ENHANCED SELECTIVITY OF HIGH RESISTANCE EARTH-FAULT CLEARING IMPROVES QUALITY OF ELECTRIC ENERGY SUPPLY IN SLOVENIA

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INTRODUCTION

A normal earth-fault protection of a MV network is based on the assumption that fault currents that flow to earth will be determined by the earth-fault impedance of the line and associated plant. In some cases, however, the nature of the ground fault may be such that it makes non effective earth connection. In such a case a system fault to earth may result in a very small residual current and as a consequence voltage too small to overcome VT-s tolerances. This does not allow the earth fault protection (E/F) to determine direction and to operate correctly. If a line conductor should break and fall on to semi-insulating objects, such as trees or hedges, the circuit will, therefore, not be isolated and the conductor, which will be maintained at normal phase voltage will constitute a serious danger to life.

THE PROBLEM OF HIGH IMPEDANCE EARTH FAULT

Distribution network in Slovenia

In Slovenian MV networks, earth fault currents are limited to 150 A of active current component. [1,2] Decision was made in early 70' influenced by grounding system and the fact, that an essential part of the country lay on karst ground, which is very rocky and dry and consequently solid grounding of transformer stations 20/0.4 kV is very difficult to be achieved. For 20 kV distribution network used predominantly in Slovenia, especially in rural areas, that means 80 Ohms resistors for neutral grounding. Resistors are thermally dimensioned for 2 A of permanent current. Therefore, they are protected with two stage over-current (O/C) protection. First stage is set to 90 A and 1.5 s, and second stage is normally set to 1A of primary current with time delay 180 s. They both trip power transformer. Second stage O/C protection starter is also used for high resistance earth fault clearing. Its time setting of 180 s is consequently the time available for a selective high resistance clearing.

High impedance earth fault

For the purpose of this paper, as a high impedance earth faults are considered faults, where current is 3 A or less. That means faults with fault impedance 3.8 k or more in the 20 kV network. But even fault current of 1 A releases a power of more than 10 KW. Such power easily burns down the wooden pole and wooden poles are mostly used for MV network in rural areas in Slovenia and so is the case in Electro Ljubljana utility. So the permanent damages on equipment can not be avoided even in the case of very common fault, where because of the broken isolator conductor touches the console.

Radial and meshed network operation

MV network in Slovenia normally operates in radial configuration. That enables use of simple O/C and E/F protection. However, during the network reconfiguration process, for short periods of time, two or more feeders from one or more substations are connected in parallel. In such case, residual currents on in parallel connected feeders increase because of slightly unsymmetrical network. This values are considerable big in case of parallel connection of feeders supplied from the same power transformer. These residual currents often exceed 5% of the load current and can reach up to 5 A at heavy loading conditions. Following table gives some idea of what is going on. Data were collected during the live tests performed on the limited part of the network with small load only in one of the substations of Electro Ljubljana utility.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Lines meshed</th>
<th>Current radial</th>
<th>Current meshed</th>
<th>Load current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>J03 KB 20kV BELT1 J08 KB 20kV BELT2</td>
<td>0.014 0.014</td>
<td>1.23 1.07</td>
<td>16 17</td>
</tr>
<tr>
<td>2</td>
<td>J02 DV 20kV ROŽNI DOL J05 DV 20kV SEMIČ</td>
<td>0.038 0.08</td>
<td>0.69 0.68</td>
<td>27 25</td>
</tr>
<tr>
<td>3</td>
<td>J11 DV 20kV VINICA J06 DV 20kV GRADAC</td>
<td>0.058 0.023</td>
<td>0.056 0.088</td>
<td>25 23</td>
</tr>
<tr>
<td>4</td>
<td>J13 DV 20kV KANIŽARIC J11 DV 20kV VINICA</td>
<td>0.044 0.059</td>
<td>1.35 1.50</td>
<td>26 19</td>
</tr>
</tbody>
</table>

Existing earth fault protection

In the past, simple non directional E/F protection was used normally set to 15 A. Because of more cables in the network, capacitive component of the fault current increased and setting should have been set higher. Now, normal settings are between 30 and even 60 A. Therefore, sensitive directional E/P protection was added to detect low fault currents in the cases of high impedance faults. But this protection is limited with a measurement of the residual voltage which is inaccurate because of small system asymmetry and VT tolerances.[3] So, minimum voltage to reliable determine the direction was estimated to 1.5 V of secondary voltage, what means about 3 A of fault current primary value. So the problem of faults with lower currents remained problematic, since beside potential damages on the network they were above the thermal rate of earthing resistors and could cause as a final consequence tripping of power transformer.

Several methods for high resistance fault clearing were used therefore in the past, but all of them were based on manual or manually initiated automated trial methods, like tripping the lines with feeder automatic re closing.
equipment. They all caused at least short interruptions in supply of healthy lines and if not successful on time, transformer was tripped and total MV network remained not supplied.

**IDEA TO SOLVE THE PROBLEM**

**Initial proposal**

In 1998, idea was placed to overcome this problem by adding another (third) E/F protection to be integrated into multifunction numerical feeder protection and control units [4]. Beside nondirectional E/F protection set to 30-60 A, 300 ms fixed time delay and directional E/F protection set to 3 A, 1 s fixed time delay, another nondirectional sensitive E/F protection would be added set to 1 A and 10 s fixed delay. This would prevent tripping of transformers. It was desired, that also currents below 1 A could be detected, but small asymmetry, voltage unbalance and used CT tolerances prevented us to go so far.

In the cases of fault under 3 A fault current, residual voltage is small and does not cause residual capacitive currents bigger than 1A, so nondirectional protection can be used. However, when meshed network configuration is applied for short period of time, residual currents on meshed lines exceed 1 A setting, what could cause unwanted operation of sensitive nondirectional protection.

In figures 1 and 2, idea is presented.

**Live measurements to check the idea**

In 1999, first prototype of the algorithm was made and live measurements were performed to prove the idea. One of the main questions was, how high get the residual capacitive currents just below the directional E/F protection set to 3 A. Additional calculations have been made therefore to determine the limitation of the proposed method. Next data are used in the calculations:

- **Overhead lines**
  - Earth capacity C = 0.000055 μF/km, capacitive earth current by nominal voltage \( I_e = 0.06 \text{ A/km} \)

- **Cables**
  - Earth capacity C = 0.00265 μF/km, capacitive earth current by nominal voltage \( I_e = 1-2 \text{ A/km} \)

The results of the calculations have shown that the method of high resistance earth fault clearing using:

- directional sensitive earth-fault protection with independent time delay characteristic and
- additional sensitive earth-fault protection with independent time delay characteristic,

limits the length of the cable in the single medium voltage line. Calculations were indicating, that current should remain under 1 A even for long lines and cables, but network parameters were estimated and not measured. On the basis of the simple calculation this length has been estimated to 15 – 20 km for cables, what is enough for the network of Slovenian distribution utilities. The accurate calculation for each type of network is recommended.

Live measurements proved estimations made by calculation. Some results are given in table 2

**TABLE 2. Residual currents of healthy feeders during high impedance fault**

<table>
<thead>
<tr>
<th>Fault Current</th>
<th>Current (A)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy Cable Length approx. 20 km</td>
<td>0.277</td>
<td>0.692</td>
</tr>
<tr>
<td>Healthy Cable Length approx. 15 km</td>
<td>0.207</td>
<td>0.519</td>
</tr>
<tr>
<td>Healthy Overhead Line Length approx. 50 km</td>
<td>0.020</td>
<td>0.052</td>
</tr>
<tr>
<td>Residual voltage (% Un)</td>
<td>0.7</td>
<td>1.73</td>
</tr>
</tbody>
</table>

**DESIGN AND INSTALLATION OF THE NEW PROTECTION**
In the year 2000, new protection function was integrated into multifunction combined feeder protection and control device (FPC) and extensive tests in the factory were made. After that, also some live testing was done and by the beginning of the year 2001, improved device was ready to be installed in the real substation. Substation 110/20 kV named Potoška Vas was selected for the first installation. Part of MV switchgear single line diagram is shown on substation SCADA screen shot given on Figure 3.

Substation was planned to be refurbished and project implementation was gradual, since the network had to be supplied all the time. So, the works were finished at the end of 2002. Every MV feeder was equipped with one FPC interconnected with other IED into substation automation system and new E/F function was activated.

FIELD TESTING

In winter 2002/2003, filed tests were performed to prove the operation of new protection function in the real system under normal operation conditions. Testing was also needed to get approval from technical commission and later by management of Elektro Ljubljana utility. That was condition for the new function to be listed in the specification and to become standard solution for new installations and for refurbishments.

Tests were performed in two stages, where the first was done under so called controlled conditions. Earth fault was initiated over the pole inside the substation fence, where fault impedance was controlled with the distance between electrodes in wood. The test site is shown in the figure 4.

After several tests, which were all successful, more tests were done on the network with real conditions. There were tests performed simulating conductor laying on the ground and three branch touching the line conductor what can be seen on figure 5.

Also in this case new protection operated according to the expectations and tests were successful. In the Figure 6, an example of oscillographic record recorded by FPC is given.

Already few days before testing, snow fall was cause of two high impedance earth faults, that were selectively switched off by new protection function. So, by accident, the new protection function was successfully live tested even before official tests started.
OPERATION

After successful conclusion of field testing, new function became standard function for all the substations, where secondary equipment was changed. So far, there are 3 substations equipped with new function and in the up to two years of regular operation, new function always worked correctly. There have been already several cases recorded, where new function also prevented outage of the transformer and consequently the whole MV network.

High impedance earth faults are mostly caused by vegetation in connection with bad weather, either heavy snow and ice or strong wind. Such conditions do not come regularly but one year once and the next may be several times. But from the experiences in the past, we can expect 1-2 such incidents per year per transformer and with conventional approach, in 30% of cases, transformer would be switched off. In all other cases, at least short interruptions in power supply of some feeders would be initiated during the faulty feeder search procedure.

In Slovenia, there are about 90 transformers supplying rural, predominantly overhead MV network. Potential of the new function is to prevent up to 30 longer (10 – 20 minutes) and more extensive (the transformer with MV busbar and all feeders) power supply interruptions and at least 200 shorter (300 ms) and less extensive (individual MV feeder) each year. This is reason enough, that beside Elektro Ljubljana also other Slovenian distribution utilities began to install this function into their substations or they will do so soon.

CONCLUSION

In order to reduce number of outages in case of non selective protection operation during high impedance earth faults in Slovenian MV network, additional E/F protection function was proposed. It was supposed to be integrated into numerical combined feeder protection and control devices normally used for MV feeder protection. Devices were made ready for Elektro Ljubljana utility by Iskra Sistemi and extensive acceptance testing was performed. After successful acceptance testing, devices were installed on regular basis. During operation, they proved expectations and practically prevented any non selective outages caused by high impedance earth faults. Function became standard protection function for MV feeder protection on rural network, not only in Elektro Ljubljana utility but also in other distribution utilities in Slovenia.

Experiences from the operation of cable networks in urban areas prove presence of high impedance earth faults in such networks. Because of number of reasons, conventional high impedance earth fault clearing is even less effective and such faults often result in transformer tripping. Therefore, protection engineers are currently evaluating possibility of application of the new E/F function in cable networks in urban areas.

REFERENCES

[3] F.Curk, I.Šantl, 1972, Study of the most convinient options for MV network neutral point grounding in Slovenia, EIMV, Ref. No. 538, Ljubljana (in Slovenian language)