Unit Protection System for Pumped-Storage Power Stations

1. Introduction

In many power systems, pumped-storage power stations are used in addition to run-of-river power stations. These power stations serve primarily to cover load peaks in the power system. In such peak load periods the machines operate as generators and feed active power into the grid. In slack periods, e.g. during the night, the machines operate as motors and pump water into the upper reservoir which is then available later as an energy source for peak load supply. In this way, large-scale thermal power units can be continuously run to cover basic load.

Fig. 2 shows a typical redundant protection system design for pumped-storage units with an active power output greater than 100 MW.

Fig. 1 SIPROTEC 7UM62

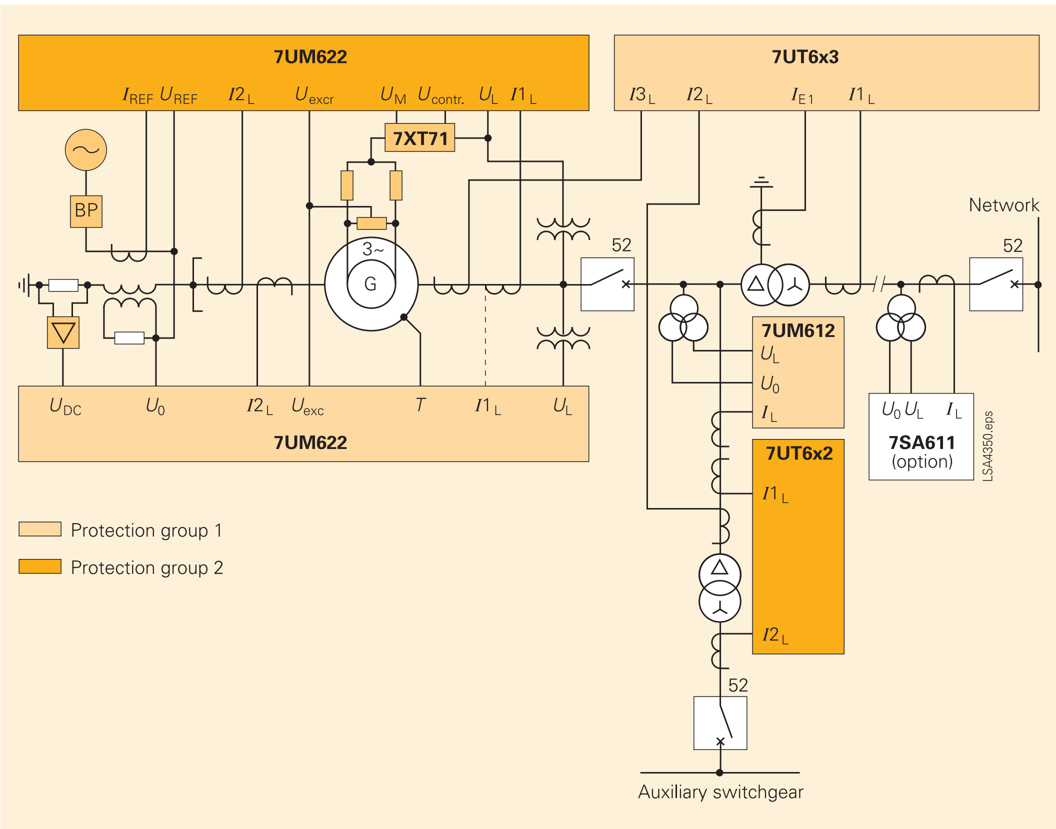

Fig. 2 Redundant protection system for pumped-storage power stations

If the protection requirements of a pumped-storage power station are compared with those of a unit for pure energy generation, certain particular features emerge as well as many parallels. Designing a protection system for medium and large-scale power stations is described in another publication. This guide explains the special protection functions and the working of a pumped-storage unit.

Table 1 below describes a typical basic concept for a pumped-storage unit.

Protection functions	ANSI code	Protection Group A	Protection Group B
Stator earth-fault protection 90 %	64		
Stator earth-fault protection 100 %	64 (100 %)	■	■
Differential protection	87	■	
Winding fault		■	
Overcurrent-time protection	51		■
Impedance protection	21		■
Rotor earth-fault protection	64R	■	■
Load unbalance protection	46	■	■
Underexcitation protection	40	■	
Out-of-step protection	78		■
Stator overload protection	49	■	■
Rotor overload protection	49E	■	
Overvoltage protection	59	■	■
Frequency protection $f>$	81 ($f>$)	■	■
Frequency protection $f<$	81 ($f<$)	■	■
Reverse power protection	32	■	
Underpower protection	37	■	
Undervoltage protection	27	■	
Overexcitation protection	24	■	

Table 1 Protection concept for pumped-storage power plants

The protection system described can be supplemented by extra protection functions, depending on technical requirements or country-specific customary protection concepts. Likewise, the level of function redundancy can be expanded or reduced.

The advantage of the 7UM6 multifunctional protection relays lies in the ease of configuration.

With the aid of the DIGSI® configuration program, each of the protection functions contained in the relay can be switched active or inactive.

2. Selected protection functions

2.1 Stator earth-fault protection

The same principle applies for generators in pumped-storage power stations as for other power station types: the most frequent electrical fault is an earth fault. Simple stator earth-faults cause no damage to the generator provided the earthing transformer and loading resistor have been correctly designed. A second earth fault would, however, result in such high fault currents that the generator would be severely damaged. For this reason a simple stator earth-fault must be detected at an early stage and at least signalled. In large generators simple earth faults nearly always result in disconnection unless restrictions in the power system operation and control exclude this.

The 100 % stator earth-fault with 20 Hz infeed (Fig. 3) complies with the requirements for reliable detection of a stator earth-fault throughout the stator winding up to the star point. With infeed of a generator-independent auxiliary voltage, this protection principle allows so-called standstill testing. External supply to the 20 Hz generator enables the machine to be tested for possible stator earth-faults before startup. In normal operation the sensitive signal level indicates the start of an earth fault early on. The protection relay calculates the resistive component from the measured earth current. The result is therefore independent of the capacitance of the stator to earth. This advantage is especially effective in large hydroelectric generators which have a high capacitance to earth. The insulation value of the earthed stator winding can be shown on the protection relay display, providing the operator with valuable information about whether the machine can continue to run until the next planned inspection shutdown.

2.2 Negative-sequence protection (ANSI 46)

Various settings are required for phase-sequence-dependent protection functions if the machine is switched between generator operation and pump operation. An example of such a function is negative-sequence (or unbalanced load) protection, whose pickup criterion is based on measuring or calculating the reverse field. One possible solution is installing two identical protection relays with respective setting values for generator operation and pump operation. One of the two protection relay is always blocked to prevent spurious operation.

A more elegant and cost-effevtive solution would be to switch over the parameter sets in the protection relay when changing between the two operating modes. The 7UM6 numerical generator protection relay allows the read-in of two independent parameter sets. When changing between the machine's two operating modes, a control signal to the protection relay digital input activates the other parameter set for protection processing. For negative-sequence protection, this means that, from the calculated symmetrical components of the measured current, the positive phase-sequence system and the negative phase-sequence system are exchanged for further protection processing.

2.3 Underexcitation protection (ANSI 40)

Large pumped-storage units are often used for reactive power compensation, in addition to balancing peak loads in the power system. Consequently, the generator can be run close to its stability limit, depending on reactive-power demand over a long period. Slight increases in reactive-power demand can make the generator fall out of step. Consequently, particular emphasis is laid on underexcitation protection in large pumped-storage power stations.

Primarily, the excitation system itself detects an overshoot of the stability characteristics of the generator and compensates this by readjusting the excitation voltage. Electrical underexcitation protection comes into action if this automatic readjustment is unsuccessful. The generator moves into the capacitive working range and finally falls out of step. This impermissible operating state can damage the generator and create instability in the power system linked to the power station. The asynchronously running generator suffers severe mechanical stressing of the shaft and bearings, which could result in costly repair work. It also produces electrical oscillations in the power system which can lead to other generators falling out of step. Asynchronous operation can be caused by defective excitation equipment or excessive reactive-power demand in the connected transmission network.

In view of the wide range for active and reactive power in such a pumped-storage unit, particular attention must be paid to setting the underexcitation protection characteristic. Simple detection of reactive-power demand by a circular protection characteristic will not meet these operating requirements. A combination of pickup characteristics in accordance with Fig. 4 is ideally suited for the requirements described here.

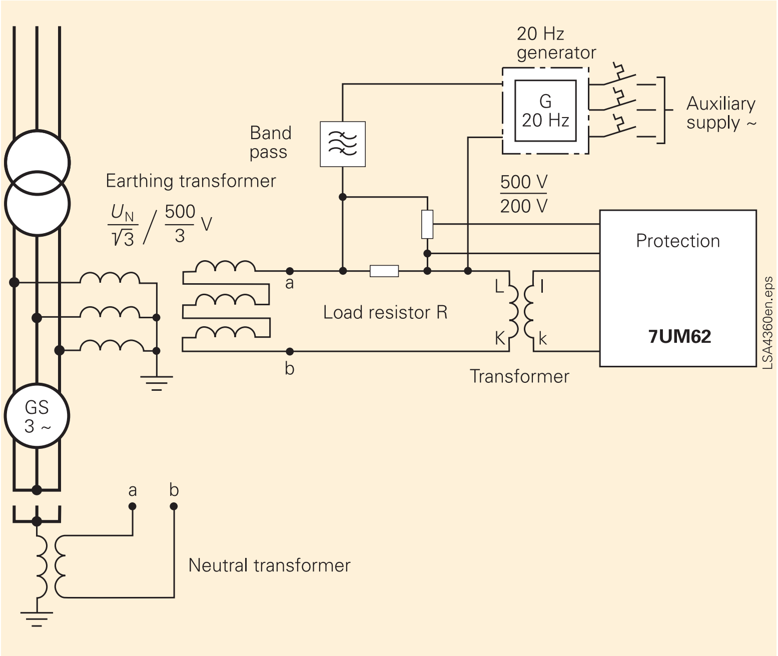

Fig. 3 Stator earth-fault protection with generator, 20 Hz

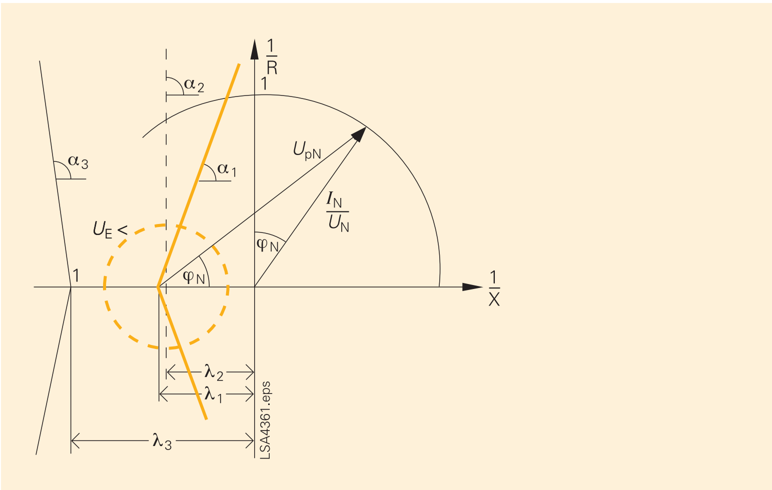

Fig. 4 Characteristic of underexcitation protection

These protection characteristics form the stability characteristics of the machine and combine high availability of the pumped-storage unit with optimum protection of the machine and the connected power system.

The pickup characteristics of the underexcitation protection are made up of the machine's steady-state and dynamic stability characteristics. An overshoot of the steady-state characteristic is an initial indication that stability is endangered.

If the excitation equipment is functioning correctly the machine can be returned to synchronous operation again by automatically readjusting the excitation voltage. Only an overshoot of the dynamic restraint characteristic finally makes the machine fall out of step. Both characteristics, sometimes referred to as the stator criterion, are calculated from machine currents and voltages. The excitation voltage U_{excit} (or rotor criterion) is used as an additional measured variable for optimum operation and control. The recommended function logic of the underexcitation protection is shown in Table 2 below.

Measurement criterion	Protection reaction
Steady-state characteristic	Indication (optional tripping approx. 10 s)
Steady-state characteristic + U_{excit} <	Tripping approx. 0.3 s
Dynamic characteristics	Tripping approx. 0.3 s
U_{excit} <	Indication

Table 2

An overshoot of the steady-state stability characteristic without simultaneous excitation voltage dip is only signalled. The operating personnel can manually intervene to return the machine to stable operation. The cause of underexcitation can lie in power factor correction.

Only a simultaneous drop in the excitation voltage below a set value causes shutdown of the machine in short time. This is probably due to a fault in the excitation equipment. It is then only a question of time before the machine reaches the dynamic stability characteristic and finally falls out of step. Shutting down at an early stage prevents this additional pole slipping and protects both machine and power system.

The setting value I_B is matched to the rated motor current

The rated temperature Θ_N is reached at $I = I_B$

The tripping temperature Θ_A is reached at $I = 1.1\ I_B$

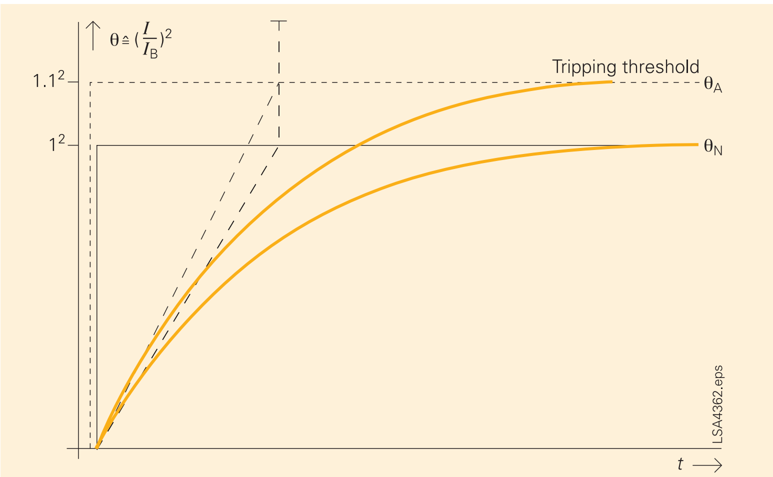

Fig. 5 Principle of overload protection

This logical linking of stator criteria with rotor criteria enables the pumped-storage unit to continue operation up to its real stability limit. The exact replica of the machine characteristics ensures that the unit does not switch off unnecessarily within the permissible limit range. On the other hand, this optimum utilization of the operating range involves no danger to the machine or power system. If the stability of the machine is no longer guaranteed, it is shut down quickly and safely.

2.4 Stator overload protection

An important protection function for pump operation is stator overload protection. In generator mode, the thermal loading on the stator winding is limited by the turbine output if the power station unit is correctly designed. In pump mode, there may be thermal overload of the machine in motor mode. A thermal replica with complete memory prevents such overloads. Particularly with quick load changes, the thermal replica is more exact than a direct temperature measurement on the winding.

The thermal replica calculates the temperature of the stator winding from the stator current practically instantaneously (Fig. 5) according to the formula I^2t. A direct measurement of the temperature on the insulation of the stator winding follows load changes only after a delay and therefore does not always show the current temperature of the conductor.

2.5 Rotor monitoring

In large machine units special attention must be paid to monitoring the rotor circuit, owing to the high power per pole. This monitoring includes insulation of the rotor winding as well as the thermal load on the rotor winding.

To monitor the rotor insulation a specially developed measurement principle is used which largely compensates for the disturbing influence of the rotor capacitance to earth and fluctuations of the excitation voltage. A reverse polarity square-wave voltage in a clock pulse from 1 to 3 Hz is applied between rotor circuit and earth (see Fig. 6). The steady-state circulating current remaining after the capacitive charging current has decayed is a measure of the insulation resistance of the rotor winding. The protection relay measures only the resistive component of the earth impedance regardless of the level of earth capacitance.

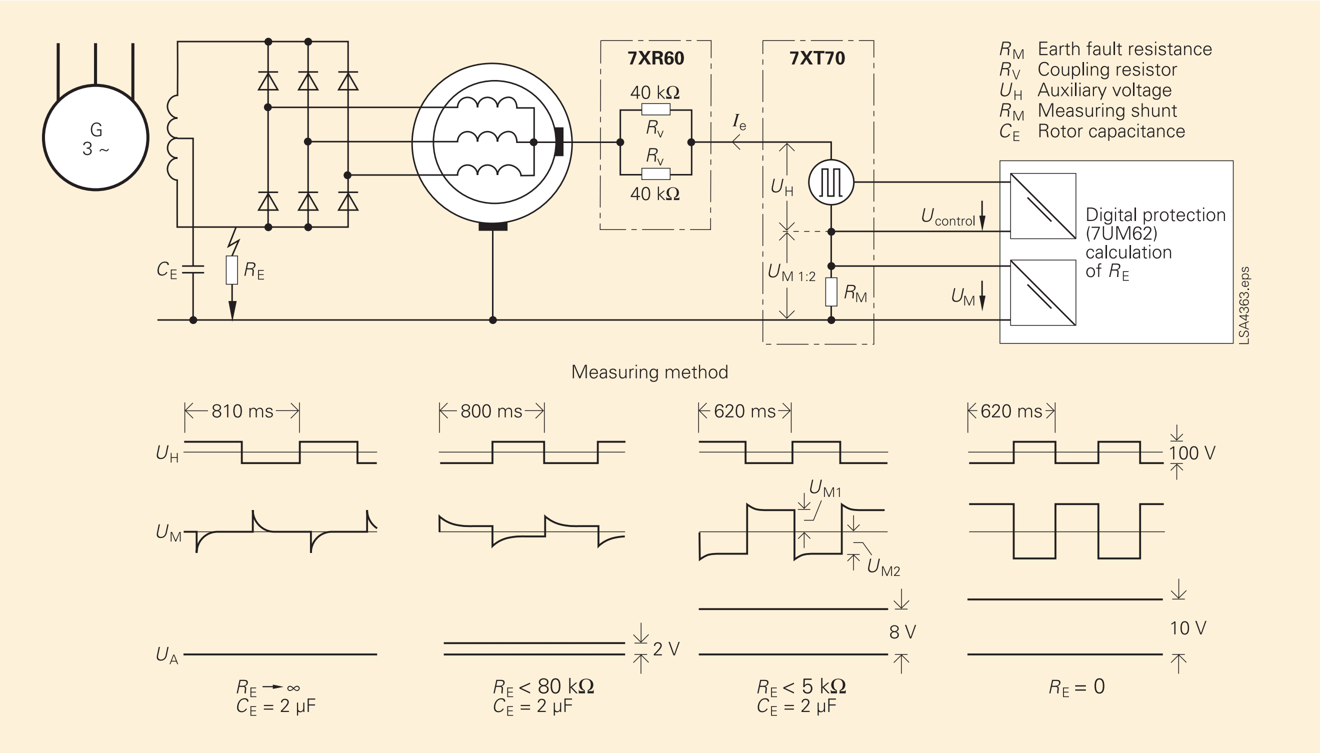

Fig. 6 Principle of rotor earth-fault protection

The differential measurement of the resistive earth current from positive and negative polarity compensates on the one hand the disturbance of the excitation voltage and also stops measurement errors owing to operation-related changes in the excitation voltage. This sophisticated measuring procedure measures an insulation resistance (to earth) in the rotor winding up to the order of 80 kΩ. Hence, the protection relay detects a rotor earth-fault as it arises. The operator can plan the necessary maintenance work on the machine for the long term. Protection-related shutdown of the pumped-storage unit is thereby almost always prevented which considerably enhances the availability of the unit.

As a result of the various operating modes of the pumped-storage unit

- Generator mode
- Generator and VAR compensation mode
- Pump mode
- Pump and VAR compensation mode
- Any electrical brake

the rotor circuit of the excitation system may be exposed to high thermal loads. Overload protection on the high-voltage side of the excitation transformer measures the current flowing there which is in direct relationship to the thermal rotor load. Overload protection works as a thermal replica with complete memory and enables flexible operation and control of the unit within the permissible limits, with simultaneous safe protection against overloads.

2.6 Power system failure in pump operation

The power-shortfall protection function is only activated in pump mode. This happens by way of the above-described parameter set changeover when the mode is changed. In the parameter set for generator mode, the power-shortfall function is deactivated. This protection function recognises the sudden failure of the power system supply (when the machine is in pump mode) by measuring the active power in the infeed direction. If a fault is detected, the pumped-storage unit is switched off and the spherical valves are closed.

A second measurement principle for detecting a line side supply failure is underfrequency protection, which is likewise included in the protection concept.

The underfrequency protection is not in operation during run-up and switchover of the system's various operating states, and is only activated after the machine has been synchronized with the power system. A binary input from the protection relay, which requests the position of the system circuit-breaker, effects this control.

3. Summary

In view of their particular status in hydropower engineering, pumped-storage power stations place special demands on the electrical protection system. Owing to the various operating modes

- Generator mode for energy supply
- Pump mode to feed back energy
- VAR compensation mode

a protection system is required that automatically adapts itself to these changing operating states. The SIPROTEC 7UM6 relays are specifically designed to handle these variable operating conditions. This applies both to the protection functions comprised in the relays and to the flexible adaptation of the protection system via external control signals from the power station.