Differential Protection of Cables up to 12 km via Pilot Wires (Relay Type: 7SD600)

■ 1. Introduction

Line differential protection systems make it possible to protect cables or overhead lines selectively and as fast as possible in the event of a short-circuit. The application domain of the SIPROTEC 7SD600 described here is predominantly in the medium-voltage sector if either the tripping times of graded overcurrent-time protection relays become too great, or if distance protection relays are no longer able to guarantee the desired selectivity.

■ 2. Protection concept

The 7SD600 digital differential protection relay provides short-circuit protection for cables and overhead lines in power supply systems, independent of the system star-point configuration. It works according to the conventional 2-conductors principle. Here, the phase currents at the two line-ends are – with the help of summation current transformers – added up to one summation current. These are then transformed by voltage dividers into proportional voltages, which are fed with reversed polarity to two pilot wires. The resultant voltage difference finally produces a current, which represents the determinant tripping magnitude for both relays. Because of its rigorous local selectivity (the protection range is limited by current transformers at both ends of the line), differential protection is generally applied as an instantaneous main protection since no other protection can disconnect the line more quickly and selectively.

2.1 Differential protection (ANSI 87L)

2.1.1 Principle and current transformer connection

The differential protection function of the 7SD600 recognizes short-circuits in the protection range by comparing the summation currents detected at both ends of the line. In order to do this, the secondary phase currents from the primary current transformers are fed with variable weighting (number of windings) into the summation current transformer which combines them to produce a summation current.

Fig. 1 SIPROTEC 7SD600 line differential protection relay

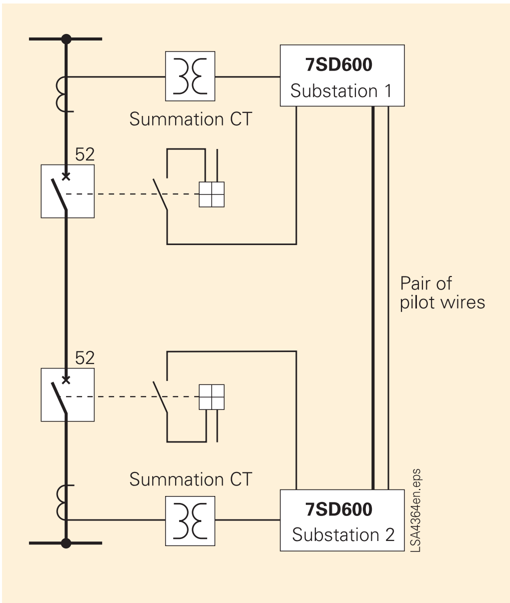


Fig. 2 Principal circuit diagram of line differential protection 7SD600

This also assumes, that current transformers with identical primary values are used at both ends, otherwise the variable windings ratio must be equalized by an appropriate arrangement of the matching transformer and/or summation current transformer.

2.1.2 Summation current transformers

The 4AM4930 summation current transformer is installed as standard in the normal circuit.

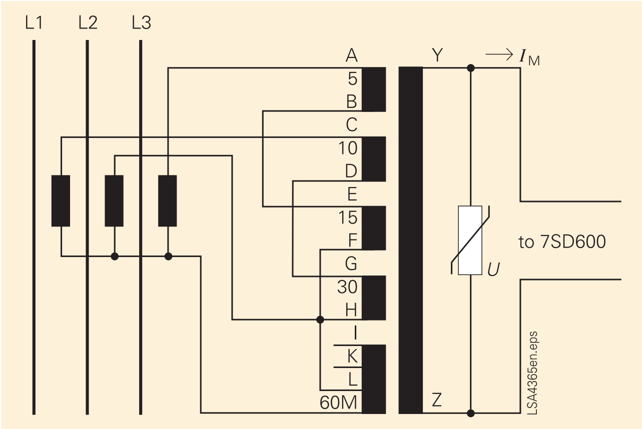


Fig. 3 4AM4930 summation current transformer normal connection

This summation current transformer has different primary windings with several tapping points allowing phase current and connection type (for example two-phase) mixing ratios to be varied. This way, increased sensitivities (e.g. of the earth current) or preferences in the case of double earth fault can be neatly ensured.

Fault	W	W / $\sqrt{3}$	I_1 for I_M = 20 mA
L1-L2-L3 (sym.)	$\sqrt{3}$	1.0	1 x I_N
L1-L2	2	1.15	0.87 x I_N
L2-L3	1	0.58	1.73 x I_N
L3-L1	1	0.58	1.73 x I_N
L1-E	5	2.89	0.35 x I_N
L2-E	3	1.73	0.58 x I_N
L3-E	4	2.31	0.43 x I_N

Table 1 Fault types and winding valencies W in case of normal connection L1 - L3 - E

The selected summation current transformer connection must be implemented identically at both ends of the line to avoid false tripping.

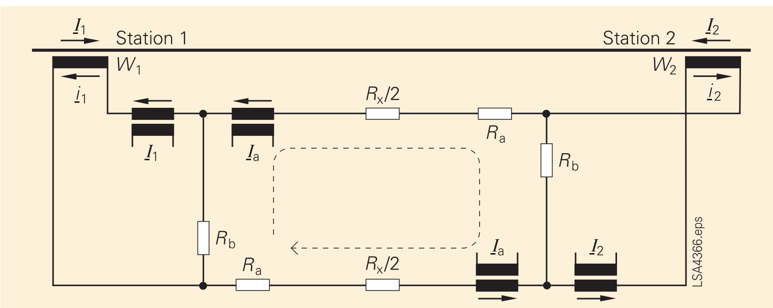


Fig. 4 Function diagram

2.1.3 Differential current

With normal summation current transformer connection and symmetrical current flow (rated quantity), 20 mA flow to the summation current transformer on the secondary side. This summation current is now measured in the local 7SD600, and also fed as voltage drop to two pilot wires via an internal resistor of the protection relay. At the remote end the summation current is formed in the same manner and also fed as voltage drop to both pilot wires, but this time with reversed polarity.

In healthy state, the reverse polarity voltages should neutralize each other out. However, under fault condition there is in the case of different summation currents a resulting voltage which will drive a current (proportional to the theoretical differential current) along both wires. This current is then measured by the protection relay and serves as a tripping parameter.

2.1.4 Transformers in the protected zone

The 7SD600 optionally also analyses the summation currents for a component of 100 Hz. This makes it possible to expand the protection range beyond a transformer. Additional external matching transformers must nevertheless ensure, that the transformation ratio of the currents and their phases is compensated analagously to the transformer.

2.1.5 Restraint current

In order to stabilize the differential protection system against overfunction (unwanted operation) in the event of external faults, the "differential current" tripping parameter is standardized to a stabilization parameter. The latter is the sum of the magnitudes of the currents detected at both ends of the protection range. This stabilization means that in the event of large currents flowing through and of measurement errors resulting from transformer faults or transformer saturation, the tripping parameter must likewise be high.

Measuring the local summation current transformer secondary currents and the current flowing through the pilot wires ensures, that each of the two protection relays can calculate both the differential and stabilizing currents and react according to the tripping characteristic.

2.1.6 Tripping characteristic

The 7SD600 tripping characteristic consists of three sections. In the area of small currents a fixed tripping threshold settable as parameter must be exceeded in order to ensure response. Both the other tripping characteristic branches have set defaults. Current-proportional transformer faults rise as the current magnitude increases. This is taken into account in the tripping diagram with a section of a straight line through the origin with a 1/3 gradient (slope). In the case of even greater currents the tripping limit is determined by a further straight line, which intersects the stabilization axis at $2.5 \cdot I_{NLine}$ and has a gradient of 2/3. This branch takes account of incipient current transformer saturation.

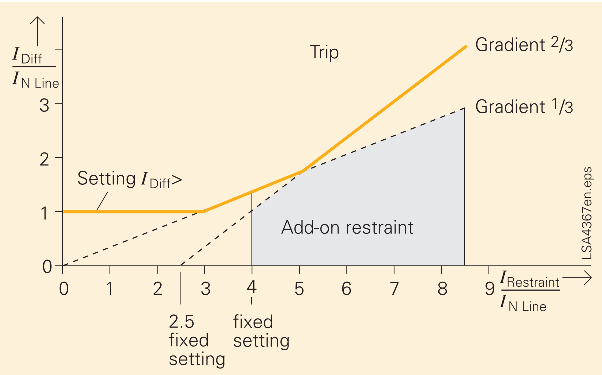


Fig. 5 Restraint characteristic of the differential protection drawn with a default of $I_{Diff}> = 1.0 \cdot I_{N\ Line}$

$I_{Diff} = |I_1 + I_2|$
$I_{Restraint} = |I_1| + |I_2|$
I_1 = Current at local line end, positive flowing into line
I_2 = Current at remote end, positive flowing into line
$I_{N\ Line}$ = Line rated current

In order that differential protection remains stable in the case of external faults with strong currents, the 7SD600 offers additional stabilization with regard to possible transformer saturation. Here, on the basis of the stabilization and differential current trend, the protection recognizes that an external fault initially occurred before the build-up of the differential current as a result of transformer saturation. When the current values enter the additional stabilization (restraint) range, the differential protection is blocked for a maximum of 1 second in order to give the transformer time to come out of saturation. However, if during this time steady state prevails in the tripping range for two network periods, blocking is neutralized and the protection makes the decision to trip.

2.1.7 Pilot wires

Symmetrical telecommunication wire pairs (typically 73 Ω/km loop resistance and 60 nF/km capacity) with a wire/wire asymmetry (at 800 Hz) of less than 10^{-3} are suitable. The loop resistance may not exceed 1200 Ω. Furthermore, the longitudinal voltage component induced in the pilot wires by the short-circuits (to earth) must be taken into account. The induced direct axis voltage component can be calculated according to the following formula:

$$U_l = 2\,\pi\, f \cdot M \cdot I_{k1} \cdot l \cdot r_1 \cdot r_2$$

where
U_l = *Induced direct axis voltage component*
f = Rated frequency [Hz]
M = Mutual inductance between power cable and pilot wires [mH/km]
I_{k1} = Maximum single-pole short-circuit current [kA]
l = Length of the parallel distance between power cable and pilot wires [km]
r_1 = Reduction factor of the power cable (in case of overhead lines $r_1 = 1$)
r_2 = Reduction factor of the pilot wire cable

The calculated induced voltage needs only be half taken into account since it builds up on the insulated pilot wires at both ends. If this exceeds 60 % of the permitted test voltage, additional measures (isolating transformers) are necessary. Isolation (barrier) transformers are available for isolation up to 5 kV and 20 kV respectively. The center tap on the side facing the protection relay must be earthed for anti-touch protection reasons, but the pilot wire connection must not be earthed or provided with surge arresters.

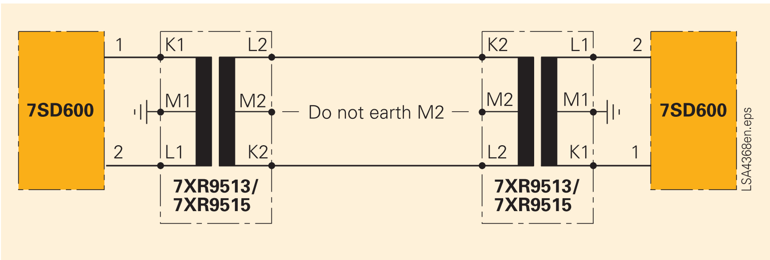


Fig. 6 Connection of isolating transformers 7XR9515 (5 kV) or 7XR9513 (20 kV)

2.2 Backup protection functions (ANSI 50)

As is usual with modern, numerical protection relays, the 7SD600 also offers further integrated protection and additional functions. The user must nevertheless be aware of the lack of hardware redundancy when deploying these functions. For this reason, at least a further separate short-circuit protection relay, for instance a 7SJ602, should be installed.

2.2.1 Overcurrent-time protection (ANSI 51)

The 7SD600 includes overcurrent-time protection alongside differential protection as an emergency function, i.e. for cases where the main function is no longer available. Parameterization makes it possible to set whether the emergency definite-time overcurrent protection should generally be activated when differential protection is ineffective, or only if the wire monitoring responds. This emergency definite-time overcurrent protection works with the local summation current and features one single stage. The current threshold is set above the maximum symmetrical load current. Since in general no time grading is possible if full selectivity is to be retained, a compromise between selectivity and speed of protection has to be found. In any case the tripping time should be delayed by at least one grading, in order to wait to see whether this high current is caused by faults on adjoining power system sections and other protection relays selectively trip upon this fault.

2.2.2 Additional functions

Pilot-wire monitoring

The ohmic resistance of the pilot-wire loop is needed for correct calculation of the summation current at the remote end of the protection range. This current is comfortably determined with the help of DIGSI during commissioning and entered into the protection relay parameters. Because no differential voltage and thus no differential current occur in flowing currents during normal operation, monitoring of the pilot-wire connection is strongly advised. Audio frequency signals are modulated onto the connection line.

Intertripping, remote tripping

In the event of protective tripping at the local end, an intertrip signal can be sent to the remote end (using the same transmission equipment) in order to isolate the faulted line. The remote tripping system, in which a signal coupled via binary input is interpreted as a shutoff command for the circuit-breaker on the remote end, works according to the same pattern. Here too an audio frequency signal is transmitted to the partner relay, as with intertripping.

■ 3. Settings

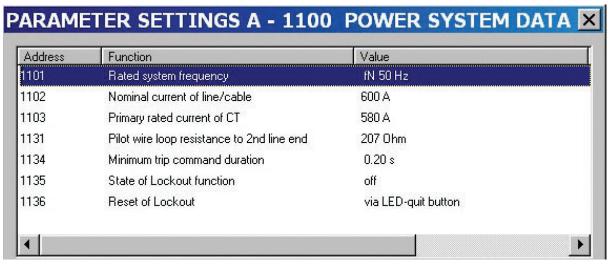
The parameter settings of both relays of the differential protection system differ in only a few points. This is the reason why only the 7SD600 settings of one line end are explained initially.

The differences are explicitly listed towards the end of this chapter.

The 7SD600 is notable for its few setting parameters, which allow it to be configured quickly and easily. Pilot-wire monitoring is the only function that can be activated (or deactivated) under "Scope of the device", provided the relay has been ordered with this option. This must be activated.

3.1 System /line data

The parameters defined by the primary equipment are set under the "system/line data" heading (see Fig. 7). These include network frequency, current transformer ratio and minimum circuit-breaker activation time in the event of protective tripping. In order to better match the differential protection characteristic, the protection parameters are referred to the line rated current; this must be input at this point and must imperatively be the same in both relays. As already described above, the resistance of the pilot-wire connection is required for correct calculation of the current value at the remote end. This can be calculated either from the pilot-wire connection data sheets or can be measured within the context of commissioning by the relay itself in accordance with the instructions in the manual. This value must subsequently be entered here. Finally, the lock-out function can be switched either on or off at this point. The activated lock-out function requires an acknowledgement of the TRIP command via the acknowledgement button on the relay or by the setting of a binary input, e.g. by using an external switch.


PARAMETER SETTINGS A - 1100 POWER SYSTEM DATA

Address	Function	Value
1101	Rated system frequency	fN 50 Hz
1102	Nominal current of line/cable	600 A
1103	Primary rated current of CT	580 A
1131	Pilot wire loop resistance to 2nd line end	207 Ohm
1134	Minimum trip command duration	0.20 s
1135	State of Lockout function	off
1136	Reset of Lockout	via LED-quit button

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Fig. 7 Settings for "Power system data"

3.2 Line differential protection

3.2.1 Line differential protection

As with all protection functions, the differential protection can be switched either on or off at this point in order to simplify function-selective testing. Additionally, there is the option to set these parameters to "indication only", so that for example at the time of commissioning all indications for this protection function are logged, but no tripping occurs. The differential protection function must of course be switched on for normal operation. Regarding the differential protection function, only the tripping threshold I_{DIFF}> must be set (referred to the line rated current).

Referred to the summation current, this value must thus lie below the minimum short-circuit current but above the inrush current and the transformer faults of the primary and summation current transformers, taking the weighting factors for the various fault types into account. The preset value of $1.0 \cdot I/I_{N,Line}$ has proved over many years to be a stable empirical figure. Taking account of a weighting factor of more than 2 for single-pole faults, this corresponds to barely five times an accepted charging current of 10 % referred to $I_{N,Line}$. Should 5 times the charging current be above this value, I_{DIFF}> must be increased.
This charging current is calculated according to the equation:

$$I_C = 3.63 \cdot 10^{-6} \cdot U_N \cdot f_N \cdot C_B' \cdot s$$

I_C = Charging current to be ascertained in A primary
U_N = System rated voltage in kV
f_N = System rated frequency in Hz
C_B' = Operating capacity of the line in nF/km
s = Line length in km

3.2.2 Blocking with second harmonic

A transformer may also be situated within the 7SD600 protection range. However, in this case the transformer ratio must be recreated with external matching transformers, so that the current magnitude and phase angle of the summation current transformer inputs correspond on both sides of the transformer. For this application it is necessary to stabilize the differential protection in relation to the transformer inrush. Because no transformer is located within the protection range, blocking of the differential protection is deactivated by means of the second harmonic. Consequently, the tripping threshold set values for both the second harmonic and the maximum differential current (which is blocked by this function) are irrelevant.

3.2.3 TRIP delay

In certain applications (e.g. reverse interlocking), it can be necessary to delay the differential protection somewhat. This delay can be set at this point.

3.2.4 Local current threshold

A local current threshold (which must be exceeded) can be set as a further tripping condition at the local end. With the preset value $0 \cdot I_{N, Line}$ the protection relays trip at both ends if the differential protection responds. The local current threshold can be raised if, for example, in the case of single-side infeed, the remote end (from which no current is feeding onto the fault) should not be tripped.

3.2.5 Intertrip function

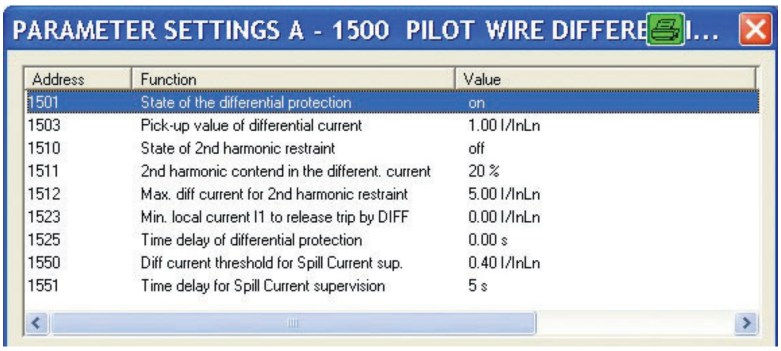
Normally, tripping is effected at both stations as a result of current comparison. Tripping at one end only can occur when an overcurrent release is used or with short-circuit currents only slightly above the tripping value. Circuit-breaker intertripping can be parameterized in the unit with integral pilot-wire monitor, so that definite tripping at both ends of the line is assured.

3.2.6 Differential protection blocking (spill current)

This differential current monitoring function reacts to a permanently low differential current, which can be produced by phase failure at the summation current transformer (e.g. due to wire break) and blocks the differential protection function. The threshold (parameter 1550) is set slightly over the capacitive losses of the pilot wires, which at a power system frequency of 50 Hz can be estimated according to

$$I_{spill}\,(\%) = 0.025 \cdot I_{N,\,Line} \cdot l_{Line}\,(\mathrm{km})$$

With a line length of 12 km, this gives a value of $0.3 \cdot I_{N,\,line}$ for the spill current. In order to prevent spurious tripping, the parameter is set at $0.4 \cdot I_{N,\,line}$. In accordance with the default (preset) value, monitoring is delayed by 5 seconds.



Address	Function	Value
1501	State of the differential protection	on
1503	Pick-up value of differential current	1.00 I/InLn
1510	State of 2nd harmonic restraint	off
1511	2nd harmonic contend in the different. current	20 %
1512	Max. diff current for 2nd harmonic restraint	5.00 I/InLn
1523	Min. local current I1 to release trip by DIFF	0.00 I/InLn
1525	Time delay of differential protection	0.00 s
1550	Diff current threshold for Spill Current sup.	0.40 I/InLn
1551	Time delay for Spill Current supervision	5 s

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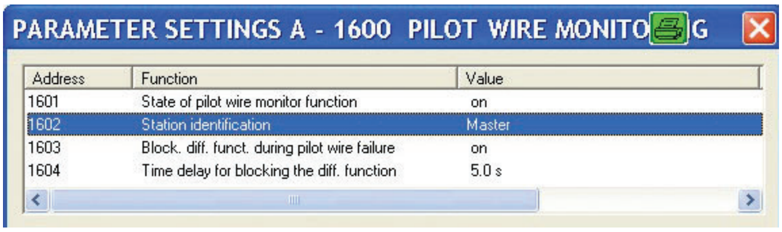
Fig. 8 Setting the differential protection function

3.3 Pilot wire monitoring

Pilot wire monitoring is extremely important for monitoring the capability of the differential protection system. Since in fault-free operation, particularly where operating currents are low, no appreciable differential current occurs (due to transformer and measurement inaccuracies), wire break or short-circuit would not be noticed, which would lead to protection malfunction. Thus the pilot-wire function will be activated and the reaction of the protection will be defined. When a connection fault is recognized, the differential protection can be blocked or the fault can simply be reported – after an adjustable delay time.

In order to begin the communication between both relays in a defined manner, the station identification must be set differently. One 7SD600 is parametrized as master, the other as slave.



PARAMETER SETTINGS A - 1600 PILOT WIRE MONITORING

Address	Function	Value
1601	State of pilot wire monitor function	on
1602	Station identification	Master
1603	Block. diff. funct. during pilot wire failure	on
1604	Time delay for blocking the diff. function	5.0 s

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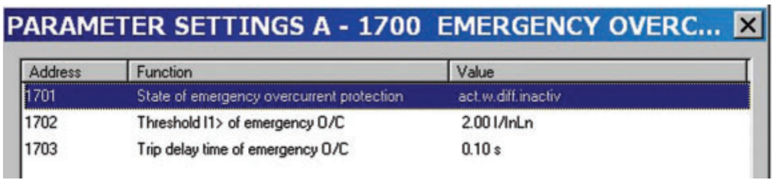
Fig. 9 Settings of the pilot-wire monitoring for the local relay (master)

3.4 Overcurrent-time protection

Emergency overcurrent-time protection can be activated either in the event of a recognized pilot-wire fault or generally when the differential protection is deactivated. The local summation current must likewise be used as a measuring quantity and the setting must be referred to the line rated current. Here too, when setting the current threshold, the weighting factors for the various fault types must also be taken into consideration. The current thresholds are set – as far as possible – between maximum operating current and minimum short-circuit current. The associated delay time is adjusted to the network grading plan as closely as possible, in order to maximize selectivity.



PARAMETER SETTINGS A - 1700 EMERGENCY OVERC...

Address	Function	Value
1701	State of emergency overcurrent protection	act.w.diff.inactiv
1702	Threshold I1> of emergency O/C	2.00 I/InLn
1703	Trip delay time of emergency O/C	0.10 s

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Fig. 10 Settings of the pilot-wire monitoring "Emergency overcurrent-time protection"

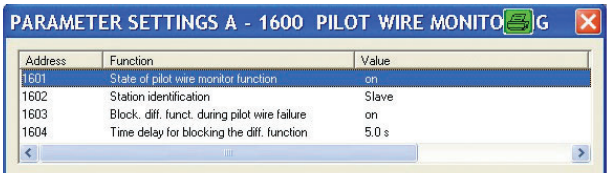
3.5 Remote tripping/Transfer trip

A signal injected via binary input (e.g. from the circuit-breaker failure protection) can be transmitted as an audio-frequency signal to the remote end through the pilot wires in order to effect tripping of the circuit-breaker there. Thus reliable transmission is ensured even when pulses are very short. The transmission duration can be prolonged. The protection relay at the remote end must be appropriately set for the reception of a remote tripping signal, i.e. the "transfer trip" function must be switched on.

To avoid an overfunction, tripping can be delayed. Hence, a transient signal will not lead to a misinterpretation. In order to ensure reliable tripping even when a short signal is received, the transfer trip signal can also be delayed until the circuit-breaker opens. The preset values are intended to ensure remote tripping.

3.6 Relay at the remote end

The parameter settings of the second 7SD600, which is installed at the remote line end, are to the greatest possible extent identical to the relay described here. The identical summation current transformer connection and the same set value for the line rated current are essential. All further parameters can normally be taken over by the local relay; however, under the key term "pilot-wire monitoring", the station identification of "master" has to be changed to "slave" so that this parameter is set differently in both relays.



PARAMETER SETTINGS A - 1600 PILOT WIRE MONITORING

Address	Function	Value
1601	State of pilot wire monitor function	on
1602	Station identification	Slave
1603	Block. diff. funct. during pilot wire failure	on
1604	Time delay for blocking the diff. function	5.0 s

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Fig. 11 Settings of the pilot-wire monitoring for the relay at the remote end (slave)

4. Summary

Undelayed and at the same time rigorously selective protection of cables and lines reduces the consequences of unavoidable power system disturbances. For one this means protection of the equipment, and secondly a contribution to a maximized level of supply security.

A differential protection system consisting of two SIPROTEC 7SD600 relays and the associated summation current transformers offers comprehensive protection of cables and overhead lines. Extensive additional functions allow trouble-free connection of the relays and integration into complex power system protection grading.

The default settings of the relay are selected in such a way, that the user only has to configure the known cable and primary transformer data. Many of the preset values can be taken over with no problem and thus substantially reduce effort involved in parameterization and setting.