AUTOMATIC FAULT CLEARING ON MV NETWORKS WITH NEUTRAL POINT CONNECTED TO GROUND THROUGH IMPEDANCE

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INTRODUCTION

At the end of 1998 ENEL Distribuzione launched a medium term program aimed at improving the quality of supply, reducing the operating costs and updating the technology of network components. This program is based on the following main projects:

- introduction of a new grounding system in medium voltage (MV) networks;
- remote control of MV/LV substations;
- automation of fault detection, isolation and service restoration procedures on MV network.

The paper describes different techniques of automatic detection and selection of MV faulty sections in both type of networks, operated with insulated neutral point, and operated with neutral point connected to earth through an impedance (Petersen coil).

The attention is focused on a new technique called FNC that takes advantage of both telecontrol and new grounding system, in case of earth faults. In fact, thanks to the above mentioned synergy, the automatic selection of a faulty section, affected by an heart fault, is possible without any tripping of the line circuit breaker.

ENEL DISTRIBUZIONE NETWORK

ENEL Distribution MV Network departs from the HV/MV substations (Primary Subs.). The HV level is 132/150kV and the MV is 10/15/20 kV. Usually the neutral point of MV networks is isolated but, at November 2002, more than 330 MV busbars of HV/MV substations are already operated with the neutral point connected to earth through an impedance (Petersen coil).

The attention is focused on a new technique called FNC that takes advantage of both telecontrol and new grounding system, in case of earth faults. In fact, thanks to the above mentioned synergy, the automatic selection of a faulty section, affected by an heart fault, is possible without any tripping of the line circuit breaker.

NEW MEDIUM VOLTAGE GROUNDING SYSTEM

In order to lower the earth currents and, at the same time, to reduce the number and the average duration of outages due to earth faults on MV networks, in some HV/MV substations the neutral conductor has been connected to the earth through a special impedance (Petersen coil + resistor)[1], [2], [3].

This impedance is usually connected directly by means of a switch disconnecter to the neutral pole of the HV/MV transformer secondary winding.

For each bar it is possible to switch between the compensated configuration and the isolated one and vice-versa. A special control device, called GSN, manages the status of the two networks (one for each bar) in the substation and allows remote operations.

A new generation of protections (NCI series) for MV lines has been developed to obtain the full protection against earth faults in both configuration (isolated/compensated) of the neutral, without any external information.
This feature is obtained by adding several programmable thresholds and angular sectors of intervention. As far as the compensation impedance is concerned, there are two possibilities:

- fixed impedance (fixed reactor + resistor); less expensive and complex but with operation limits and lower performances;
- variable impedance (moving coil reactor + resistor); more expensive but with higher performances.

A third solution, dedicated mainly to overhead networks with values of earth fault current lower than 60A (with reference to 20 kV level), is possible, consisting in a simple resistance of about 770 Ω.

**MV NETWORK TELECONTROL**

In parallel with the new grounding system in primary substations, another big project started to improve the quality of service in a relatively short time period with respect to long-term structural intervention on the network: the remote control and supervision of Secondary Substations [2], [4], [5].

The main goal of the project is the remote control of 80,000 secondary substations within the year 2004. The main features of the System are the following:

- motorised switch disconnectors;
- low cost/high performance Remote Terminal Units;
- telecom modules based on GSM system;
- 29 Control Centres for all the territory.

**RTUS FOR MV/LV SUBSTATIONS**

There are different kinds of UP (Peripheral Unit) to operate signals, commands and, optionally, measurements. UPs are able to operate the switch disconnectors to localize the fault, isolate it and restore supply automatically, without the intervention of man.

UPs are fully programmable through a PC based local configuration terminal, which can be used also for diagnostic. The application program and all the main important parameters are downloadable from the control centre: that is a fundamental function to support quick and reliable software maintenance.

**TELECOMMUNICATION SUBSYSTEM**

The key point of the project is the adoption of the existent GSM cellular network. ENEL Distribuzione developed and standardised by itself all procedures and criteria to measure the Electro-magnetic field level, choose the right antenna and the right mobile provider in the area, monitor and maintain the efficiency of all the connections.

A special integrated GSM module has been adopted, with a raw bit rate of 9600 bps and able to detect and establish the data link in both modes:

- V32 (analog);
- V110 (digital).

Even PSTN lines or leased lines can be used.

**CONTROL CENTRES**

Control centres are based on powerful servers for operation and network configuration.

The integration with the information coming from the remote controlled HV/MV substations and MV/LV substations has been fully implemented.

Multiserial interface boards and ISDN modems implement the connections with RTUs.

As far as the connection with the field is concerned, the basic working mode is the following:

- the control centre according to a specific table of calls performs scheduled polling of peripherals weekly.
- Alarms are acquired by the operator and recorded in the daily electric service log;
- spontaneous call originates directly from the peripheral when a severe alarm generates in the substation; this way of working is limited to alarms of particular gravity;
- at any moment the operator in order to acquire alarms, measurements or to send command on switches can launch a request of connection.

Of course, each alarm or command or change in open/closed status of the switches is displayed on the video diagrams and recorded in the log of the day.

**MV NETWORK AUTOMATION**

Along the way of the reduction of time duration of interruptions, further improvement can be obtained by the introduction of network automation.

This word in ENEL’s jargon means the introduction of a system capable to operate fault location, isolation and service restoration automatically, without the intervention of man.

In normal operating conditions of MV networks, the reduction of the duration of the interruption consists in 5+10 minutes on the healthy sections (see TABLE I, were a fault on a branch supplying 5,5% of the LV customers fed by the feeder is considered [5]).

Nevertheless, in case of large extended perturbation in the electric system, these techniques overcome telecontrol making possible the supply restoration of the healthy sections of the MV lines affected by faults, without any delay due to the operator's service time.

This is very important for the considerations above:

- the driver of all strategic plans developed by ENEL is the reduction of cumulative duration of outages;
- the lower is the cumulative duration in a certain area (high quality of supply), the greater is the percentage of cumulative duration itself generated during large perturbations for contemporaneous faults on different feeders.

As a consequence of this, the effect of automation is more appreciable in the areas where this value is low (40+50 minutes) than in the areas where this value is high (150+200 minutes).

Therefore it's in the best areas that the automation technique works better.

The automation techniques had been already adopted in the
past, but, for not being supported by telecontrol, they often presented malfunctions or side effects that could not be quickly detected by the operators.

Today, the synergy with telecontrol and with the new grounding system adopted on MV network allows methods of automatic earth fault isolation not applicable before (see ahead).

BASIC CONCEPTS OF AUTOMATION

Automation on MV network is based on a group of automatons resident into the UP memory. These automatons which can be programmed, activated, deactivated and trimmed by suitable messages from the Control Centre, operate fault detection and selection through simple actions and delays triggered locally by two signals:
• Presence/absence of voltage at the line input;
• Intervention of fault detector.
The recloser unit, installed in correspondence of each MV line inside the line protection panel, masters the timing sequence of the operations.

FAULT DETECTORS (RGDAT)

Apart from the right design of the automatons in the UPs, the core of the system is the fault detector. This device must be able to detect earth faults and short circuit activating different outputs and as far as earth fault detection is concerned, must have the following feature:
• directional sensitivity;
• remote changing of the working direction;
• high sensitivity in both grounding configuration of the MV network (isolated/compensated neutral)
Of course it must be cheap and easy to install. These requirements are met by the RGDAT, a new equipment standardized by ENEL Distribuzione for MV automation. The characteristics of the device had been tested in CESI laboratories and installations in field are in progress. It is too early for saying more but we expect great results.

DESCRIPTION OF FRG AND FNC AUTOMATION TECHNIQUES

FRG and FNC are two different methods of automatic fault location, isolation and service restoration on the healthy sections located upstream the faulty ones. These methods are based on special logic programmed inside the RTU and applied to one or more of the switches connected to the secondary substation MV bus bars and on the automatic reclosing device installed in correspondence of the circuit breaker at the line departure in Primary substations. The operator in the Control Centre can:
• configure the chosen procedure for each line departing from the Primary subs;
• enable/disable the procedure for each line, each secondary subs and each switch;
• receive the spontaneous call from RTUs in order be alerted and complete the procedure, re-supplying the healthy sections of the line located downstream the faulty section.

FRG TECHNIQUE

It can be applied on cables and overhead lines (only time parameters are differently chosen) and with both configuration – isolated/compensated - of the neutral point. The logic utilizes fault (FD) and voltage detectors (VD) integrated into the RGDAT installed in correspondence of each automated MV switch. Usually, in a secondary substation (S.S.), only the energy input switch disconnector is automated but the system allows to automate more than one switch. The simple rules performed by each automated switch are the following:
1. The switch is opened if there is a lack of voltage on the VD lasting more that a certain time and the FD has been activated by the fault current;
2. the switch is closed (there is a priority order in case of more automated switches) when the VD detects the voltage restoration due to the reclosing of the circuit breaker or the switch located upstream;
3. the switch is opened and locked in the open position when, executing the closing operation according to the rule n.2, there was a lack of voltage (VD) and at the same time the activation of FD, both within a time window starting from the close position of the switch. The lock in the open position of a switch causes a spontaneous call towards the Control center so that the operator is alerted and can proceed to re-supply the other feeder sections.

FNC TECHNIQUE

It can be applied on cables and overhead lines, but only on networks with neutral compensated configuration of the neutral point. The adopted logic is different in dependence on the type of fault so as detected by RGDAT:
• for short-circuits (overcurrent detector) the logic act as in the FRG procedure;
• for earth faults (earth detector) the automatons act in such a way to isolate the fault without any tripping of the circuit breaker at the line departure.

The second case is the peculiarity of the procedure and deserves a more detailed description. The simple rule performed by each automated switch is the following:
• the switch is opened and locked, after a programmed delay, if there is the intervention of the earth fault detector and the intervention itself lasts until the end of the calculated delay;
the delay programmed for each automated switch is calculated according to the position of the substation along the feeder so as to open the farthest switch from the Primary substation among those having detected the fault.

Two cases are possible:

1. If the fault is not located in the first section of the line, the circuit breaker at the line departure remains closed all the time the selection is performed, avoiding any power supply interruptions on the healthy line sections located upstream the faulty one.

2. If the fault is located in the first section (immediately before the first automated switch), the circuit breaker performs all the reclosing cycle and trips definitively. The lock in the open position of a switch (first case) or the definitive trip of a breaker (second case) causes the spontaneous call towards the Control centre to alert the operator and let him manage the fault.

As far as the open capacity of the switches is concerned, the following considerations ensure the proper functionality of the system:

- thanks to the Petersen coil the single phase earth fault current is lower than 50A and mainly resistive (not less than 70%);
- the current along the feeder is the vectorial composition of inductive and resistive currents of the Petersen coil, the capacitive current of the network and of the faulty feeder and the load current of the faulty feeder itself (max 360 A, cos \( \varphi \approx 0.9 \));
- the resulting value of all these components is less than 400 A (nominal working current of on-load disconnectors) with a high power factor.

CONSIDERATIONS ON HUMAN SAFETY AND EARTH PLANTS (CENELEC HARMONIZATION DOCUMENT HD 637 S1)

In case of FNC technique, considering a maximum of 3 switch disconnectors in series along the line and taking into account the timing of logic and the operating times of switches (4 s in standard conditions), the maximum delay for the fault clearing is 20s, corresponding to a fault on the first feeder section (upstream the first automated switch). For Details see Fig. 1.

According to Italian Standard CEI 11-1 (based on CENELEC harmonisation document HD 637 S1) this means a value of \( t_f \gg 10 \) s and a value of \( U_{TP} = 75 \) V. All the different solutions for Petersen coils installation are engineered in such a way to guarantee a maximum value of \( I_f \) lower than 50 A (calculations are referred to a earth fault without appreciable fault resistance and taking into account a certain mismatch of the coil with respect to the capacitive earth current of the network).

This fact has a great impact on earth plants. The average value of earth fault current in ENEL MV networks is about 105A on 15 kV networks and 145A on 20 kV networks with insulated neutral. Fault clearing time is 0,55 s (for Secondary Subs. realized according to national Standard CEI 11-8, which was the reference standard before HD 637 S1) or 0,65 s (for Secondary Subs. realized according to HD 637 S1). Moreover, requirements on earth plants of national Standard (CEI 11-8) exceeded those cited in HD 637 S1.

As a consequence of this, in spite of the important enlargement of fault clearing time, the application of FNC technique is viable even on networks with low values of earth (capacitive) current with reference to operation with insulated neutral status.

TABLE III shows the value of \( I_e \) which is the lower value of capacitive current to assure, in case of changing of the operation mode of a network from insulated neutral to grounded one:

- the “automatic” respect of HD 637 S1 (no need of tests or interventions) of earth plants realized (according both to CEI 11-8 and HD 637 S1) and maintained on networks previously operated with insulated neutral status;
- an economic return due to lower need of maintenance of the earth plants (simpler periodic tests, smaller new earth plants, independence from the natural growth of capacitive current).

COSTS/BENEFITS EVALUATION OF AUTOMATISATION SYSTEM

Automation is an additional function of telecontrol and, apart from RGDAT, no other components are needed in addition to pure telecontrol system components. Therefore, cost/benefit evaluation is calculated comparing the value of bonuses/penalties connected to variations of cumulative duration due to the sole automation with the total cost of RGDAT (which is, installation included, about 7% of the total cost of telecontrol for a single secondary subs.).

The pay-back period of automation is shown in TABLE II, with reference to the different techniques described above and to the state of the neutral point (insulated or connected to earth by means of an impedance); anyway, it varies from 1,2 years to 2,5 years, without considering the additional benefits achievable during the large perturbations.

With reference to the effects of neutral point status, the following can be considered:

- in case of insulated neutral a greater number of long interruptions happens on MV networks; thus automation should act more times and the reduction of cumulative duration with respect to telecontrol should be higher (shorter pay back period);
- in case of compensated neutral point, the number of long interruption decrease of about 30%, thus automation should act only sometimes, increasing the pay back period more than 40%

All the possible combinations of automation techniques and neutral point status are shown in TABLE II which takes into account service time in case of only one faulted feeder. In case of multiple contemporary faults, service time values connected to automation technique are the same, those connected to pure telecontrol technique are much higher because of the operator service time.
STARTING OF AUTOMATION APPLICATIONS AND FIRST OPERATION RESULTS

At moment some hundreds of feeders (about 350) are operated with FRG in the North of Italy (Lombardia and Triveneto). In addition, only a small number of feeders are operated with FNC technique.

All these techniques, however, are not in the definitive configuration and their performances can slightly lower than expected.

Many experimental tests have been performed to improve the functionality of UP and the training of personnel has been completed. At the end of 2003 a definitive decision will be taken after the analysis of the operation results.

Data coming from Lombardia referred to a period between the 1st of February and the 31st of October 2002 show the following improvements in terms of average time delays to perform the first attempt of fault selection on a feeder:

- Manual: 40.9 min;
- Telecontrol: 8.2 min;
- Automation: 1.3 min.

**TABLE I: “Comparison of times for the selection of a faulty section”**

(Manual selection, selection by remote commands, automatic selection)

<table>
<thead>
<tr>
<th>FAULT 1</th>
<th>OPERATING TIMES (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MANUAL (2 TEAMS)</td>
</tr>
<tr>
<td>1) Opening of CB (A)</td>
<td>0</td>
</tr>
<tr>
<td>2) First reclosure CB (A) (0.4-1 s) with negative effect</td>
<td>1</td>
</tr>
<tr>
<td>3) Second reclosure CB (A) (30 s) with negative effect</td>
<td>30</td>
</tr>
<tr>
<td>4) Opening of disconnector 1 in SS1</td>
<td>2400</td>
</tr>
<tr>
<td>5) Opening of disconnector 2 in SS1</td>
<td>2700</td>
</tr>
<tr>
<td>7) Closing of CB (A)</td>
<td>2410</td>
</tr>
<tr>
<td>8) Closing of disconnector 1 in SS1</td>
<td>2820</td>
</tr>
<tr>
<td>9) Closing of disconnector 2 in SS1</td>
<td>2940</td>
</tr>
<tr>
<td>11) Opening of CB (A)</td>
<td>2940</td>
</tr>
<tr>
<td>12) (Definitive) opening of disconnector 2 in SS1</td>
<td>2950</td>
</tr>
<tr>
<td>13) Closing of CB (A)</td>
<td>2970</td>
</tr>
<tr>
<td>Differences [min]</td>
<td>38.33</td>
</tr>
</tbody>
</table>

With manual operation (traditional) 94.5% of customers are supplied in 50 minutes.
With simple telecontrol operation 94.5% of customers are supplied in 11 minutes.
With automated operation 94.5% of customers are supplied in 6 minutes.

**TABLE II “Payback period of automation application”**

<table>
<thead>
<tr>
<th>AUTOMATISATION TECHNIQUE</th>
<th>WITHOUT NEUTRAL POINT CONNECTED TO EARTH (INSULATED NEUTRAL)</th>
<th>WITH NEUTRAL POINT CONNECTED TO EARTH WITH AN IMPEDANCE (PETERSEN COIL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRG - 1 SWITCH DISCONNECTOR ALONG THE FEEDER</td>
<td>85.46</td>
<td>59.98</td>
</tr>
<tr>
<td>FNC - 1 SWITCH DISCONNECTOR ALONG THE FEEDER</td>
<td></td>
<td>73.92</td>
</tr>
<tr>
<td>FRG - 1 SWITCH DISCONNECTOR ALONG THE FEEDER + 1 SWITCH DISCONNECTOR ON A LATERAL BRANCH</td>
<td>73.57</td>
<td>43.14</td>
</tr>
</tbody>
</table>
TABLE III “Value of the lower value of capacitive current ($I_L$) able to assure, in case of changing of the operation mode of a network from insulated neutral to grounded one, respect of safety standards and economic advantages with respect to earth plants”

<table>
<thead>
<tr>
<th>Operation with insulated neutral</th>
<th>Operation with neutral connected to earth through an impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference Standard</strong></td>
<td><strong>Reference Standard</strong></td>
</tr>
<tr>
<td>CEI 11-8</td>
<td>CEI 11-1 (HD 637 S1)</td>
</tr>
<tr>
<td>CEI 11-1 (HD 637 S1)</td>
<td>CEI 11-1 (HD 637 S1)</td>
</tr>
</tbody>
</table>

$\begin{align*}
\tau_f & \text{ earth fault clearing time} \\
I_f & \text{ earth fault current} \\
I_L \text{ limit} & \text{Lower value of earth fault capacitive current (operation with insulated neutral) able to assure economic return on earth plants and respect of HD 637 S1 by the adoption of Petersen coil in spite of enlargement of fault clearing time due to FNC automatisation technique}
\end{align*}$

CONCLUSIONS

ENEL Distribuzione ha s planned important investments to improve the quality of supply according to decisions made by the Italian regulator. These investments consist in the connection to earth of MV neutral point through an impedance (Petersen coil + resistor) and in the remote control of switch disconnectors along MV feeders. Results coming from the field are compliant with or overcome the expectations.

Moreover, another additional intervention is possible, consisting in the automation of the switch disconnectors; the additional investment required is nearly negligible. The first limited results confirm the possibility of additional reduction of cumulative duration, particularly when many MV feeders are contemporaneously affected by faults.

In addition, by a complete integration between automation and new grounding system, a new technique of faulty branch selection is possible without the opening of feeder breaker.

This technique is able to avoid any interruption (transient, short and long) to customers located upstream the faulty branch, and, consequently, to lower the cumulative duration.

After the definitive results coming from the field experiences, a decision will be taken as far as further extensions of all these applications are concerned.

REFERENCES


[4] Sergio Rogai - “Le scelte dell’ENEL Distribuzione per il telecontrollo e l’automazione della rete”, ANIE’s Meeting, Cagliari, September 1999


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Figura 1

**Table**

<table>
<thead>
<tr>
<th>LEVEL (N)</th>
<th>Dead time between each level [s]</th>
<th>Switching time [s]</th>
<th>Delay time to send the opening command [s]</th>
<th>Total switching time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>4*</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>4*</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4*</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0,07</td>
<td>20</td>
<td>20,07</td>
</tr>
</tbody>
</table>