A new digital protection of the 3 kV DC electric traction lines
Results of the Application of Four Prototypes in Italy

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Abstract

Due to the increase of the train traffic and of the power absorption of the trains, especially the new High Speed trains, the intensities of the current in the electric traction lines, in normal operation, have been continuously increasing. In some cases the line currents may approach the fault currents flowing in case of critical faults. The detection of such cases and the discrimination of a faulty situation from that of a temporary high load condition has become difficult for the short circuit protections now in operation, sensitive to the amplitude and to the rate of rise of the current. The paper presents the results of a study performed by experimental tests and numerical simulations aimed to analyze the possibility of applying the new technique of the digital relays for the protection of the lines under consideration. A digital protection with innovative functions has been developed and is also presented in the paper together with the first results of the experimental application.

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 internal overcurrent protection also sensitive 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 and characterized by a high fault resistance.

In order to face this situation, 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 also been 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 reinforced by addition of intermediate substations.

These measures have made it possible to increase the setting of the overcurrent 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 in conjunction with the transit through the commutation zones of the contact wire, 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 to 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 the untimely trippings above;
- record the current through the line terminals in order to check the possibility of improving distinction ability of the fault currents from the temporary overload currents;
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 a first experimental installation was set up in the 3 kV dc line Campoleone-Cisterna and digital fault recording apparatuses were installed in order to record the line voltage and current and the state of the digital signals of the protections in conjunction with the trippings of the circuit breakers. The main results of the studies above are summarized in [1]. In particular it was found that:

- the rate of rise (gradient) of the current normally absorbed by the trains may reach in normal operation 60-70 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;
- 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;
- it is difficult with the protections presently in use in Italy 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 lower than the preset value.

On the basis of the analysis performed, a new digital relay protection was developed with innovative functions. Four prototypes of the new relay were set up by ABB-Energy Automation on FS SpA specifications and installed at the terminal ends of the double-track line Farneta-Montallese, on the High Speed line Roma-Firenze, called “Direttissima” (see Fig. 1) characterized by heavier traffic than the line Campoleone - Cisterna and by the presence of faster trains. In each substations high precision sensors and two recording instruments were installed: an ABB Indactic 650 data recorder activated by a triggering signal command, and an IMC μ-Musics recorder for continuous data acquisition. The recording instruments were synchronized via GPS system. In the following the principles of the new protection are presented together with the first results of the experimental application in the line above.

2. Analysis of the recordings of some significant events

In the following the recordings of some significant events recorded during the field test campaign are reported as typical examples.

a) Fig. 3 shows the shape of the current through breaker n. 12 at Montallese during a solid fault between the contact wire and the truck at 7.7 km from Montallese converter Station on one of the lines Farneta-Montallese radially fed from Montallese, followed by tripping of the protective high speed breaker at the sending end. The peak value of the current reaches 5.8 kA with a mean slope of the fault current through the breaker of about 135 A/ms. Opening of the breaker takes about 25 ms from the time the setting of the breaker (3000 A) is exceeded. Arcing extinction time takes about 15 ms.

b) Fig 4 shows the current through breaker n. 15 in the line Farneta - Montallese at the entrance in the line of a train coming from the line Rigutino - Farneta, protected at Farneta by breaker n. 21. The train was absorbing a current of about 1500A. From the diagram the commutation phenomena can be observed, during the transit of the train through the zone, 30-50 m long, were power supply to the trains is provided at same time by both contact wires, the one fed through breaker n. 21 and that fed by breaker n. 15 above, that run in parallel, isolated each other, at about 40 cm distance. At the instant the pantograph touches the contact wire of the line
Farneta - Montallese about 750 A out of the 1500 totally absorbed by the train, suddenly are fed by the feeder above through breaker n. 15. In this phase the current through this breaker increases with a mean slope of about 20 A/ms and a recorded maximum slope of 30 A/ms lasting less than 5 ms. During the following period of time, the pantograph touches both feeders and the current is fed in two approximately equal parts through breaker n. 21 and n. 15. At leaving the overlapping zone by the pantograph, the total current absorbed by the train is fed through breaker n. 15. In this circumstance the gradient of the current through breaker n. 15 reaches about 25-30 A/ms and approaches 50-60 A/ms for about 3.5 - 4 ms. This commutation phenomenon, as it has been observed in many cases, is typical and in the following will be indicated as “normal commutation”.

c) Fig. 5 shows a case where, because of possible oscillation of the two supply feeders in the commutation zone due to dynamic phenomena caused by the transit of the train or by other mechanical reasons the pick of the current from the feeder of the line entered by the train is abrupt. Following phenomena of loosing and regain contact during the transition time may also be observed. In the case under consideration the mean value of the current gradient recorded, calculated in a time interval of 10 ms, is about 30-40 A/ms. For limited time intervals, lasting 4-5 ms, maximum value reached by the gradient reaches 70-80 A/ms. This is a case of commutation where the mean value of the slope of the current through the breaker of the entered line is much higher than in the previous case; it will be indicated in the following as a “critical commutation” case.

d) Fig 6 shows the current absorbed by an High Speed train (ETR500) during normal running of the train entered in the line. The current absorbed is increasing up to about 1350 A and is slowly oscillating in between 1350 A and approximately 0 A due to the combined effect of the regulation of the power absorbed by the train and of the rapid leaving from the substation. The slope of the current during this phenomenon is very low, less than 7-8 A/ms.

From the analysis of the above and similar oscillograms observed it may be concluded that the gradient of the current absorbed by the trains in the line under consideration is contained under 7-8 A/ms in normal operation; it may reach 25-30 A/ms at the entrance in the line of a train and in “normal commutation” cases. In “critical commutation” cases, the mean value of the gradient of the current through the circuit breaker protecting the line entered by the train may reach 40 A/ms with peaks up to 70-80 A/ms.

3. Computer simulation of 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 Città della Pieve- Montallese – Farneta – Rigutino 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 in one of the lines Farneta - Montallese have been represented. A summary of some significant cases run is reported in Tab. I.
Tab. I – Computer analysis of faults in the line Farneta Montallese.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>System configuration</th>
<th>Fault Type(*)</th>
<th>Arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base Case: All the lines (Città del Pieve – Montallese – Farneta – Rigutino) in service; all the transformer-converter units in service.</td>
<td>Solid</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>As per case No. 1</td>
<td>Solid</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>As per case No. 1 but with the contact wires weared by friction with the pantograph (cross section reduced to 70%).</td>
<td>Solid</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>As per case No. 1</td>
<td>Resistive</td>
<td>no</td>
</tr>
<tr>
<td>5</td>
<td>As per case No. 3</td>
<td>Resistive</td>
<td>yes</td>
</tr>
<tr>
<td>6</td>
<td>As per case No. 3 but with one converter unit at Farneta out of service.</td>
<td>Resistive</td>
<td>yes</td>
</tr>
<tr>
<td>7</td>
<td>As per case No. 3 but with two converter units at Farneta out of service.</td>
<td>Resistive</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
<td>As per case No. 1 but Farneta Montallese line radially operated from Farneta</td>
<td>Resistive</td>
<td>yes</td>
</tr>
</tbody>
</table>

In all the cases, except than case No. 9, the fault was supposed to occur in the center of one of the lines Montallese-Farneta, at 8 km from Farneta. In case No 9 a fault at the terminal end of the line (Montallese) was supposed. In addition it was assumed that a train absorbing a current of I=1000 A was present in the middle of the lines Farneta - Montallese. In the case of resistive faults, the fault was simulated as a short circuit to the poles supporting the catenary at the end of a line section. The two 125 sqmm aluminum cables grounding the poles were also represented as well as the diodes that connect the grounding system of the poles to the truck every 4 km. In order to consider a very unfavourable cases one of the diodes above was supposed to be faulty (open). The arc was represented as an e.m.f. of 400 V.

Tab.II reports the values that may be virtually reached, in the absence of any tripping, by the currents, I, through the breakers at Farneta and Montallese and the initial value, G, of the slope of the current through the circuit breakers at the ends of the line. The value is also reported of the virtual apparent resistance, defined as the ratio of the voltage to the current at steady state, as seen from the section of the breakers.

Tab. II - Summary of the results of the digital computer simulations in the cases of Tab. I

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Montallese</th>
<th>Farneta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6350</td>
<td>209.2</td>
</tr>
<tr>
<td>2</td>
<td>5650</td>
<td>184.7</td>
</tr>
<tr>
<td>3</td>
<td>4883</td>
<td>180.7</td>
</tr>
<tr>
<td>4</td>
<td>4570</td>
<td>251.6</td>
</tr>
<tr>
<td>5</td>
<td>4077</td>
<td>222.0</td>
</tr>
<tr>
<td>6</td>
<td>3680</td>
<td>216.5</td>
</tr>
</tbody>
</table>
Fig. 7 shows the shape of the current, $I$, of the gradient of the current, $G$, and of the apparent resistance as a function of the time, $t$, following the fault in cases No. 6, 7 and 8 in Tab. II.

The study brought to the following conclusions:

- As it could be expected, in case of solid faults (case No. 1) the current through the protective breakers of the faulty line reaches values much higher than the setting usually adopted in the line under consideration; the virtual value of the apparent resistance reached at regime is very low, about $0.5 \, \Omega$; the initial gradient is very high, much greater than the gradient of the current recorded in normal operation;
- The combined effect of the fault resistance, of the fault occurring through an arc across an insulator and of the increase of the resistance of the line conductors due to the wearing caused by the friction with the pantographs (see cases 2 through 6) causes the reduction of the current through the protective breaker at the terminal of the line up to 3680 A, i.e. only 15-20% higher than the setting at present adopted for the protective breakers. The initial slope of the current remains high, about 200 A/ms. The virtual value of the apparent resistance drops down to 0.87 $\Omega$, i.e. to a value higher than in case n. 1 but lower than in the case of an even high load (14-15 MW at steady state).
- If only one converter unit is supposed to be in operation at Farneta (case No. 7) the fault current increases up to only 3470 A, the gradient $G$ remaining relatively high.
- The most unfavourable case is the one with no converter unit in operation at Farneta (Case No. 8). In this case the virtual value of the current through the protective breaker drops down to 2340A, comparable with the load current. The initial value of the gradient is relatively high ($G=153.1 \, A/ms$). Tripping of the breakers at the line terminal may be assured by the teleconnection as the current through the breaker at Montallese, i.e. at the terminal opposite to Farneta, reaches a relatively high value (3830 A).
- In this case (Case no. 8), while the line current at Farneta terminal reduces to very low values, the apparent resistance as seen from Farneta remains lower than the value due to the load in normal operation ($1.02 \, \Omega$).

4. The digital protection applied – Main features. Experimental results of the first application

On the basis of the results summarized above a digital protection with the following main features was conceived:
- Directional overcurrent relay with sensitivity to the slope of the current, $G$, adjustable in steps in a proper field (say in the range 0 through 300A/ms and for $G >1000 \, A/ms$);
- Directional minimum resistance relay, with a sensitivity to the gradient of the current;
- Teleconnection of the terminals at the ends of the same line for teleprotection;
- Thermal image protection of the most critical element of the line, taking into account the ambient temperature;
- Fault recording capacity;
- Control of the voltage amplitude and of the harmonic content through control of the current through the filter capacitors;
- Diagnostic, station automation and monitoring functions.
In addition to the directional overcurrent function, combined with the sensitivity to the
derivative of the current, the protection relay calculates the ratio of the voltage to the current in the
relay section. In the first instants of the fault, this ratio is relatively high, much higher than the
effective resistance of the line in between the protective breaker and the fault location due to the
effect of the inductance of the line up to the fault point and to the arc. Thereafter the slope of the
current decreases and the effect of the line inductance reduces. The ratio above approaches to the
steady state value. In critical cases, as in case No. 8 in Tab. II, where due to the limited short circuit
capacity the fault current is very low (2340 A), the apparent resistance remains relatively low. From
Fig. 7 it can be seen that in case No. 8, the apparent resistance drops below 1.1 \( \Omega \) after about 30-35
ms from the fault inception. In the very critical case No. 9, where the line Farneta - Montallese is
radially operated from Farneta and the fault is a resistive fault occurring through an arc, the current
through the protective breaker is very low ( 2980 A) while the apparent resistance reduces to about
1.2 \( \Omega \) after about 50 ms from the fault inception.

Another positive aspect of the new protection is the possibility to perform diagnostic
automation and monitoring functions in addition to the protective functions. For instance it is
possible to check the quality of the dc voltage and detect if a second order harmonic is present as a
consequence of a significant unbalance in the supply voltage due to an important single-phase load
or to a single pole failure on the ac main supply side; it is possible to store the number of tripings on
fault of the breakers in order to optimize its maintenance operations.

If necessary a time delay may be added in order to enable selective operation of the line
protections.

Four experimental prototypes of the protections, based on the concepts above, were set up
and installed in the double track line Farneta-Montallese during the period July – August 2000 in
addition to the traditional protections. The setting values of the current/gradient and apparent
resistance/gradient of the digital protection above were obtained as a first approach on the basis of
the transient analysis performed for the most critical cases of fault summarized in Tab. II. For
instance Fig 8 reports the trajectories after a fault of the point whose coordinates are: the current, I,
and the gradient of the current, G; the apparent resistance, R , and the gradient G; in case No. 8 in
Tab. II.

The results of the first period of operation of the protection under consideration have been
positive. During the last three months, with the setting adopted, no untimely tripings occurred. In
the cases of short circuit in the line a proper detection of the fault has been performed and tripping
command has been delivered.

Fig. 9 shows for example the plots recorded during a fault on board of a locomotive. The event
occurred on June 23, 2001 at 21. The plots are those recorded by the internal fault recorder of the
protection. Tripping was initiated by the current/gradient function on the first step of the
characteristic, after the value of 1900 A with a rate of rise of about 100 A/ms was exceeded by the
current.

It is interesting to note that if the overcurrent gradient function had not tripped, at \( t=t_3 \) operation
of the resistance gradient function would have started.

At the time of writing experimental studies are under way in order:

- to optimize the setting chart of the protection under consideration;
- to assess the possibility to make the protection sensitive to the derivative of the sum of the
currents through the two breakers connected to the parallel feeders in a commutation zone,
rather than simply to the current through the protective breaker equipped by the relay under
consideration. This practice may be useful to avoid, in the critical commutation cases depicted
above, untimely tripings in conjunction with the entering in the line of a train coming from the
line section behind.
5. Conclusions

The increase of the load and of the power absorbed by the trains in the 3 kV dc electric traction lines in Italy 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 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 lower from the preset value;
- a new digital protection has been set up with innovative functions able to behave as overcurrent protection sensitive also to the slope of the current as a function of the time and minimum apparent resistance with sensitivity to the gradient above. The protection is provided also with numerous different functions: thermal protection of the critical elements; maximum and minimum voltage relay; 100 Hz harmonic component in the dc supply voltage.
- The new protection device has also automation and diagnostic features.
- In order to avoid untimely trippings in conjunction with the transit of the trains through the commutation zones it is possible to make the new protections sensitive to the derivative of the sum of the currents through the two breakers feeding the feeders in the commutation zone, instead of to the current through the breaker. Studies are under way on the subject.

Acknowledgements

The authors wish to acknowledge the contribution to the research by ABB Energy Automation that arranged the sensors and the recording apparatuses at Farneta and Montallese and engineered and set up, under specifications by FS SpA – Divisione Infrastruttura, the prototypes of the digital relay protection. The authors wish also to thank the contributions by Dr. Raffaella Valeriani and Dr. Leonardo Tricarico, that performed numerous digital calculations and analyses of the experimental recordings, as part of their master thesis.

References

Fig. 1- Schematic diagram of the Farneta-Montallese double track line.

Fig 2 - Sensor connections – schematic diagram
Fig. 3 - Shape of the current through breaker n. 12, I_{12}, and of the voltage downstream the same breaker at Montallese during a solid fault between the contact wire and the track at 7.7 km from Montallese converter station on one of the lines Farneta Montallese radially fed from Montallese (see Fig. 1), followed by tripping of the protective high speed breaker at the sending end.
Fig. 4 – Normal commutation case. Current through breaker n. 15 at Farneta substation and gradient of the current at the entrance in the line Farneta-Montallese. of a train coming from the line Rigutino-Farneta.
Fig. 5 – Critical commutation case. Current through breaker n. 15 at Farneta substation and gradient of the current at the entrance in the line Farneta-Montallese, of a train coming from the line Rigutino-Farneta “ ”.
Fig. 6 – Current, through breaker n. 15 at Farneta substation, gradient of the current and apparent resistance in case of a typical load.
Fig. 7 – Cases 6, 7 and 8 in Tab. II. Virtual values of: a)- current I; b)- slope of the current G; c)- apparent resistance R, through the breaker at Farneta substation protecting the faulty line, as a function of the time, t.
Fig. 8 - Current-gradient, I(G), and resistance-gradient R(G) at Farneta substation in case n°8 in table II compared with an assumed relay setting.
Fig 9  Current $I_{14}$, apparent resistance $R_{14}$ and gradient $G_{14}$ at circuit breaker 14 of Farneta substation during a fault occurred on June 23, 2001 at h21, recorded by the experimental digital protection installed on the line Montallese-Farneta. $t_1$=overcurrent/gradient setting exceeded; $t_2$=trip signal on overcurrent/gradient; $t_3$=resistance/gradient setting exceeded.