redundancy concept is crucial in the design of protection systems. Many concepts are based on the n-1 principle. That means that the failure of a component is under control and does not lead to a total system failure. However, this principle is not always applied consistently. In smaller systems there is a compromise between redundancy and costs. The following strategies are common in practice for medium-sized and large generators.

Partial redundancy (see Fig. 4)

At least 2 protection relays are used here. The protection relays/functions are selected so that the system can continue to operate when a relay fails. However, certain restrictions have to be accepted. This system design is seldom used in high-power generators. The protection is connected to the same transformers for example.

Full redundancy (see Fig. 5)

In this system design the redundancy concept is applied consistently throughout by duplicating all the essential components. As shown in Fig. 5, the redundancy begins with separate transformers or transformer cores, continues through the protection relays, and the TRIP signal is passed through separate DC voltage paths to switchgear with 2 circuit-breaker coils (see Fig. 5). In the protection relays the protection functions can be duplicated on the one hand; on the other hand additional protection functions with different measuring principles are desired. Typical examples are earth-fault and short-circuit protection.

The displacement voltage measurement covers about 90 % of the protected zone in the event of an earth fault. The totally different method – injecting an external voltage (20 Hz) into the stator circuit – ensures 100 % protection.

The same can be implemented for the short-circuit protection. The main protection is the fast and selective current differential protection. Supplementary to this, impedance protection is used, with which the backup protection for the power system protection can be achieved by appropriate grading.

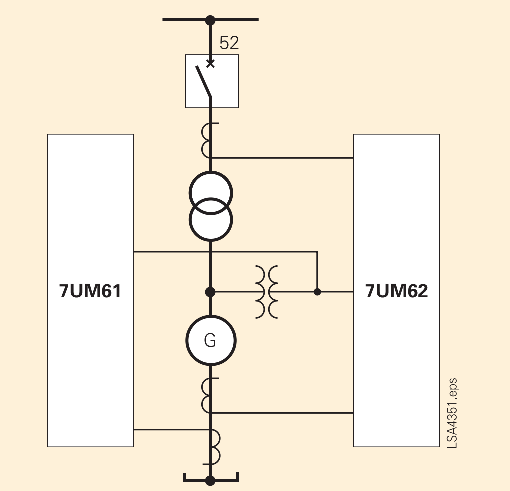

Fig. 4 Example: Partial redundancy

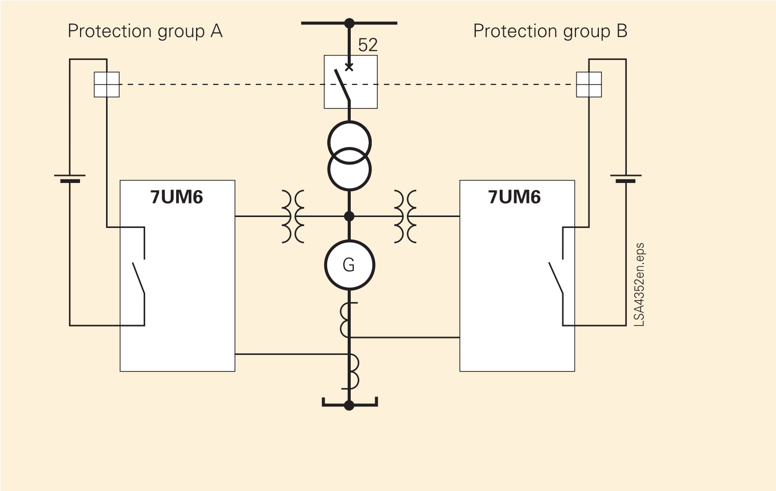

Fig. 5 Example: Full redundancy

3.2 Tripping concept

The special feature of generator protection is that different switching devices have to be activated depending on the fault. The number is basically determined by the system/plant concept. As a rule, most of the switching devices need to be actuated in the larger units. Special trippings are used in hydro-electric power stations.

Fig. 6 shows the basic concepts. On one side there are the switching devices to be actuated and on the other side the connected protection functions. The tripping program or tripping concept depends on the recommendations/experiences and the operating conditions. There are two opposing philosophies. The tripping program is determined individually by a tripping matrix (a software matrix in digital technology) and the switching devices are activated directly. The other (American-influenced) variant reduces the tripping to two programs, e.g. exclusive shutdown of the generator and shutdown of the power station unit. Lockout relays are used to control the switching devices. The protection needs only a few trip contacts.

3.3 Protection function scope

Numerous protection functions are necessary for reliable protection of electrical generators. The scope and the combination are determined by various factors such as generator size, operating principle, system design, availability requirements, experiences and philosophies. This automatically leads to a multifunctionality which can be controlled excellently by numerical technology.

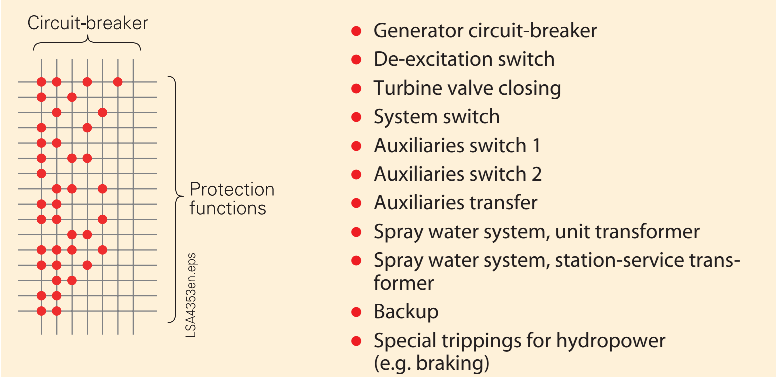

Fig. 6 Protection tripping by the matrix

The function matrix is scalable to meet different requirements (see Table 1).

The selection simplifies division into object and application-related groups.

Protection functions	Generator rated power		
	5 - 50 MVA	50 - 200 MVA	> 200 MVA
Stator earth-fault protection 90 %	■	■	■
Stator earth-fault protection 100 %		■	■
Differential protection	■	■	■
Overcurrent-time protection	■	○	○
Impedance protection		■	■
Rotor earth-fault protection	■	■	■
Negative-sequence (or load unbalance) protection	■	■	■
Underexcitation protection	■	■	■
Out-of-step protection		○	■
Stator overload protection	■	■	■
Rotor overload protection			■
Overvoltage protection	■	■	■
Frequency protection *f* >	■	■	■
Frequency protection *f* <	■	■	■
Reverse-power protection	■	■	■
Undervoltage protection	⊙	⊙	⊙
Overexcitation protection	○	■	■

■ Available
○ Optional
⊙ Pumped-storage station (motor protection and phase modifier operation)

Table 1 Recommended protection functions according to generator rated power

A function selection taking redundancy into consideration is shown in Table 2.

Protection group A (System 1, 7UM622)	Protection group B (System 2, 7UM622)
Stator earth-fault 100 %	Stator earth-fault 90 %
Differential protection	Differential protection (as unit protection)
Impedance	Impedance
Rotor earth-fault	Negative-sequence
Negative-sequence	Underexcitation
Underexcitation	Out-of-step
Overvoltage	Stator overload
Frequency *f* ><	Overvoltage
Reverse power	Frequency *f* ><
Overexcitation	Reverse power
	Overexcitation

Table 2 Function selection for a redundancy concept

4. Protection functions and setting

The basic connection (Fig. 2) is considered for the setting value calculation – with generator data from the Table 3. Manufacturer characteristics (e.g. power diagram) are necessary for some protection settings. The physical backgrounds and the formulae for calculation are in the manual. The secondary setting values are shown.

Generator data	
Rated voltage U_N	15.75 kV ± 5 %
Rated apparent power (40 °C cold gas) S_N	327 MVA
Circuit-breaker cos φ	0.8
Rated active power P_N	261.6 MW
Rated current I_N	12 kA
Rated frequency f_N	50 Hz
Maximum overexcitation (U/f)max %	from the manufacturer’s overexcitation characteristic
Permissible overexcitation duration t (U/f)max	from the manufacturer’s overexcitation characteristic
Synchronous longitudinal reactance x_d (for drum rotor generators: $x_d = x_q$)	264.6 %
Transient reactance x_{d1}	29.2 %
Maximum exciter voltage $U_{exc\text{-}min}$	77 V
Maximum continuous permissible inverse current $I_{max\ prim}$ / I_N	10 %
Thermal continuous permissible primary current I_{max} / I_N	1.2
Asymmetry factor (I_2) K = $(I_2/I_N)^2$ t	20 s

Current transformer	I_{prim}	I_{sec}	ü	Target
Star-point side				
T1, core 1	14 kA	1 A	14 000	System 1
T1, core 3	14 kA	1 A	14 000	System 2
Busbar side				
T2, core 1	14 kA	1 A	14 000	System 1
T2, core 3	14 kA	1 A	14 000	System 2
110 kV side				
T3, core 1	2 000 A	1 A	2 000	System 2

Earthing transformer	U_{prim}	U_{sec}	ü	Target
T4; U_0	15.75 kV/$\sqrt{3}$	5 V/$\sqrt{3}$	54.56	System 1

External voltage transformer	U_{prim}	U_{sec}	ü	Target
Generator side T5, U_{L1}, U_{L2}, U_{L3}	15.75 kV/$\sqrt{3}$	100 V/$\sqrt{3}$	157.5	System 1, 2

Unit transformer data Vector group	Ynd5	
Total coupling capacity HV-LV C_k	14.4 nF (4.8 per phase)	
Maximum overexcitation (U/f)max	120 %	
Permissible overexcitation time t (U/f)max	from the manufacturer’s overexcitation characteristic	
Permissible overload I_{max} / I_N	from the manufacturer’s overexcitation characteristic	
Winding	Primary	Secondary
Rated voltage U_N	115 kV	15.75 kV
Rated apparent power S_N	318 MVA	318 MVA
Rated current I_N	1.596 kA	11.657 kA
Short-circuit voltage u_{SC}	15 %	
Control range of the tap changer	± 9 x 1.25 %	

Table 3 Data of the power station unit with gas turbine

4.1 Current differential protection (ANSI 87G, 87M, 87T)

The function is the instantaneous short-circuit protection in generators, motors and transformers and is based on the current differential protection principle (node set). The difference and restraint (stabilization) current is calculated from the phase currents. Optimized digital filters safely attenuate disturbance variables such as aperiodic DC elements and harmonics. The high resolution of the measuring variables enables small difference currents (10 % of I_N) to be picked up, i.e. a very high sensitivity. A settable restraint characteristic allows optimum adaptation to the conditions of the protected object.

Setting instructions

An important setting is the position of the star points of the current transformer sets on both sides of the protected object. In addition, the rated data ($S_{\mathrm{N\ GEN/MOTOR}}$, $U_{\mathrm{N\ GEN/MOTOR}}$) of the generator to be protected and the primary and secondary rated currents of the main current transformers are requested on both sides. The setting values refer to these. In addition, they are used for example to determine the primary measured values.

As an additional security measure against unwanted operation when connecting a previously non-energized protected object, the increased pickup value can be switched on when starting up.

The table below shows the setting options of selected parameters. The settings are relevant for the generator and not for the unit (protection group A).

Parameter	Setting options	Default *)
Pickup value of the trip stage $I_{\mathrm{diff}}>$	0.05 to 2.0 I/I_{NObject}	0.2 I/I_{NObject}
Delay of the trip stage $I_{\mathrm{diff}}>$	0 to 60.0 s; ∞	0.00 s
Pickup value of the trip stage $I_{\mathrm{diff}}>>$	0.05 to 12.0 I/I_{NObject}	7 I/I_{NObject}
Delay of the trip stage $I_{\mathrm{diff}}>>$	0 to 60.0 s; ∞	0.00 s
Slope 1 of the trip characteristic	0.1 to 0.5	0.15
Foot of slope 1 of the trip characteristic	0 to 2.0 I/I_{NObject}	0 I/I_{NObject}
Slope 2 of the trip characteristic	0.25 to 0.95	0.5
Foot for slope 2 of the trip characteristic	0 to 10.0 I/I_{NObject}	2.50 I/I_{NObject}

Table 4 Parameter overview for the differential protection

4.2 Stator overload protection (ANSI 49)

The overload protection should protect the stator winding of generators and motors against excessively high continuous current overloads. All load cycles are evaluated by a mathematical model. The basis for the calculation is the thermal effect of the current r.m.s. value. The transformation corresponds to IEC 60255-8.

Setting instructions

The cooling time constant is prolonged automatically, dependent on the current. If the ambient temperature or coolant temperature is fed in through a transducer (MU2) or via the PROFIBUS-DP, the model automatically adapts to the ambient conditions; otherwise a constant ambient temperature is assumed.

The following table shows the setting options and the setting example of important parameters (without taking the ambient or coolant temperature into account).

Parameter	Setting options	Setting
k-factor	0.1 to 4.0	1.11
Thermal warning level	70 to 100 %	95 %
Current warning level	0.1 to 4.0 A	1.0 A
k_t-time factor at standstill	1.0 to 10.0	1.0
Limit current for the thermal replica	0.5 to 8.0 A	3.30 A
Dropout time after emergency start	10 to 15000 s	100 s

Table 5 Parameter overview for the stator overload protection

The setting ranges and presettings (defaults) are specified for a secondary rated current of $I_N = 1$ A. At a secondary rated current of $I_N = 5$ A, these values must be multiplied by 5. The ratio of the current transformer must be taken into account additionally for settings of primary values.

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*) In this example, most of the default settings can be used.

4.3 Negative-sequence protection (ANSI 46)

Asymmetrical current loads of the three phases of a generator lead to heating up in the rotor due to the reverse field. The protection detects an unbalanced load of three-phase generators. It operates on the basis of symmetrical components and evaluates the negative-sequence component of the phase currents. The thermal processes are taken into account in the algorithm and lead to an inverse-time characteristic. In addition, the negative-sequence is evaluated by a definite-time warning and tripping stage which is supplemented by delay elements.

Setting instructions
Thermal characteristic

The generator manufacturers specify the permissible negative-sequence with the following formula:

$$t_{\text{perm}} = \frac{K}{\left(\frac{I_2}{I_N}\right)^2}$$

t_{perm} = Maximum permissible application time of the negative-sequence current I_2

K = Asymmetry factor (generator constant)

I_2/I_N = Negative-sequence (ratio of negative-sequence current I_2 to rated current I_N)

The asymmetry factor is generator-dependent and represents the time in seconds for which the generator may be loaded at the maximum with 100 % unbalanced load. The factor is mainly in the range between 5 s and 30 s. On exceeding the permissible load unbalance (value of the continuously permissible negative-sequence current), simulation of the heating of the object to be protected in the relay begins. The current-time-area is calculated continuously taking different load cases correctly into consideration. If the current-time-area $((I_2/I_N)^2 \cdot t)$ reaches the asymmetry factor K, tripping takes place with the thermal characteristic.

Table 6 shows the setting options and the setting example.

Parameter	Setting options	Setting
Continuously permissible load unbalance	3.0 to 30.0 %	8.6 %
Delay time of warning stage	0 to 60.0 s; ∞	10.0 s
Asymmetry factor K	2.0 to 100.0 s; ∞	11 s
Cooling time of thermal model	0 to 50000 s	1500 s
Excitation current I_2>>	10 to 100 %	51.4 %
Delay time T I_2>>	0 to 60.0 s; ∞	3.0 s

Table 6 Parameter overview for negative-sequence protection

4.4 Underexcitation protection (ANSI 40)

The protection prevents damage due to out-of-steps resulting from underexcitation. The complex master value is calculated from the generator terminal voltage and current. The protection function offers three characteristics for monitoring the static and dynamic stability. The exciter voltage can be fed in through a transducer and a fast response of the protection can be achieved by timer switching in the event of a failure. The straight line characteristics allow optimum adaptation of the protection to the generator diagram. The setting values can be read out directly from the per-unit representation of the diagram. The positive-sequence components of the currents and voltages are used for calculating the variables, whereby correct operation is ensured even under asymmetrical conditions.

Setting instructions

The tripping characteristics of the underexcitation protection are made up of straight lines in the master value diagram, defined by their reactive part of the admittance $1/x_d$ and their angle of inclination α.
Table 7 shows the settings for this application example.

Parameter	Setting options	Default *)
Pickup threshold $1/x_d$ characteristic 1	0.25 to 3.0	0.37
Characteristic slope characteristic 1	50 to 120 °	80 °
Delay time characteristic 1	0 to 60.0 s; ∞	10.0 s
Pickup threshold $1/x_d$ characteristic 2	0.25 to 3.0	0.33
Characteristic slope characteristic 2	50 to 120 °	90 °
Delay time characteristic 2	0 to 60.0 s; ∞	10.0 s
Pickup threshold $1/x_d$ characteristic 3	0.25 to 3.0	1.0
Characteristic slope characteristic 3	50 to 120 °	100 °
Delay time characteristic 3	0 to 60.0 s; ∞	1.5 s

Table 7 Parameter overview for underexcitation protection

*) In this example, most of the default settings can be used.

4.5 Reverse-power protection (ANSI 32R)

The reverse-power protection monitors the active power direction and picks up in the event of a mechanical energy failure, because the drive energy is then taken out of the system. This function can be used for operational shutdown of the generator but also prevents damage to steam turbines. The position of the emergency tripping valve is entered as binary information. This switches between two delays of the open command. The reverse power is calculated from the positive phase sequence systems of current and voltage. Asymmetrical system conditions therefore do not impair the measuring accuracy.

If reverse power occurs, the turbo set must be disconnected from the system, because operation of the turbines is not permissible without a certain minimum steam throughput (cooling effect), or the motorized load is too great for the system in a gas turbo set.

The trip command is delayed by an adjustable time to bridge any brief power consumption during synchronization or in the event of power swings due to system faults. In the event of a closed emergency tripping valve on the other hand, the unit must be shut down with a short delay. By entering the position of the emergency tripping valve through a binary input, the short delay becomes effective in the event of emergency tripping. It is also possible to block the tripping by means of an external signal.

The value of the consumed active power is determined by the friction losses to be overcome and, depending on the system, is approximately:

- Steam turbines: $P_{\mathrm{rev}}/S_{\mathrm{N}}$ 1 % to 3 %
- Gas turbines: $P_{\mathrm{rev}}/S_{\mathrm{N}}$ 3 % to 5 %
- Diesel drives: $P_{\mathrm{rev}}/S_{\mathrm{N}} > 5$ %

However, it is advisable to measure the reverse power with the protection itself in the primary test. About 0.5 times of the measured motoring energy, which can be read out under the “percentage operational measured values”, is chosen as a setting value.

Table 8 shows the setting of selected parameters.

Parameter	Setting options	Setting
Delay time with emergency tripping	0 to 60.0 s; ∞	∞ s
Delay time without emergency tripping	0 to 60.0 s; ∞	6.00 s
Pickup threshold reverse power	30.0 to 0.50 %	-3.42 %
Pickup seal-in time	0 to 60.0 s; ∞	1.00 s

Table 8 Parameter overview of reverse-power protection

4.6 Impedance protection (ANSI 21)

This fast acting short-circuit protection protects the generator or unit transformer on the one hand and is the backup protection for the system. It has two adjustable impedance stages whereby the first stage is additionally switchable by a binary input. The impedance measuring range can be extended with open system switch. The overcurrent pickup with undervoltage seal-in provides reliable pickup and loop selection logic for determining the faulty loop. It also allows correct measurement through the transformer.

Setting instructions

The maximum load current occurring during operation is decisive for setting the overcurrent pickup. Pickup by overload must be ruled out. The pickup value must therefore be set above the maximum expected (over) load current. Recommended setting: 1.2 to 1.5 times rated generator current.

The pickup logic corresponds to that of the definite-time overcurrent protection $I>$. If the excitation is derived from the generator terminals and the short-circuit current is able to drop below the pickup value due to collapsing voltage, the undervoltage seal-in is activated.
The undervoltage seal-in $U<$ is set to a value just below the lowest phase-to-phase voltage occurring during operation, e.g. to $U< = 75$ % to 80 % of the rated voltage. The seal-in time must be greater than the maximum fault clearance time in the backup case. (Recommended: This time + 1 s).

As described in the manual, the protection has three characteristics which can be set independently:

- Zone (instantaneous zone Z1) with the setting parameters
  ZONE Z1 reactance = reach,
  ZONE1 T1 = 0 or short delay if necessary.
- Overreach zone Z1B, controlled externally by a binary input with the setting parameters
  OVERR. Z1B reactance = reach,
  OVERR. T1B T1B = 0 or short delay if necessary.
- 2nd zone (Zone Z2) with the setting parameters
  ZONE Z2 reactance = reach,
  ZONE2 T2 T2 should be chosen so high that it is above the grading time of the system protection.
- Undirected final stage with the setting parameters T END T END must be chosen such that the second or third stage of the series-connected power system distance protection is overreached.

Since it can be assumed that the impedance protection measures into the generator transformer, it must be ensured that the parameterization selection sufficiently considers the control range of the transformer. For ZONE Z1, a reach of about 70 % of the zone to be protected is therefore normally chosen (i.e. about 70 % of the transformer reactance) without or with only slight delay (i.e. = 0 s to 0.50 s).

For ZONE Z2, the reach could be set to about 100 % of the transformer reactance or a system impedance additionally. The corresponding time stage ZONE2 T2 must be chosen so that it overgrades the system protection relays of the following lines.

The following settings apply for the configuration example (without activation of the out-of-step block):

Parameter	Setting options	Setting
Pickup value of the overcurrent pickup	0.10 to 20.0 A	1.20 A
Pickup voltage of the undervoltage seal-in	10.0 to 125.0 V	75.0 V
Seal-in time of the undervoltage seal-in	0.1 to 60.0 s	10.0 s
Trip time of the end time stage	0.1 to 60.0 s	3.0 s
Impedance zone Z1	0.05 to 130.0 Ω	7.28 Ω
Trip time zone Z1	0 to 60.0 s; ∞	0.30 s
Impedance overreach stage Z1B	0.05 to 65.0 Ω	11.44 Ω
Trip time overreach stage Z1B	0 to 60.0 s; ∞	8.00 s
Impedance zone Z2	0.05 to 65.0 Ω	11.44 Ω
Trip time Z2	0 to 60.0 s; ∞	8.00 s

Table 9 Parameter overview for the impedance protection

4.7 Overvoltage protection (ANSI 59)

This protection prevents insulation faults as a result of high voltage. Optionally the maximum phase-to-phase voltages or phase-to-earth voltages (in low-voltage generators) can be evaluated. In the phase-to-phase voltages, the measuring result is independent of the zero point displacements resulting from earth-faults. The protection function is designed in two stages.

The setting of the limit values and delay times of the overvoltage protection depends on the speed at which the voltage regulator can regulate voltage fluctuations. The protection may not intervene in the regulating process of the voltage regulator when it is operating trouble-free. The two-stage characteristic must therefore always be above the voltage time characteristic of the regulating process.

Setting instructions

The long-time stage $U>$ and T $U>$ should intervene in the case of steady-state overvoltages. It is set to about 110 to 115 % U_N and to 1.5 to 5 s, depending on the regulator speed. In the event of a full load disconnection of the generator, the voltage first rises according to the transient voltage and is reduced to its rated value by the voltage regulator afterwards. The $U>>$ stage is generally set as a short-time stage so that the transient process in full load shutdown does not lead to tripping. About 130 % U_N – with a delay T $U>>$ ranging from zero to 0.5 s – are usual (for example) for $U>>$.

Parameter	Setting options	Default *)
Pickup voltage *U*>	30 to 170 V	115 V
Delay time *T U*>	0 to 60 s; ∞	3 s
Pickup voltage *U*>>	30 to 170 V	130 V
Delay time *T U*>>	0 to 60 s; ∞	0.50 s
Dropout ratio RV *U*>	0.90 to 0.99	0.95

Table 10 Parameter overview for the overvoltage protection

4.8 Frequency protection (ANSI 81)

Frequency protection prevents impermissible loading of the equipment (e.g. turbine) at under and overfrequency, and also serves often as a monitoring and control element. The function is designed in four stages, whereby the stages can operate either as under or overfrequency protection. Each stage can be delayed individually. The complex frequency measuring algorithm also filters out the fundamental harmonic reliably in the event of distorted voltages and determines frequency very accurately. The frequency measurement can be blocked by an undervoltage stage.

Setting instructions

If the frequency protection is used for the task of system decoupling and load shedding, the setting values depend on the concrete system conditions. Usually a grading according to the importance of the consumers or consumer groups is aimed at for load shedding. Other applications are to be found in the power station sector. Basically the frequency values to be set depend on the presettings of the system or power station operator.

The following table shows the settings which meet practical requirements.

Parameter	Setting options	Setting
Pickup frequency *f*1	40 to 65 Hz	47.5 Hz
Delay time *T f*1	0 to 600 s	40 s
Pickup frequency *f*2	40 to 65 Hz	47 Hz
Delay time *T f*2	0 to 100 s	20 s
Pickup frequency *f*3	40 to 65 Hz	51.50 Hz
Delay time *T f*3	0 to 100 s	40 s
Pickup frequency *f*4	40 to 65 Hz	52 Hz
Delay time *T f*4	0 to 100 s	20 s
Minimum voltage	10 to 125 V; 0	65 V

Table 11 Parameter overview for frequency protection

4.9 Overexcitation protection (ANSI 24)

Overexcitation protection serves to detect an impermissibly high induction (proportional to *U*/*f*) in generators or transformers which leads to thermal overloading. This danger can occur in start-up processes, in full load disconnections, in "weak" systems and in separate island operation. The inverse-time characteristic is set with the manufacturer data by way of 8 points. A definite-time alarm stage and a short-time stage can be used additionally. Apart from the frequency, the maximum of the three phase-to-phase voltages is used for calculating the quotient *U*/*f*. The monitorable frequency range is between 11 and 69 Hz.

Setting instructions

The overexcitation protection contains two-staged characteristics and one thermal characteristic for approximate simulation of the heating of the protected object due to overexcitation. On exceeding of an initial pickup threshold (alarm stage *U*/*f*), a time stage T *U*/*f* > is started, at the end of which an alarm message is output.

The limit value of induction in relation to the rated induction (B/B_N) specified by the protected object manufacturer forms the basis for setting the limit value *U*/*f* >.

The characteristic for a Siemens standard transformer has been chosen as default. If the protected object manufacturer supplies no data, the default standard characteristic is retained. Otherwise, any tripping characteristic can be specified by point-by-point input of parameters by a maximum of 7 straight sections.

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*) In this example, most of the default settings can be used.

4.10 90 % stator earth-fault protection directional, non-directional (ANSI 59N, 64G, 67G)

In generators operated with an isolated star point, an earth fault is indicated by occurrence of a displacement voltage. In unit connection, the displacement voltage is a sufficient, selective protection criterion. If a generator is connected electrically to a busbar, the direction of the flowing earth-current must be evaluated additionally for selective earth-fault detection. The protection measures the displacement voltage on a voltage transformer in the generator star point, or at the open delta winding of a voltage transformer. Optionally the zero-sequence voltage can also be calculated from the phase-to-earth voltages. Depending on the system design, 90 to 95 % of the stator winding of a generator can be protected.

When starting, it is possible to switch over to zero-sequence voltage measurement via an externally coupled signal. Various earth-fault protection concepts can be implemented with the function, according to the protection setting.

Setting instructions

For generators in unit connection, the pickup value must be chosen so high that displacement voltages, which affect the stator circuit through the coupling capacitances of the unit transformer, do not lead to pickup. The damping by the load resistance must also be taken into account here. The setting value is twice the displacement voltage value coupled in at full system displacement. Final specification of the setting comes during commissioning with primary variables according to the manual. Tripping in the event of stator earth-fault is set time-delayed (*T* SES). The overload capacity of the load equipment must also be taken into account when setting the delay. All set times are additional delays which do not include the operating times (measuring time, dropout time) of the protection function.

Table 12 shows the setting options for selected parameters. The settings are selected for this protection configuration.

Parameter	Setting options	Setting
Pickup voltage U_0>	2 to 125 V	10 V
Pickup current $3I_0$>	2 to 1000 mA	5 mA
Slope angle of the directional lines	0 to 360 °	15 °
Delay time *T* SES	0 to 60 s; ∞	0.30 s

Table 12 Parameter overview for the stator earth-fault protection

4.11 Rotor earth-fault protection (ANSI 64R)

This protection function can be effected with the 7UM62 in three ways. The simplest form is the method of rotor earth-current measurement (see the manual: Chapter on sensitive earth-fault protection, resistance measurement at system frequency voltage).

The second form is rotor earth-resistance measurement with system frequency voltage coupling into the rotor circuit (see the manual: Chapter on rotor earth-fault protection). The coupled voltage and the flowing rotor earth-current are detected by the protection. Taking account of the complex resistance of the coupling device (7XR61), the rotor earth resistance is calculated by a mathematical model. This form is often used for medium-sized generators.

The third form is resistance measurement with square-wave voltage injection of 1 to 3 Hz. In larger generators a higher sensitivity is required. On the one hand, disturbances caused by the rotor earth capacitance must be eliminated better, and on the other hand the interference margin to the harmonic (e.g. 6th harmonic) of the exciter device must be increased. The injection of a low-frequency square-wave voltage into the rotor circuit has proven effective here (recommended for this application). The square-wave voltage injected by the controller unit 7XT1 leads to polarity reversal of the rotor earth capacitance. Through a shunt in the 7XT1, the flowing earth-current is detected and injected into the protection (measuring input). In a fault-free case ($R_E \sim \infty$), the rotor earth-current after charging of the earth capacitance is nearly zero. In the event of a fault, the earth resistance – including coupling resistance (7XR6004) and the incoming supply voltage – determines the steady-state current. Via the second input (control input), the transfers, the current square-wave voltage and the polarity reversal frequency are recorded. Fault resistances up to 80 kΩ can be detected with this measuring principle.

Monitoring of the rotor earth circuit for interruption takes place by evaluating the current during polarity reversals.

Setting instructions (1 to 3 Hz protection)
Since the protection calculates the resistive rotor earth resistance directly from the values of applied voltage, series resistance and flowing earth-current, the limit values for the alarm stage (R_E WARN) and the trip stage (R_E TRIP) can be set immediately as resistance values. In most cases the preset values (R_E WARN = 40 kΩ and R_E TRIP = 5 kΩ) are sufficient. Depending on the insulation resistance and coolant, these values can be changed. It is important to pay attention to an adequate margin between the setting value and the actual insulation resistance. As a result of possible disturbances due to the exciter device, the setting for the alarm stage is finally determined during the primary tests.
The delay is usually set for the alarm stage (T R_E WARN) to about 10 s, and for the trip stage (T R_E TRIP) to a short time of about 1 s.
The set times are additional time delays which do not include the operating times (measuring time, dropout time) of the protection function.

Parameter	Setting options	Default *)
Pickup value of the alarm stage	5 to 80 kΩ	40 kΩ
Pickup value of the trip stage	1 to 10 kΩ	5 kΩ
Delay time of the alarm stage	0 to 60 s; ∞	10 s
Delay time of the trip stage	0 to 60 s; ∞	1 s

Table 13 Parameter overview for the rotor earth-fault protection

4.12 100 % stator earth-fault protection with 20 Hz injection (ANSI 64 G (100 %))

The injection of a 20 Hz voltage for detection of faults in the star point or close to the star point of generators has proven a safe and reliable method. Unlike the 3rd harmonic criterion (see page 12, Catalog SIP 6.1), it is independent of the generator properties and the operating method. Measurement at system standstill is still possible. This protection function is designed so that it detects earth-faults both in the whole generator (real 100 %) and in all galvanically connected system components. The protection relay detects the injected 20 Hz voltage and the flowing 20 Hz current. Disturbance variables such as stator earth capacitances are eliminated, and the ohmic fault resistance is determined by a mathematical model. As a result, high sensitivity is ensured and the use in generators with high earth capacitances – e.g. large hydroelectric generators – is enabled. Angle faults due to the earthing or star-point transformer are detected during commissioning and corrected in the algorithm. The protection function has a warning and trip stage. In addition, the measuring circuit is monitored and a failure of the 20 Hz generator detected. Regardless of the earth resistance calculation, the protection function additionally evaluates the r.m.s. value of the current. Another stage is available for earth-faults in which the displacement voltage and thus the fault current exceed a certain value.

Taking the following parameters into consideration, the following settings for the application example apply.

- Load resistance on the earthing transformer $R_L = 4.63\ \Omega$
- Transformation ratio, voltage divider $\ddot{u}_{Kl} = 200 / 5$
- Transformation ratio, voltage divider $\ddot{u}_{divider} = 2 / 5$
- Transformation ratio, earthing transformer $\ddot{u}_{transf} = 15.75{:}\ \sqrt{3} / 0.5$ kV

Parameter	Setting options	Setting
Pickup value of the alarm stage SES 100 %	20 to 700 Ω	193 Ω
Pickup value of the trip stage SES 100 %	20 to 700 Ω	48 Ω
Delay time of the alarm stage SES 100 %	0 to 60 s; ∞	10 s
Delay time of the trip stage SES 100 %	0 to 60 s; ∞	1 s
Pickup value 100 % I>>	0.02 to 1.5 A	0.27 A
Monitoring threshold for 20 Hz voltage	0.3 to 15 V	1 V
Monitoring threshold for 20 Hz current	5 to 40 mA	10 mA
Angle correction for I SES	60 °	0 °
Transition resistance Rps	0 to 700 Ω	0 Ω
Parallel load resistance	20 to 700 Ω; ∞	∞ Ω

Table 14 Parameter overview for the 100 % stator earth-fault protection

*) In this example, most of the default settings can be used.

4.13 Out-of-step protection (ANSI 78)

This protection function serves to detect power swings in the system. If generators feed too long onto a system short-circuit, a compensation process (active power swings) may take place between the system and the generator after fault disconnection. If the center of power swings is in the area of the unit, the “active power surges” lead to impermissible mechanical stressing of the generator and the whole generator mounting – including the turbine. Since these are symmetrical processes, the positive-sequence impedance is calculated from the voltage and current positive-sequence components and the impedance curve is evaluated. In addition, the symmetry is monitored by evaluating the negative-phase sequence system current. Two characteristics in the R/X diagram describe the range of effect (generator, unit transformer or system) of the out-of-step protection. The appropriate counters are incremented, depending on in which characteristic range the impedance vector enters and exits. If the set counter reading is reached, tripping takes place. If no more power swings occur after a set time, the counters are automatically reset. Every power swing can be signalled by a settable pulse. The extending of the characteristic in R direction determines the detectable power swing angle. 120 ° are practicable. The characteristic can be tilted at an adjustable angle to adapt to the conditions when the system is feeding off several parallel generators.

Setting instructions

A minimum value of the positive-sequence components of the currents $I_1>$ must be exceeded (overcurrent pickup) to enable the measurement. In addition, a maximum value of the negative-sequence components of the currents $I_2<$ may not be exceeded, due to the symmetry condition. As a rule, the setting value $I_1>$ is chosen above rated current – i.e. about 120 % I_N – to avoid pickup by overload. The pickup threshold of the negative-sequence component of the current $I_2<$ is set to about 20 % I_N.

The impedances of the protected zone seen from the protection relay are decisive for determining the setting values. In the direction of the generator (seen from the installation position of the voltage transformer set), the power swing reactance of the generator must be taken into account; it can be set approximately equal to the transient reactance $x_{d'}$. This means the transient reactance related to the secondary side is calculated and set for Zb $x_{d'}$ (see Fig. 7).

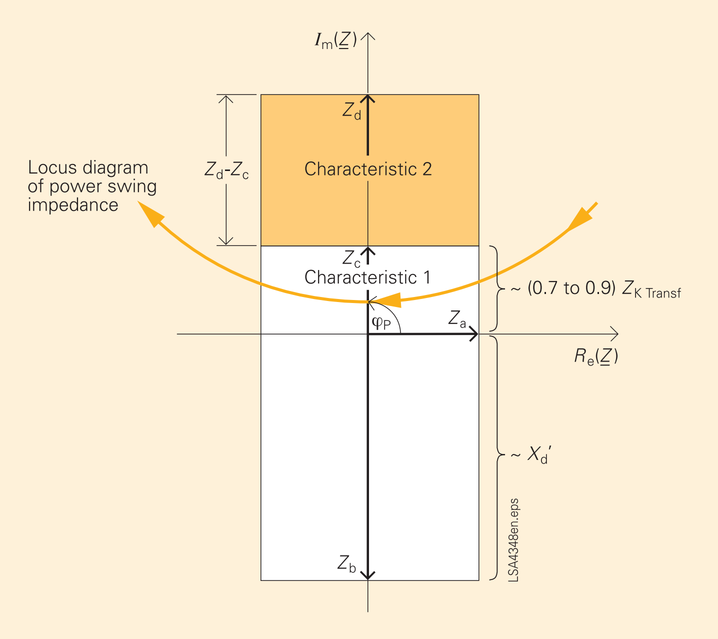

Fig. 7 Power swing polygon

The meaning, calculation and setting of the parameters for the trip characteristics are described in detail in the manual.

The following table shows the setting options and the calculated settings.

Parameter	Setting options	Setting
Pickup value of the measurement release $I_1>$	20 to 400 %	120 %
Pickup value of the measurement release $I_2>$	5 to 100 %	20 %
Resistance Z_a of the polygon (width)	0.2 to 130 Ω	8.25 Ω
Reactance Z_b of the polygon (reverse)	0.1 to 130 Ω	19.60 Ω
Reactance Z_c of the polygon (forward char. 1)	0.1 to 130 Ω	8.90 Ω
Reactance difference char. 2 – char. 1	0 to 130 Ω	1.10 Ω
Inclination angle of the polygon	60 to 90 °	90 °
Number of oscillations by characteristic 1	1 to 4	1
Number of oscillations by characteristic 2	1 to 8	4
Seal-in time of characteristic 1 and characteristic 2	0.2 to 60 s	20 s
Seal-in time of the message out-of-step, char. 1 and out-of-step char. 2	0.02 to 0.15 s	0.05 s

Table 15 Parameter overview for out-of-step protection

The setting ranges and presettings are specified for a secondary rated current of I_N = 1 A.

5. Connection diagram

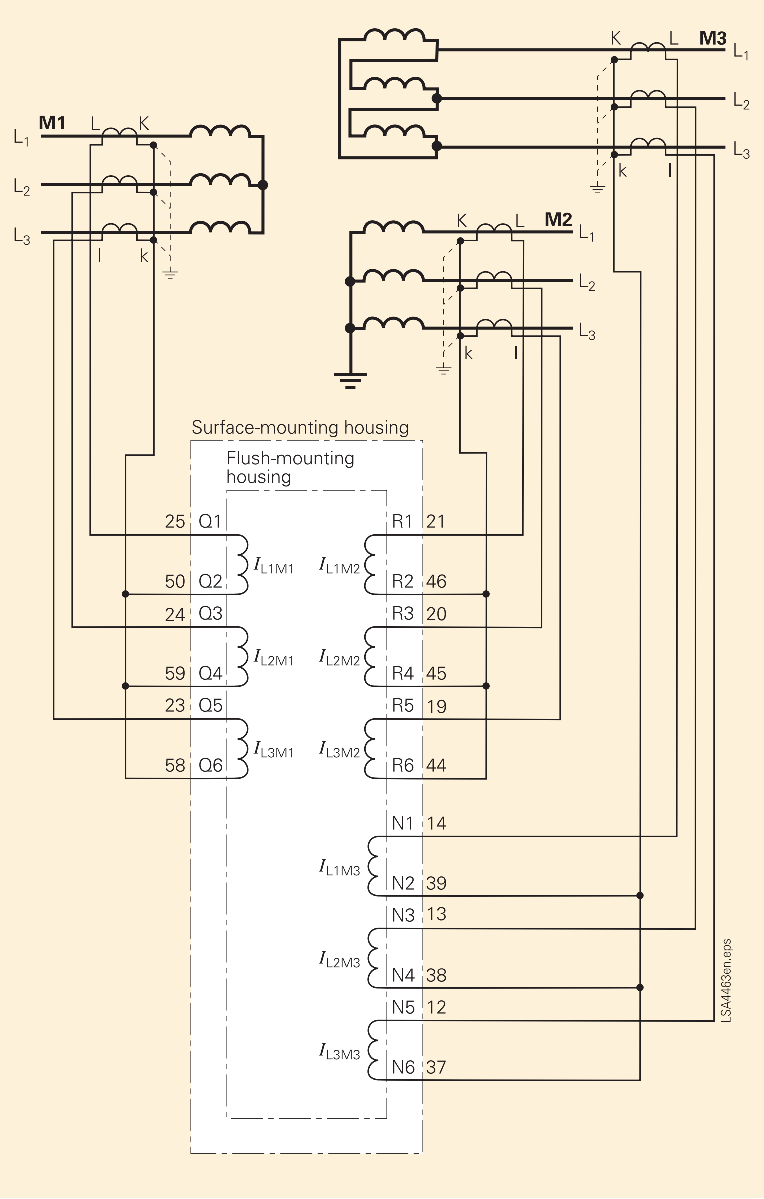

Fig. 8 Connection diagram of 7UM6

6. Communication

The 7UM6 relays fully meet the requirements of modern communication technology. They have interfaces which allow integration in master control stations, convenient parameterization and operation by PC (locally or via a modem). The 7UM6 supports the widely used international open communication standards

- PROFIBUS-DP, RS485 or optical 820 nm double-ring ST connector
- IEC 60870-5-103,
- DNP3.0, RS485 or optical 820 nm double-ring ST connector and
- MODBUS, RS485 or optical 820 nm double-ring ST connector

Note
All SIPROTEC 4 relays also operate with star coupler. This enables the user to access all information from the office or en route (for simple applications). With the PROFIBUS-DP protocol, SIPROTEC relays can easily be integrated in PLC-based process control systems (e.g. SIMATIC S5/S7). The protocols DNP3.0 and MODBUS ASCII/RTU allow integration in numerous instrumentation and control systems of other manufacturers.

7. Summary

Beginning with the recommendations for protection functions [1], it has been described that efficient concepts can be created with modern SIPROTEC relays in medium-sized generators, despite the need to consider cost factors. The multifunctional, numerical SIPROTEC relays enable a greater functional scope than the previous single relays. Self-monitoring substantially improves the availability of the protection relays.

For further information about the function range and setting, the 7UM62 manual is recommended, chapter 2 of which has been compiled as an application manual.

8. References

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