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New prospectives for digital protections of the 3 kV DC electric traction lines

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Abstract

The increase of currents through lines in normal operation, due to the increase of train traffic and of the power absorption of the trains, especially the new High Speed trains, has led to a condition such that the intensity of the currents in normal operation is approaching the same order of magnitude of that for faults located in positions far from the ends stations. It is therefore a difficult task to discriminate between a faulty situation and that of a temporary high load condition. The addition to the maximum current protection relays of devices sensitive to the derivative of the current has not solved this problem in many practical cases. This paper present the results of a study performed by experimental tests and numerical simulations designed to analyze the possibility of applying the new technique of the digital relays for the protection of the lines under consideration. A first proposal for a new digital protection is presented.

1 Introduction

At present in Italy, according to the current technology, the protection of the 3 kV dc electric traction lines is provided by dc circuit breakers equipped with an intrinsic overcurrent protection also sensible to the derivative of the current with respect to the time. Because of the heavy train traffic and due to the increasing power absorption of the trains, the intensity of the line currents in normal operation is now approaching the magnitude of the fault currents, for faults located in positions far from the terminal stations.

In order to face the increase of the load currents various measures have been adopted. The breakers at the two terminals of each 3 kV dc line have been normally equipped with teleconnection devices, in order to safely detect faults located in unfavorable positions and/or characterized by high fault resistance. In some cases minimum voltage relays have been also added. The line conductor cross section has been normally increased from 320 to 440 mm^2 of copper. In some critical cases the system has been made more powerful by addition of new substations.

These measures have made it possible to increase the setting of the overcurrrent protection from the old values of 1-1.5 kA to 3-3.5 kA, but also because of the increasing presence of High Speed trains and due to the fact that currents of an amplitude and shape close to the fault currents may also be absorbed by the locomotives, especially by the ones equipped with power electronic regulating devices in conjunction with the transit through the commutation zones of the contact wire, commutation of the motors and other phenomena, a relatively high number of untimely breaker trippings occurs at present with high life expenditure of the breakers and risk of damages to the catenary in conjunction with non necessary trippings.

Getting the train traffic heavier and heavier it is thus to be expected that in the next future it will become difficult, for the protections presently in use, to safely detect the faults, in the unfavorable cases of fault location and discriminate them from the temporary high load condition.

In order to maintain a good quality of service and improve it as far as possible it was thus decided to perform an in depth analysis in order to:

- detect the most common causes of untimely tripping of the protections currently in operation;
- record the current through the line terminals in order to check the possibility of distinguishing the fault currents from the temporary overload currents by analyzing the current characteristics;
- analyze the possibility of applying a new digital protection able to perform more complex functions on the quantities under control.

An extensive field test campaign was first performed by the Italian State Railways (FS SpA) in cooperation with the University of L'Aquila on about 1000 km of lines electrified at 3 kV dc, 20 Substations and 200 circuit breakers, in order to make a statistical evaluation of the frequency and of the causes of the line trippings in the Lazio district in Italy.

Thereafter at the substations of Campoleone and Cisterna an experimental installation was set up and digital fault recording apparatuses were installed in order to record the line voltage and current and the state of the logical contacts of the protections in conjunction with the trippings of the circuit breakers. A number of recordings was obtained and analyzed. Some examples of significant recordings are presented hereinafter. The main results of the research study are hereunder summarized.

From the analysis of the recordings it was found that:

- in some cases, especially with locomotives equipped with chopper devices an overcurrent able to cause tripping of the line protections can be absorbed in conjunction with the transit of the above train from one section to another;

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- the gradient of the current normally absorbed by the trains may reach in normal operation 60-80 A/ms, i.e. it may be of the same order of magnitude of the one in cases of faults far from the supply terminals;
- it is difficult with the present protections to perform an accurate setting of the current tripping soil, especially as far as the sensitivity to the gradient is concerned;
- the setting of the protections currently in operation is subject to a sort of instability, i.e. to a phenomenon of natural change of the setting during the time that causes untimely trippings of the breakers with currents less than the preset value.

These elements have suggested to try to get advantage from the application of the new technology of the digital protections that may make it possible to implement more complex functions on the quantities drawn to the protective relays as better explained further ahead.

The paper presents the results of the field campaign above and of the computer studies performed in order to analyze the influence on the shape of the fault current of the various parameters. On the basis of these first results the principles for a new digital line protection were proposed and presented here.

2 Experimental installation set up at Campoleone and Cisterna SSE

Fig. 1 shows the double-track line Torricola - Campoleone – Cisterna – Sezze where the experimental recordings were performed.

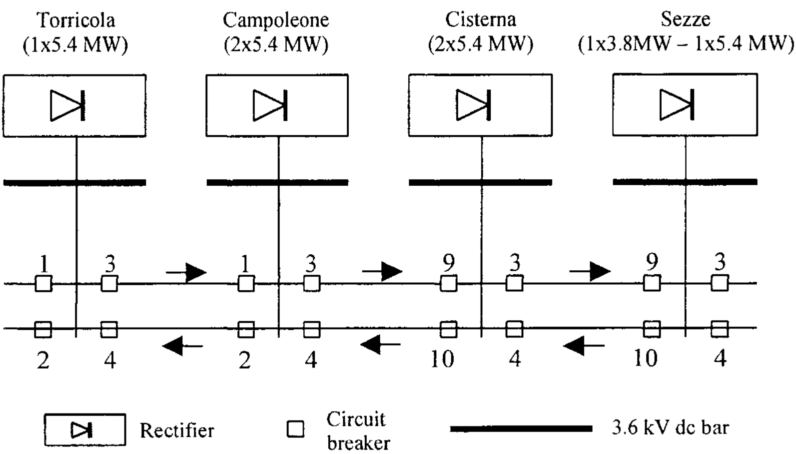

Fig. 1- Schematic diagram of the experimental recording site

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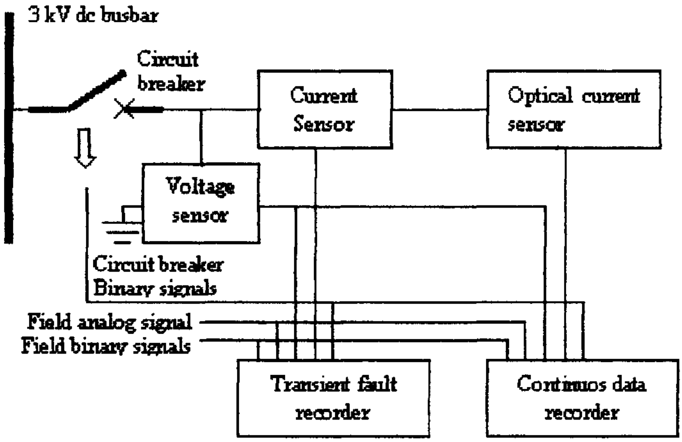

Fig 2- Sensor connections – schematic diagram

Fig.2 shows the schematic diagram of the measuring apparatuses installed in the substations of Campoleone and Cisterna.

In the substations high precision sensors and two recording instruments were installed, the first, a fault recorder activated by a triggering signal command, the second for continuous data acquisition. All recording instruments were synchronized via GPS system.

The fault recorder adopted was an ABB Indactic 650 data recorder characterized by 9 analog inputs and 16 digital inputs and a maximum sampling rate of 4800 Hz. The recording time interval was set to 5 seconds as a surrounding of the trigger signal. The opening and closing of circuit breakers produced the generation of trigger signal. Hall effect sensors were positioned downstream circuit breakers in order to take current signals and send them to the storage unit.

Table 1: Measured parameters

Measured parameters	Number of channels	Type A/D
Current in the circuit breakers	4	analog
Voltage at the lineside terminals of the breakers	4	analog
Voltage to earth of the negative pole	1	analog
Negative return current	1	analog
Earth relay current	4	analog
Voltage of the telephone circuit for teleprotection	2	analog
Circuit breakers status	20	digital
Other substation logical signals	20	digital

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For continuous data acquisition of the voltage and current an IMC μ-Musics was adopted, equipped with 16 analog channels with a sampling rate up to 80 kHz including a compression software for memory occupancy reduction. Optical sensors, Faraday-effect, were positioned downstream the circuit breakers in order to take signals and send them to storage unit.

3 Analysis of the recordings of some significant events

In the following the results are presented of the analysis of some significant recordings obtained in the field test campaign.

a) The oscillogram in Fig.3 reports the shape of the current through the CB n. 4 at Campoleone. The recording was made by means of the μ-Musics recorder on December 2, 1998 at time 8:46. The current through the breaker 4 has increased continuously at a gradient of about 70 A/ms, up to the value of about 2500 A (somewhat higher than the breaker setting) and remained around that value for about 10s without any breaker intervention.

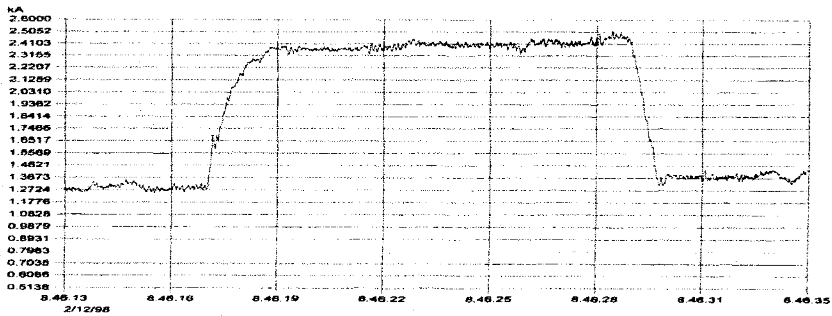

Fig.3 - Shape of the current through breaker 4 at Campoleone in a case of high current absorption and without tripping of the protective breaker.

b) The diagram in Fig. 4a shows the current through CB n.4 at Campoleone. The recording refers to an event occurred on 2/12/98 at 9:27. Probably because of the entrance in the line section of a train equipped with chopper regulation, in a time Δt=44ms, the current through CB n.4 above has increased up to about 2850 A causing the tripping of the breaker. After breaking of the current, overvoltages are generated of an amplitude of 2, in per unit of the nominal voltage. Thereafter, after about 5 s from opening CB n.4 at Campoleone, a successful breaker reclosure occurs (see Fig. 4b). The mean gradient of the current during the fault in this case has been of about di/dt= 65 A/ms.

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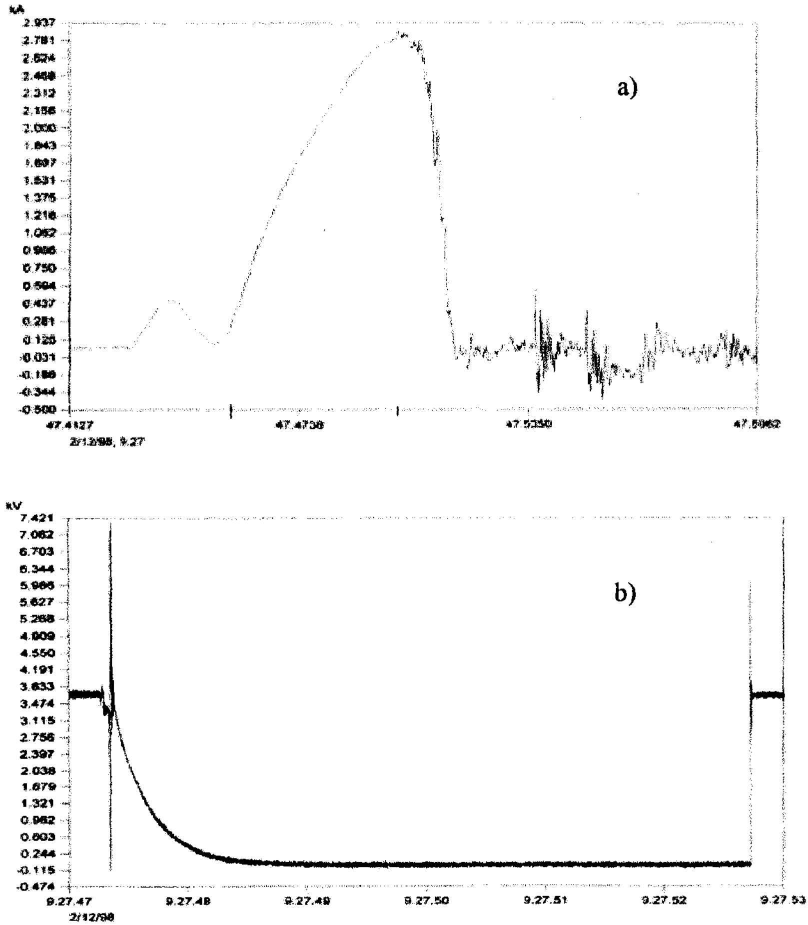

Fig 4: a) Current through breaker n.4 at Campoleone following the entrance in the line section of a train equipped with power electronic regulated devices.
b) Shape of the voltage downstream breaker 4.

c) The diagrams in Fig 5a show the oscillograms recorded at Campoleone on December the 2nd 1998 at 8:49. At the regime before the transient, through the CB n.2, a current of about 1000 A was flowing. At the entrance in the section of the train IC 718, the current has increased up to about 2600 A causing the tripping of the breakers protecting the line Campoleone-Torricola (at Campoleone and at Torricola by teleconnection). From the diagram in Fig 5b, relevant to the voltages lineside of the breaker n.2 it is possible to notice the slow decay (in about 2.5 s) of the line voltage after the line tripping. This fact indicates that no permanent fault affects the line. After about 5 s, a

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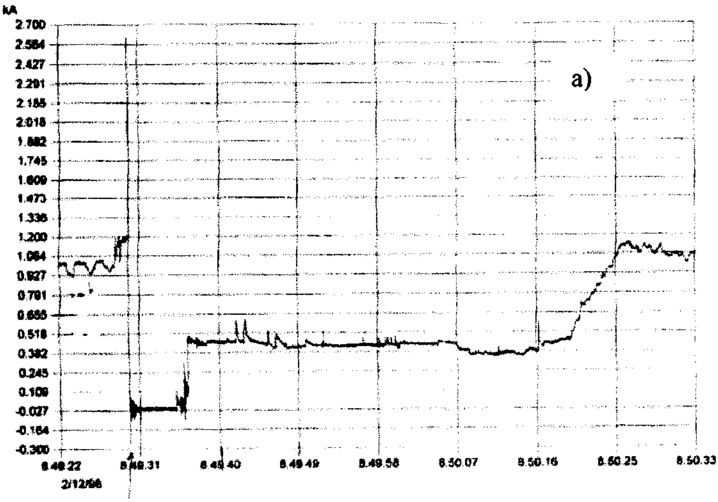
positive test of the line insulation is performed and then the line is successfully reclosed.



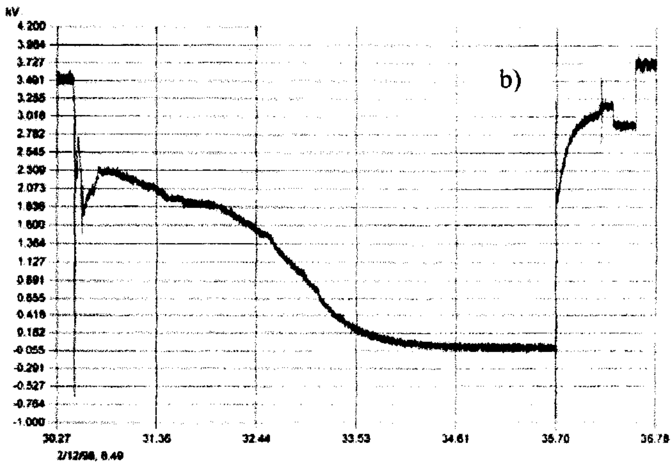


Fig 5: Tripping of breaker n.2 at Campoleone on overload and reclosure

d) The diagrams in Fig 6 show the case of a very rare and complex fault occurred on the line Campoleone – Cisterna. At time 8:08 during the transit of the train IC n. 1924, on the even track of the line Campoleone – Cisterna, at a distance of about 100 m from the entrance of the station of Campoleone, the supporting cable of the line broke and one of the ends of the cable got entangled in the pantograph of the abovementioned train, causing a fault to ground.

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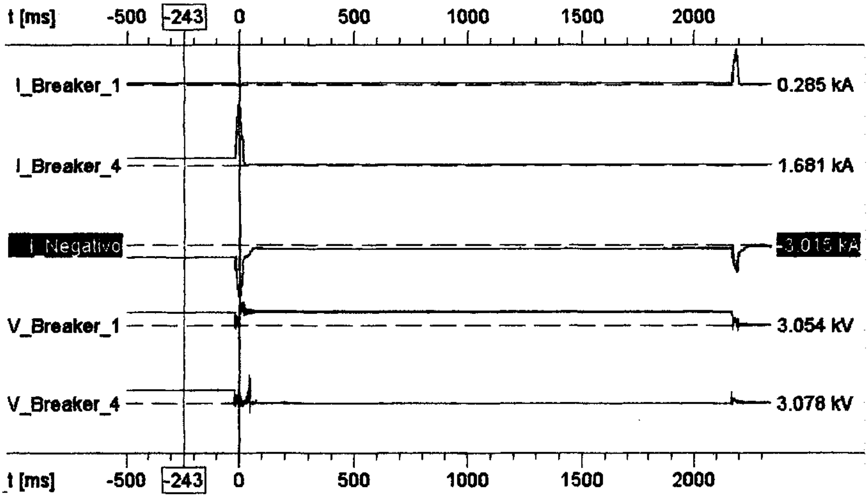

Fig 6: Currents trough breakers n.1 and 4 at Campoleone, total current through the negative pole and voltage downstream the breakers during a multiple fault.

Following the fault, at t=8:08:6 the current through the breaker n.4 at Campoleone has started increasing, and has reached in about 1ms the setting of the breaker (I_s=2400 A) thus causing the tripping of the breaker. The contacts of the breaker opened in about 4 ms and the short circuit current has been limited up to about 16 kA (the value was reached in about 19 ms from the fault). Thereafter, in about 15 ms, the arc through the contacts of the breaker extinguished.

Fig. 6 shows the shape of the currents through CBs n. 1, 4 and through the connection to the negative pole at Campoleone. The current through CB n.4, from the value of about 1300 A, has reached 16 kA. Because of the severe fault the breaker protecting one of the two converter unit transformers has also tripped on overcurrent.

About 2 s after, the fault appears downstream CB n. 1 at Campoleone. The breaker trips, limiting the current to I= 9 kA. CBs n. 9 (at Cisterna) and n. 3 (at Campoleone) also trip. Six seconds after the first event, the breakers n. 4 at Campoleone and n. 10 at Cisterna initiate a reclosure. But the line insulation was not completely restored as a non-solid contact to ground of the line conductor was present. The insulation test preceding the reclosure was thus partially successful for a time enough to permit the breaker reclosure. These thus reclosed and a new short circuit occurred. Thereafter breakers n. 9 and n. 2 at Campoleone opened.

As conclusive remarks it should also be said that during the tests it has been evidenced that the sensitivity of the breakers to the gradient of the current should have be better reduced in some cases. A sort of instability of the setting of the protective breakers has been also evidenced.

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4 Computer simulation of the short circuit transients

In order to determine the current versus time through the line protective breakers following the faults in the various possible cases that may occur in practice, a mathematical model has been set-up by use of the EMTP/ATP Program of the 3 kV d.c. system Torricola - Campoleone - Cisterna - Sezze in Fig1 In the model it has been represented: the unit transformers with their equivalent circuit and winding connections; the 6-pulse rectifier bridges at secondary side of each transformer together with the snubber and damping circuits; the filters equipping each converter unit; the traction lines. The non-linearity of the rails was disregarded in the simulation. For some cases the results of the simulations were compared with the experimental test results available and the agreement was satisfactory.

Cases of faults at the ends of the line Campoleone Cisterna were simulated in the configurations here under specified and assuming a fault resistance Rg variable in between 0 and 0.15 Ω.

Tab. II –Computer analysis of faults in the line Torricola-Sezze

Case n.	System configuration	Fault position	Rg [Ω.]
1	All the lines (Torricola – Campoleone, Campoleone – Cisterna, Cisterna – Sezze) and the converter units at Torricola (1 x 5,4 MW), Campoleone (2x5,4 MW), Sezze (2x5,4 MW) in operation	At 100 m from Campoleone SSE	0
2	See case n. 1	See case n. 1	0.15
3	See case n. 1	At 100 m from Cisterna SSE	0
4	See case n. 1	At 100 m from Cisterna SSE	0.15
5	The busbar at Cisterna is supposed to be out of service and the lines Campoleone Cisterna and Cisterna Sezze by-pass the Substation of Cisterna	Cisterna SSE	0
6	As per case 5	Cisterna SSE	0.15
7	As per case n. 6 but with only one unit in operation at Campoleone.	Cisterna SSE	0.15
8	No converter units in operation at Cisterna. All the lines in operation and connected to the busbar at Cisterna	Cisterna SSE	0.15

In all the cases it was assumed that a train absorbing a current of I=1000 A was present in the middle of the lines Campoleone –Cisterna.

For the sake of simplicity the plots of the current calculated are not reported here. They are available at the authors on the reader's request. Only the main results are referred to here.

Tab.V reports the values that may be virtually reached, in the absence of any tripping, by the currents through the breakers at Campoleone and Cisterna

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and the mean values, G_1 and G_2, of the slope of the current through the circuit breaker at the ends of the lines Campoleone - Cisterna and Campoleone – Sezze. The gradient has been calculated at the intervals 1400 to1900 A (G_1) and 1900 to 2400 A (G_2).

Tab. III -Summary of the current amplitude and slope for the cases of Tab.II

Case	CAMPOLEONE				CISTERNA			
	I_3	I_4	Slope breaker 3 [A/ms]		I_9	I_10	Slope breaker 9 [A/ms]	
	[kA]	[kA]	1400-1900	1900-2400	[kA]	[kA]	1400-1900	1900-2400
1	25.41	-2	> 10000	> 10000	2.95	2.63	50.8	27.9
2	15.67	-0.8	> 10000	> 10000	1.79	1.6	< 5	---
3	2.92	2.58	52	28.2	38.9	-3.83	> 10000	> 10000
4	1.79	1.59	< 5	---	16.29	-0.89	> 10000	> 10000
	CAMPOLEONE				SEZZE			
	I_3	I_4	Slope breaker 3 [A/ms]		I_9	I_10	Slope breaker 9 [A/ms]	
	[kA]	[kA]	1400-1900	1900-2400	[kA]	[kA]	1400-1900	1900-2400
5	5.7	0.61	112.6	101.2	4.79	0.11	88.0	84.6
6	4.3	0.65	101.6	77.9	3.5	0.15	67.9	53.0
7	3.9	0.47	90.7	67.9	3.51	0.28	67.3	52.7
8	2.98	2.98	52	31.2	2.29	2.29	26.3	< 7

The study brought to the following conclusions:

- As it could be expected, in case of faults in the close proximities of the Substations (cases n.1 to 4) the current reaches a virtual value very high with a very high slope. $G_1=G_2>10000$A/ms. At the terminal of the line far from the fault location the current is reduced, especially in the case of high fault resistance and the gradient very low. In this case because of the high amplitude of the current and of the gradient, safe and selective detection of the fault by the circuit breaker at the line terminal close to the fault is easily accomplished. Tripping of the breakers at the line terminals far from the fault may be assured by the teleconnection;
- In cases 5, 6, 7 the currents at the breakers 3 of Campoleone and 9 of Sezze are high enough as to cause the tripping of the breakers above; the least value of the gradient recorded in this case is 52.7 A/ms,
- In case n. 8, which is a very rare case, the currents through the breakers n.3 and n. 4 at Campoleone have the same values and shapes as it occurs for breakers n. 9 and 10 at Sezze. They will probably initiate tripping of the faulty line, and an untimely tripping of the healthy one. The breaker 9 at Cisterna (not reported in the Table) draws a very high current which is contributed by breakers 10, 3, 4 of Cisterna and will open certainly.

As a conclusion it could be said that, for faults located in unfavourable locations the minimum value of the gradient calculated is about 53 A/ms, i.e. it has the same order of magnitude of the gradient of the load current recorded in

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some cases (see Para. 3). In some particular cases (see case n. 8) untimely trippings may occur.

5 Proposal of a new dc electric traction line digital protection

On the basis of the results summarized it was proposed to apply a new dc electric traction line digital protection with the following main features:

- Directional overcurrent relay with sensitivity to the slope of the current, adjustable in a proper field (say in the range 0-100-1000, >1000 A/ms);
- As an alternative, directional minimum resistance relay, possibly with a sensitivity to the gradient of the resistance;
- Teleconnection of the terminals at the ends of the same line for teleprotection;
- Thermal image protection of the most critical element of the line;
- Control of the quality of the voltage: abnormal values of the amplitude, presence of the 2^{nd} order harmonic, etc.).

Such a protection shows the possibility to:

- improve the performances of the line protections enabling them to be sensitive to quantities different from the simple current amplitude: for instance they may be sensitive to the apparent resistance, as seen from the terminal, thus behaving like a sort of distance protection;
- improve the accuracy when setting the relay, especially the sensitivity to the derivative of the current or of the apparent resistance as a function of the time;
- take advantage from the fact that a numerical protection, as it is known, has a setting which is constant during the time and it is not subject to drift phenomena; the protection in principle may also be set from a remote center;
- make easier the coordination among line protections and protections on board of the locomotives.

Other positive aspects of the new envisaged protections that should be mentioned are:

- the possibility of checking the quality of the dc voltage provided, for instance to check if a second order harmonic is present in the voltage above as a consequence of a single pole failure on the ac main supply side;
- the possibility to transmit the number of trippings on fault of the breakers and the other informations of interest in a remote center where an analysis can be performed on the working conditions of the circuit breaker and decisions may be taken for its optimal maintenance operation.

An experimental testing of a digital terminal made according to the principles above has been started on the line “Direttissima” Roma-Firenze. A report of the experimental results will be presented as soon as the first results will be available.

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6 Conclusions

The increase of the load and of the power absorbed by the trains is leading to a condition such that the load currents are approaching the order of magnitude of the short circuit currents for faults located in unfavorable locations and of high resistance. It is thus to be expected that in the next future it will become difficult, for the protections presently in use, to safely detect the faults, in the unfavorable cases of fault location and discriminate them from the temporary high load conditions.

A statistical analysis of the trippings in the Lazio district and an experimental field test campaign performed in order to record the shape as a function of the time of the voltages and currents immediately before and shortly after the breaker trippings has revealed that:

- untimely trippings of the breakers may occur for excessive sensitivity of the protections to the derivative of the current;
- the locomotives equipped with electronic devices may absorb currents of an amplitude and shape close to the fault currents in conjunction with the transit through the commutation zones of the contact wire, causing untimely line trippings;
- it is difficult with the present protections to perform an accurate setting of the current tripping soil, especially as far as the sensitivity to the gradient is concerned;
- the setting of the protections currently in operation is subject to a sort of instability, i.e. to a phenomenon of natural change of the setting during the time, that causes untimely trippings of the breakers with currents different from the preset value;
- a computer analysis has also shown that the shape of the currents through the breakers for faults far from the stations and characterized by high resistances, is similar to that absorbed by the load; in particular the derivative of the current may be of 50-60 A/ms as for the values recorded in high load but normal operation cases.

The findings above have suggested the principles for a new digital protection that will be tested on the "Direttissima" Roma-Firenze. The principles above are presented in the paper.