Protection of a Medium-Sized Generator up to 5 MW

1. Introduction

Small-scale stations are making a significant contribution to power generation. Hydropower plants currently still account for the largest share of system infeed. The most significant increase in the number of generating plants has been in wind energy.

Electrical protection is essential for the reliable operation of such equipment.

The scope of protection must be in proportion to the overall costs and importance of the plant. The scope and choice of protection functions are influenced by plant type, generator design and additional equipment, output level and power system connection. The following table gives an overview of the protection functions used depending on generator output.

Fig. 1 SIPROTEC 7UM generator, motor and transformer protection

	For hydropower generators				For diesel generators and turbogenerators			
	Up to 300 kVA	300 to 700 kVA	700 to 1500 kVA	> 1500 kVA	up to 300 kVA	300 to 700 kVA	700 to 1500 kVA	> 1500 kVA
Thermal and short-time delayed trip and shunt release for *U*~ on generator circuit-breaker	x	–	–	–	x	–	–	–
Only shunt releases for *U*~ on generator circuit-breaker	–	x	x	x	–	x	x	x
Rise-in-voltage protection	x	x	x	x	–	–	x	x
Reverse-power protection	–	–	–	–	x	x	x	x
Overcurrent-time protection	–	x	x	x	–	x	x	x
Differential protection	–	–	–	x	–	–	–	x
Rotor earth-fault protection	–	–	–	x	–	–	–	x
Is DC auxiliary voltage for protection required?	–	x	x	x	–	x	x	x

Table 1 Protection functions for small-scale power stations

2. *Protection concept*

In small-scale power stations, the basic circuits for busbar and unit connection (as shown in Fig. 1) can be assumed.

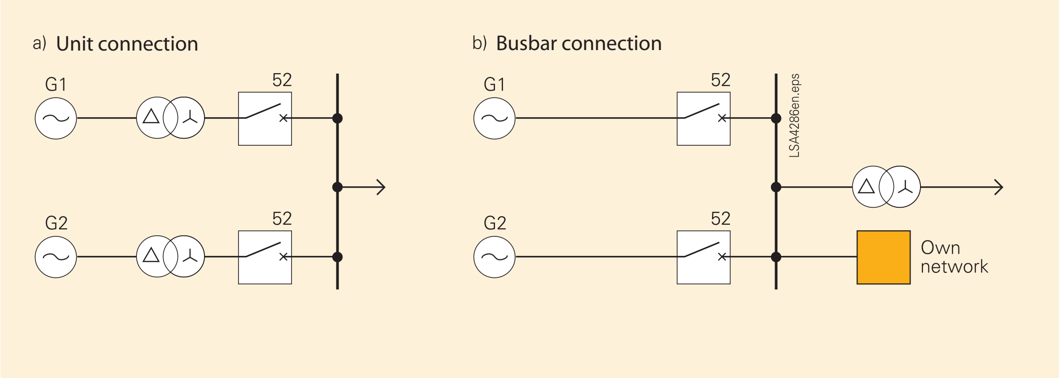

Fig. 2 Plant basic circuit

Fault type	Cause	Protection function	Remarks
Overload	$S_{ab} > S_{produced}$ Controller error Maloperation	Thermal overload protection (I^2t)	Evaluation of current r.m.s. value with previous load recording
Short-circuit (2 or 3 phase)	Deterioration of insulation Winding displacement Overvoltages Manufacturing defects	Overcurrent-time protection (I>) Differential protection (ΔI)	Time delay must be coordinated with system protection
Earth fault (Stator)	Same cause as for short-circuit	Stator earth-fault protection U_0> in unit connection Earth-fault direction in busbar connection ($/U_E$, I_E)	The protected zone (approximately 80 %) is determined by plant conditions (see discussion in text)
Earth fault (Rotor)	Deterioration of insulation Winding displacement Brush abrasion on the slipring surface Material fatigue	Rotor earth-fault protection with system frequency signal coupling in rotor circuit	Used as from 5 MW, if sliprings available; below 5 MW optional
Reverse-power	Drive failure Shutdown	Reverse-power protection ($-P$)	Only necessary for steam and diesel drive systems
Speed irregularities	Leaking stream valves Sudden changes in active power Overload	Frequency protection (f> or f<)	As from 5 MW f> and f< Below 5 MW so far only f>; f< is likewise recommended if available
Overvoltage	Controller error or manual maloperation	Overvoltage protection (U>)	Evaluation of phase-to-phase voltage
Unpermissible under-excitation	Fault in exciter circuit Operation in underexcited state (high reactive power demand in system) Maloperation, controller error	Underexcitation protection (e.g. $-Q$, or Z)	Used as from 5 MW Below 5 MW so far not usual; recommended if function available
Asymmetric load	Unequal loading of conductor	Negative-sequence (or load unbalance) protection (I_2>)	Used from 5 MW; Below 5 MW so far not usual; recommended if possible,

Table 2 Fault type, protection functions

In **unit connection**, the generator is linked to the higher voltage level busbar via a transformer. In the case of several parallel units, the generators are electrically isolated by the transformers.

In **busbar connection**, several generators feed onto a common busbar. Subsequently, the next higher voltage level is fed via a transformer. The generators are galvanically connected.

Owing to the low overall plant costs, the busbar connection is frequently chosen for **small-scale power stations**. This application is therefore considered in greater detail in the following.

Table 2 shows the protection functions suitable for small-scale power stations in accordance with today's state-of-the-art. Fault type, cause and the protection function to be deployed are indicated, together with general notes on particular features of the protection function.

■ 3. *Applications*

Table 1 shows, that even with small generators of < 5MW, relays must be used with a number of protection functions. Numerical protection relays are the current state-of-the-art.
The SIPROTEC range provides a good choice. As shown in Table 3, 7SJ relays are well suited for simple protection functions for small generators.

The decisive advantage of the 7UM6* generator protection relay is the automatic adjustment of the sampling frequency. To ensure that the protection and measurement functions deliver correct results over a wide frequency range, the actual frequency is continuously measured and the measurement processing sampling frequency continuously tracked. This ensures the measuring accuracy in the frequency range from 11 Hz to 69 Hz. This relay offers a wide range of additional protection functions. If differential protection is required and the appropriate transformer sets are available, a 7UM62 is recommended. As differential protection is applied usually for generators above 5 MW, the example shown opposite refers to a 7UM61 relay for a 5 MW generator in busbar connection.

■ 4. *Settings*

In the following sections, the individual protection and additional functions (see Table 3) are explained. Notes on the setting values are also given. The calculation examples are oriented towards the reference plant shown in Fig. 3. For the tripping concept, it is assumed that the protection directly actuates the tripping (circuit-breaker, de-excitation, turbine valve closing or diesel cut-off).

4.1 Thermal overload protection (ANSI 49)

Overload protection prevents thermal overload of the stator windings on the machine to be protected. The relay calculates the temperature rise in accordance with a thermal single-body model by means of the thermal differential equation and takes account of both previous overload history and emission of heat into the ambient area.

After an initial, adjustable threshold has been reached, an alarm signal is emitted for the purpose of enabling a load reduction in good time, for example.
The second temperature threshold disconnects the machine from the system. For example, ambient or coolant temperatures can be input via the PROFIBUS-DP interface.

Protection functions	ANSI	7SJ60	7SJ61	7SJ62	7SJ63/64	7UM61
Rotor overload protection	49	X	X	X	X	X
Earth-fault protection directional / non directional	64G 50G 67G	X X X	 X 	X X X	X X X	X X X
Overcurrent-time protection	50 51	X	X	X	X	X
Negative-sequence protection	46	X	X	X	X	X
Rotor earth-fault protection	64R		X1)	X1)	X1)	X1)
Reverse-power protection	32				X2)	X
Overcurrent protection	59			X	X	X
Underexcitation protection	40					X
Frequency protection	81			X	X	X
Temperature monitoring (by an external monitoring box called thermo-box)	38	X		X	X	X
Breaker failure protection	50BF	X	X	X	X	X
Programmable logic			X	X	X	X
Control functions		X	X	X	X	X
Flexible serial interface		1	2	2	2/3	2

1) via I_{EE} measuring input if earth-fault direction function is not used.
2) in 7SJ63 with CFC, in 7SJ64 with flexible functions.

Table 3 Protection relays – selection matrix

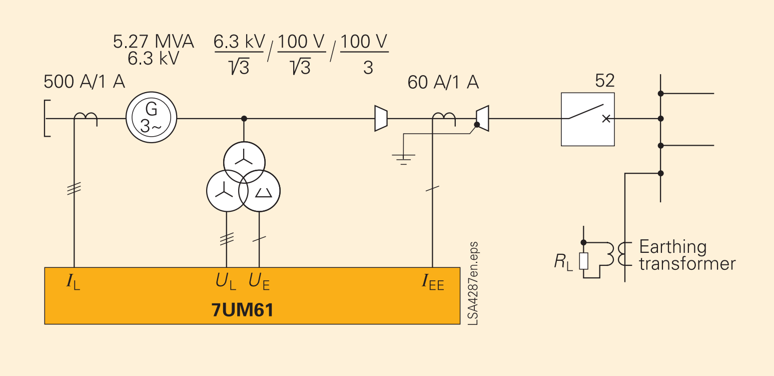

Fig. 3 Busbar connection with core-balance CT

Low ambient or coolant temperatures mean that the generator can be loaded with more current; high temperatures signify that the loadability is less.

Example
Generator and transformer with the following data:

- Permissible continuous current $I_{\text{max prim}} = 1.15 \cdot I_{\text{N, generator}}$
- Rated generator current $I_{\text{N, generator}} = 483$ A
- Current transformer 500 A/1 A

Set value k-factor = 1.15 483A/500A = 1.11

Note:
Taking the k factor at the usual figure of 1.1, applying the generator rated current (with the primary transformer current matched) produces a temperature rise of $\Theta / \Theta_K = 1 / 1.1^2 = 0.83$ of the tripping temperature. The alarm stage should thus be set between end temperature at rated current (83 % in this case) and tripping temperature (100 %).

With an assumed load current of $I = 1.5\ I_N$ (relay) and a preload of $I_{pre} = 0$, the following tripping times are derived for various ambient temperatures

$\Theta_K = 40$ °C $t = 463$ s
$\Theta_K = 80$ °C $t = 366$ s
$\Theta_K = 0$ °C $t = 637$ s

4.2 Definite-time overcurrent-time protection (*I*>, *I*>>) (ANSI 50/51)

General
Overcurrent-time is the form of short-circuit protection for extra-low or low voltage generators. In order that internal faults are always responded to, the generator protection is connected to the current transformer set located in the star point connection of the generator. In the case of generators whose excitation voltage is taken from the machine terminals, in the event of nearby faults (i.e. in the generator or the unit transformer region) the short-circuit current decays very quickly since there is no longer any excitation current, and within a few seconds falls below the overcurrent-time protection pickup value. In these cases undervoltage seal-in is used.

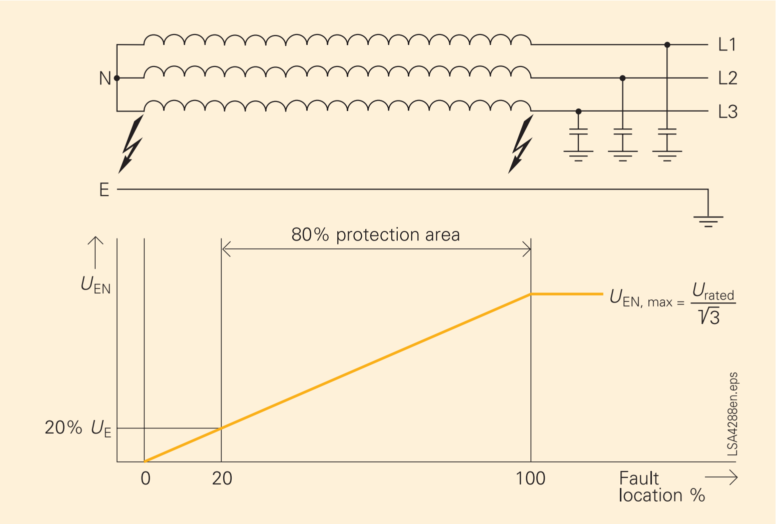

Fig. 4
Displacement voltage as a function of the fault location in the stator winding

4.3 Definite-time overcurrent-time protection (*I*>) with undervoltage seal-in (ANSI 51V)

Setting example:
Pickup value $1.4 \cdot I_{NGenerator}$
Tripping delay 3 s
Undervoltage seal-in $0.8\ U_{NGenerator}$
Seal-in time of $U < 4$ s
Dropout ratio 0.95

4.4 Earth-fault protection

In addition to short-circuit protection, which as described above is provided in a familiar fashion via overcurrent (or differential) protection, earth-fault protection is of particular significance for small-scale machines.

4.4.1 Principle

A particular feature of electric machines with isolated star point is that the displacement voltage decreases linearly as the fault location moves in the direction of the generator star-point (Fig. 4). The earth-fault current, the magnitude of which is determined by the earth capacitances in addition to the displacement voltage, thus also decreases. In the event of faults close to the star point, the displacement voltage and earth current become so small that they can no longer be reliably measured.

A protected zone of 80 – 90 % is consequently spoken of.

In unit connection (Fig. 2a), the protected zone discussed above is additionally determined by the disturbance signal injection from the upstream system. If an earth fault occurs in the system, a displacement voltage is identifiable via the coupling capacitance of the unit transformer. The magnitude of the interference voltage is determined by the coupling capacitance, the generator-side earth capacitance (stator, incoming line) and the difference between rated system voltage and rated generator voltage.

In busbar connection, the displacement voltage can only be used for earth-fault indication due to the galvanical connection of the generators. The earth-fault direction protection makes selective tripping possible. The protected zone is determined by the earth current, which is measured by a core-balance current transformer (60 A/1 A). As shown in Fig. 2b the sum of the component earth currents flows through the generator affected by the fault. The cable network connected to the generators is decisive for the fault current magnitude.

Example:
In the case of 10 kV cables (lead sheath, polymer-insulated) the capacitive earth-fault current lies between 1.2 to 3.5 A/km. If with a full displacement voltage we assume an earth current of max. 3 A and aim for a protected zone of 80 %, approximately 0.6 A flows on the primary side. This current (secondary approximately 10 mA) can be handled reliably by the protection.

If the capacitive current is not sufficient where higher power levels are concerned, it is worth investing in an earthing transformer on the busbar or in disconnectable load resistors on the generator star point. The earth-current increases as a result of the resistive current.

4.4.2 Note

In industry, busbar systems are designed with high or low resitive switchable star-point resistors. For earth-fault detection, the star-point current and the summation current are measured by the core-balance current transformer and fed into the protection relay as a current difference (see Fig. 4). The earth-current component coming from the star-point resistor, as well as any from the system, contribute to the total earth-current. In order to rule out overfunction as a result of transformer faults, the displacement voltage serves for tripping. The protection then decides on generator earth-fault if both of the following criteria apply:

- Displacement voltage is greater than setting value U_0>,
- Earth-fault current difference ΔI_E greater than setting value 3 I_0>, magnitude.

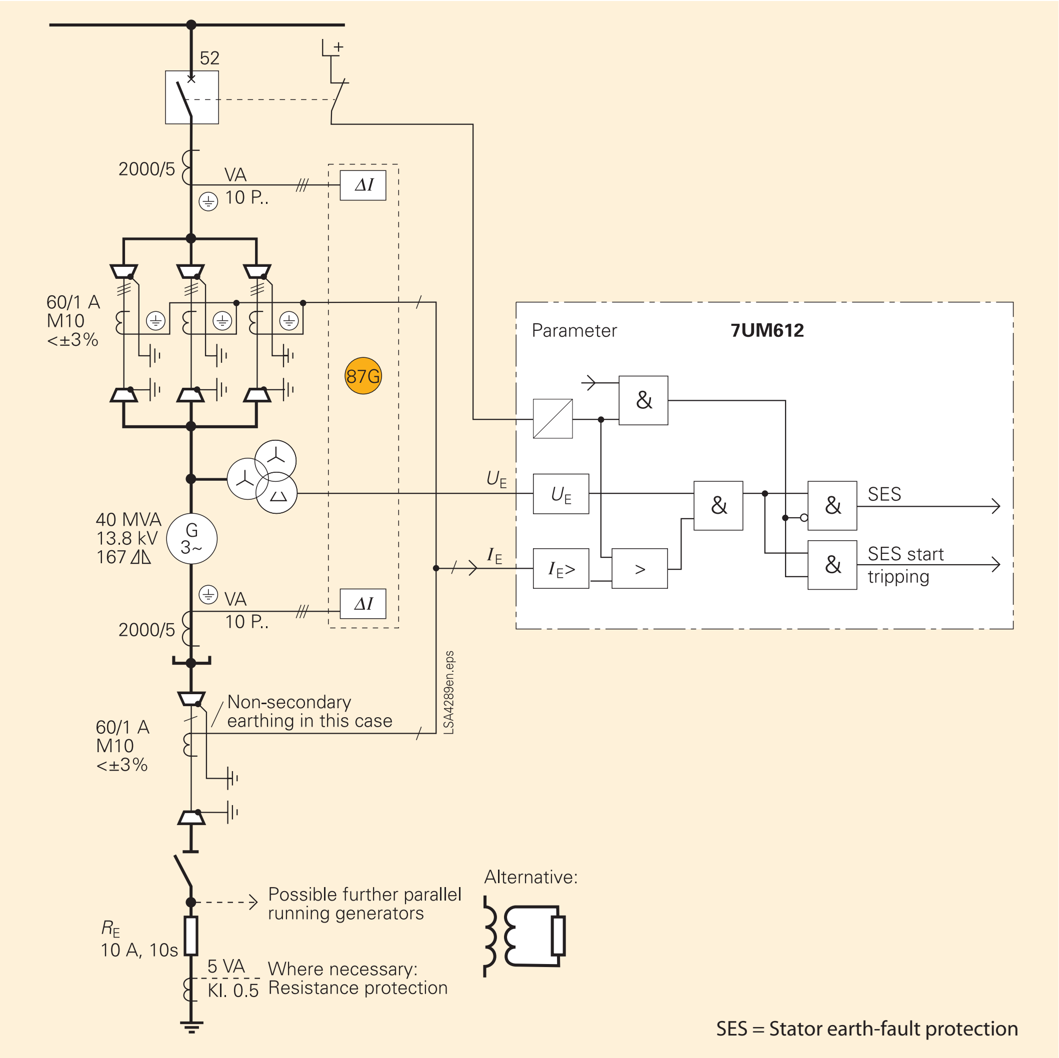

Fig. 5 Earth-fault protection by differentiation with core-balance current transformers

The pickup value should be at least twice the operational asymmetries. A value of 10% of the full displacement voltage is normal.

4.5 Sensitive earth-fault detection (ANSI 50/51 GN)/ rotor earth-fault protection (ANSI 64R)

Sensitive earth-current protection is used for detecting earth faults in isolated or high-resistance earthed systems. This protection function can also serve to detect rotor winding earth-faults if the rotor circuit is artificially displaced with a system-frequency voltage to earth ($U_V \approx 42$ V by means of 7XR61 coupling device). In this case the maximum flowing earth current is limited by the magnitude of the selected U_{RE} voltage and by the capacitive coupling to the rotor circuit. Monitoring of the measuring circuit is provided (for this application) as rotor earth-fault protection via the sensitive earth-current measuring input. It is regarded as closed if the earth current (which also flows with healthy insulation) resulting from the earth capacitance of the rotor circuit exceeds a parametrizable minimum value $I_{EE}<$. Should the earth-current fall below this value, a failure signal is issued after a short delay time (2 s).

A typical pickup value is approximately 2 mA. If this value is set at 0, the monitoring stage is ineffective. This can become necessary if the earth capacitances are too low. The setting of the earth-fault pickup $I_{EE}>$ is selected in such a way that the insulation (earth) resistances R_E can be detected in the range from about 3 kΩ to 5 kΩ: The value set should in this case be at least twice as high as the interference current owing to the earth capacitances of the rotor circuit. The tripping delays T $I_{EE}>$ and T $I_{EE}>>$ do not include operating times.

4.6 Reverse-power protection (ANSI 32R)

Reverse-power protection serves to protect a turbine generator unit if, in the event of drive power failure, the synchronous generator runs as a motor and drives the turbine and is thereby drawing the required motoring energy out of the system. This state will endanger the turbine blades and must be interrupted without delay by opening the network circuit-breaker. For the generator there exists the additional danger that in the event of residual steam leakage (defective seal valves) after opening of the circuit-breaker, the turbine generator unit can be run up to overspeed. For this reason disconnection from the power system should only take place after detection of active power input into the machine. 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: $P_{\text{Reverse}}/S_N \approx 1$ % to 3%
- Gas turbines: $P_{\text{Reverse}}/S_N \approx 3$ % to 3%
- Diesel drives: $P_{\text{Reverse}}/S_N > 5$ %

However, it is advisible to measure the reverse power with the protection itself in the primary test. About 0.5 times of the measured motoring energy is chosen as a setting value. The motoring energy value can be found at the “percentage operational measured-values”.

4.7 Frequency protection (ANSI 81)

Frequency protection detects overfrequencies and underfrequencies of the generator. If the frequency lies outside the permitted range, the appropriate switching operations are initiated, such as separating the generator from the system. Decrease of frequency is caused by an increase active power demand the system or by malfunctions in the frequency or speed control. Frequency decrease protection is also used on generators that (temporarily) feed a separate island system, since in such a case the reverse-power protection cannot work if the drive power fails. The generator can be disconnected from the system by the frequency decrease protection. Frequency increase is caused for example by load shedding (separate island system) or malfunctions in the frequency control. In such cases there is a danger of self-excitation of generators which feed long, no-load lines. The frequency values are generally set in accordance with the specifications of the system or power station operator. Frequency decrease protection has the task of securing power for the station-service equipment by disconnecting it from the system in good time. The turbo regulator then adjusts the machine set to rated speed so that the station-service power can continue to be supplied at rated frequency. A frequency increase can occur for example in the event of load shedding or speed control malfunction (e.g. in a separate island system). The frequency increase protection is thus used for example as overspeed protection.

Stage	Cause	Setting values		
		at $f_N = 50$ Hz	at $f_N = 60$ Hz	Delay
f_1	Disconnection from system	48.00 Hz	58.00 Hz	1 s
f_2	Shutdown	47.00 Hz	57.00 Hz	6 s
f_3	Alarm	49.50 Hz	59.50 Hz	20 s
f_4	Alarm or tripping	52.00 Hz	62.00 Hz	10 s

Setting example

4.8 Overvoltage protection (ANSI 59)

Overvoltage protection serves to protect the electric machine and the connected system components from impermissible voltage increases, thereby protecting the insulation from damage. Voltage increases result for example from incorrect operation in manual control of the excitation system, from malfunction of the automatic voltage regulator or from (full) shedding of a generator load, separation of a generator from the system or in separate island operation. Setting of the limit values and delay times of the overvoltage protection depends on the speed with which the voltage regulator can control voltage changes. The protection may not intervene in the control process when it is operating trouble-free. The two-stage characteristic must therefore always be above the voltage time characteristic of the control process. The long-time stage should intervene in the event of steady-state overvoltages. It is set to approximately 110 % to 115 % of U_N and, depending on the regulator speed, at 1.5 s to 5 s.

4.9 Underexcitation protection (ANSI 40)

Underexcitation protection (loss-of-field) protects a synchronous machine from loss of synchronism in the event of malfunction of excitation or control and from local rotor overheating.
In order to detect underexcitation, the relay processes all three phase currents and all three voltages as stator circuit criteria as well as the signal of an external excitation voltage monitor as rotor circuit criterion (Fig. 6).

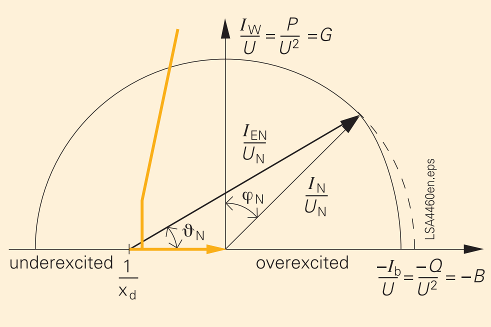

Fig. 6 Admittance diagram of turbo generators

The tripping characteristics of the underexcitation protection are composed of straight lines in the diagram, each defined by its conductance section $1/x_d$ (= coordinate admittance distance) and its angle of inclination α (Fig. 7).

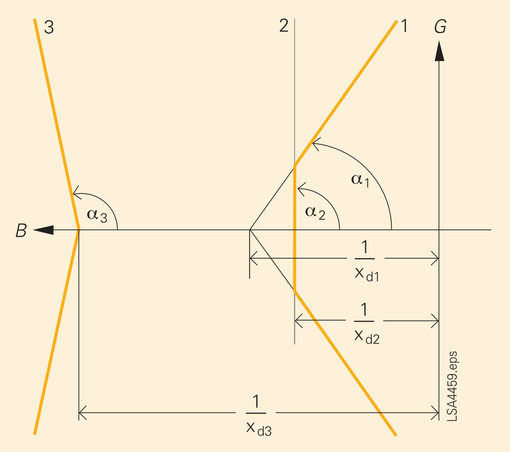

Fig. 7 Underexcitation protection characteristics in the admittance plane

The straight lines ($1/x_d$ Char. 1) / α 1 (characteristic 1) and ($1/x_d$ Char. 2) / α 2 (characteristic 2) form the static underexcitation limit. ($1/x_d$ Char.1) corresponds to the reciprocal value of the reference synchronous direct reactance

$$\frac{1}{x_d} = \frac{1}{x_d} \cdot \frac{U_N}{\sqrt{3} \cdot I_N}$$

If the synchronous machine voltage regulator includes underexcitation limitation, the static characteristics are set such that intervention by the underexcitation limitation is enabled before the characteristic 1 is reached. The generator performance diagram can be used as a basis for setting. If the axis sizes are divided by the rated apparent power, the generator diagram is obtained in “per unit” form (corresponding to a “per unit” representation of the admittance diagram). Multiplying $1/x_d$ by a safety factor of approximately 1.05 produces the setting value.

For α 1 the angle of the voltage regulator underexcitation limitation is selected, or the inclination angle from the restraint characteristic of the machine can be read. α 1 is normally between 60° to 80°. For low active power levels, the machine manufacturer normally specifies a minimum excitation. Here the characteristic 1 is cut off from characteristic 2 when the active power is low. α 2 is set to 90 °. With characteristic 3, the protection can be matched to the dynamic stability limits of the machine. If no more precise details are available, a value roughly between the synchronous direct-axis reactance x_d and the transient reactance x_d is selected; it should however be greater than 1.

For the angle α 3, 80 ° to 110 ° is normally selected, in order to ensure that only dynamic instability can lead to tripping with characteristic 3. If the static limit curve (consisting of characteristics 1 and 2) is exceeded, initially the voltage regulator must be given the opportunity to increase the excitation; for this reason an alarm signal is delayed "long time" (at least 10 s). If the relay is nevertheless "informed" of excitation voltage failure (by an external excitation voltage monitor via binary input), disconnection can take place with a short delay time.

Characteristic 1 and 2 steady-state stability	Instantaneous	Excitation signal Exc < Exc
Characteristic 1 and 2 steady-state stability	Long time-delay T Char. 1 = T Char. 2 ≈ 10 s	Trippings Exc < Char. 1 TRIP / Err < Char. 2 TRIP
Characteristic 1 and 2 Excitation voltage failure	Short time-delay T SHORT U_{ex} < ≈ 1.5 s	Tripping Exc < UPU < TRIP
Characteristic 3 Dynamic stability	Short time-delay T Char. 3 ≈ 0,5 s	Tripping Exc < Char. 3 TRIP

Setting of underexcitation protection

Note:
Selecting very short delay times can lead to dynamic transients (possibly overfunctions).
It is therefore advisable not to set the times below 0.05 s.

4.10 Negative-sequence protection (ANSI 46)

Negative-sequence (or unbalanced load) protection is used to detect asymmetrical loading of three-phase induction machines. Asymmetrical loads create a reverse field, which affects the rotors with double the frequency. Eddy currents are induced on the surface of the rotor, leading to local overheating in the rotor end zones and slot wedges. Furthermore, interruptions, faults or incorrectly inter-changed connections to the current transformers can also be detected with this protection function. Additionally, single and two-phase faults with fault currents lower than the maximum load currents can be identified.

Setting example:
Setting value $I_{2\ \text{permissible}} = 11\ \% \cdot (483\ \text{A}/500\ \text{A}) = 10.6\ \%$
Factor k = 18.7 s
T cooling = 1650 s

5. Communication

The SIPROTEC 7UM6 relays fully satisfy the requirements of modern communication technology. They have interfaces that enable integration into
– superordinate control centers,
– convenient parameter assignment and operation via PC (locally or via modem connection).

- 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

7UM6 supports the widely used, internationally standardized open communication standards.

6. Summary

Based on the recommendations for protection functions [1] it has been described how, despite the cost aspects that have to be taken into account in small-scale power generating plants, modern relays can be used to create technically effective yet uncomplicated concepts.

In contrast to traditional individual relays, state-of-the-art multifunctional numerical protection equipment now provides a wider scope of functions. Self-monitoring contributes to avoidance of underfunctions (failure to detect relay failure). A generator can be adequately protected with a single relay. For more detailed information on selecting functions and settings, the 7UM61 manual is recommended, chapter 2.1 of which has been provided as an application handbook.

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