Application of overvoltage protection to the Peruvian Power System

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Abstract:

In a sparse power system, the shunt capacitances and series inductances of long transmission lines can cause significant voltage variations between high and low load periods. Overvoltage relays in substations are used to protect power transformers from damage due to high voltage. In the Peruvian system, these relays are usually located only at power transformers or busbars. But sometimes it is better to trip selected long lines before tripping power transformers to mitigate temporary overvoltages. Tripping of power transformers and their connected loads exacerbates the temporary overvoltage leading to the possibility of a widespread black out.

Another important issue is coordinating the overvoltage relay settings system wide.

This paper describes a methodology to set overvoltage relays considering the overvoltage protection as a system protection more than a local protection. An application of the coordination done in the Peruvian Power system is described.

1. Introduction

In Peru, overvoltage relays traditionally were applied to protect power transformers. So if a temporary overvoltage occurred in the system, affected power transformers were tripped with their loads. The load loss exacerbates the overvoltage, causing more transformers disconnection and possible cascading and blackout in some areas.

In order to avoid these blackouts, it was necessary to implement a system overvoltage scheme that would not trip load unnecessarily. Such a scheme would meet a commitment to shed the lowest possible of load and also prevent equipment damage.

The new scheme was proposed and applied for the northern area of the Peruvian Power System. This area is characterized as a radial system. In this system if a contingency such as sudden load shedding or reactor tripping occurs, the resulting overvoltages may stress the system and in the long term, reduce the life of power transformers. In the new scheme, tripping of lines was used as the last resort to control overvoltages.

2. The overvoltage phenomena

In an electrical power system overvoltage may be classified into three types which are [1]:

- Lightning Overvoltage
- Switching Overvoltage
- Temporary Overvoltage (power frequency overvoltage)

In Medium Voltage and High Voltage systems, lightning overvoltage has a greater effect than switching overvoltage. However in Extra High Voltage systems switching overvoltage can be more critical than lightning overvoltages.

Lightning overvoltages are produced by atmospheric discharges. These overvoltages reach values more than 4 p.u (per unit), are severe for medium and high voltage systems. Durations of
lightning overvoltages are in the order of microseconds (µs) and have a wave front in the order of MV/µs. Another feature of this overvoltage is its high damping.

Switching overvoltages are produced by breaking small inductive currents, or switching on capacitive circuits such as transmission lines. These overvoltages reach values from 2 to 4 p.u. Their duration is in the order of milliseconds (ms), and their frequency ranges from 1 to 200kHz. We can say that these overvoltages have medium damping.

Temporary overvoltages (at power frequency) can reach values of 1.73 p.u. in weakly grounded systems. Overvoltages may arise from two causes.

a) Unbalanced overvoltages are caused by voltage rise on healthy phases during single line to ground faults.

b) Balanced overvoltages may result from sudden disconnection of load or voltage regulating devices in a sparse transmission network. Uncompensated transmission line shunt capacitance together with light load may result in unacceptable voltage rise on all three phases.

These overvoltages happen at power frequency. Their duration is in the range of seconds with a low damping. The focus of this paper is how to control this overvoltage.

The main protection against lightning and switching overvoltages are surge arresters. The arresters are designed to dissipate a specific amount of energy in short times so these arresters must be selected correctly [2]. Arresters are not intended limit temporary overvoltages. If an arrester conducts during a temporary overvoltage the dissipated energy can cause a fault in the arrester or and even a violent failure. This is because the arrester is not designed to dissipate energy supplied over a long time.

Temporary overvoltages are mitigated by shunt reactors, voltage regulators, static var compensators, and, as a last resort, transmission line disconnections. In some cases voltage relays are used to connect or disconnect voltage control equipment.

In Peru, overvoltage relays were previously used only to directly protect power transformers in the substations, and generators. The disadvantage of this protection scheme against temporary overvoltages is that the tripping of the generators or power transformers, exacerbates the overvoltage, affecting more equipment and possibly triggering blackouts or arrester failures.

These phenomena are produced in systems with long transmission lines and highly variable loads (sparse systems). The Northern area of the Peruvian power system is such a sparse system.

3. Temporary overvoltages limits in power systems.

Lightning and switching overvoltages are controlled by arresters. Such fast surges cannot be controlled by generators or voltage relays because the operating time of such devices are in the range of one or more fundamental frequency cycles.

Temporary overvoltages can be controlled by devices operating on fundamental frequency. However, in many cases settings for voltage relays have not been coordinated with any other control devices. In Peru there were no system wide criteria for setting these relays. Overvoltage
protection relay settings were applied according to criteria developed by the power equipment owner or manufacturer.

In Peru the operating voltage must normally be within the limits of 0.95 p.u and 1.05 p.u, in order to have a good quality of voltage for the customers or clients. These limits in Peru are known as the “Voltage Quality Limits”.

During a contingency or emergency the quality limits can be exceeded. In such cases the criteria to control the overvoltage are those required to protect power equipment such as transformers and generators from damage. The limits of overvoltage in this case are defined by the capability limits of the power transformers and the generators.

Power transformer capabilities often form the limiting criteria for tolerable overvoltages. The limits are defined by the over excitation capability characteristics. One example of such a characteristic is shown in Figure 1.

![Figure 1. Example overexcitation characteristic of a power transformer](image)

The voltage in inductive equipment is determined by the equation (1).

\[ E = 4.44 \times 10^(-4) N f \Phi \]  

(1)

Where:
- \( E \): Induced Voltage, in volts
- \( N \): Number of turns
- \( f \): Frequency, in hertz
- \( \Phi \): Magnetic flux, in webers

If the voltage (E) is increased and/or the frequency (f) is decreased, the flux (\( \Phi \)) will be increased. If the flux is increased such that the transformer core becomes saturated, the flux will leave the core and enter parts of the transformer that are not designed to be magnetized, such as the tank. Excess flux in a power transformer causes overheating, thus reducing the transformer life. Voltage increase and/or frequency decrease is most likely in transformers near generators.

An overvoltage condition without a frequency decrease will still result in an overexcitation situation, and the characteristic of Figure 1 will apply, with the frequency being constant [3]. The curve then becomes an overvoltage capability curve as shown in Figure 2.
From this new curve we can define three regions of operation in order to control the temporary overvoltage.

![Graph showing regions 1, 2, and 3]

**Figure 2.** Temporary Overvoltage Limits based on example overexcitation characteristic.

- **Region 1:** Normal Operation Region
- **Region 2:** Operation region under emergency conditions controllable by the power system operators.
- **Region 3:** Critical operation limit, in this region the voltage must be automatically controlled by devices such as automatic voltage controllers, static var compensators (SVC), Shunt reactors, and as a last resort, tripping lines.

So overvoltage relays must operate in the region 3. In considering their set point, the reset ratio of the voltage relays is also important. This ratio can vary from 0.99 to 0.95, depending on the specific type of relay.

### 4. Criteria to set an overvoltage relay in Peru.

As discussed in Section 3, the overvoltage relays must set to operate in the region 3 of Figure 2. An overvoltage relay with an inverse characteristic would be the best match with the overexcitation characteristic of the power transformers.

However not all voltage relays have an inverse characteristic so two steps of definite time overvoltage can be used to approximate the requirements. One step for fast tripping, and the other for slow tripping. The intent is to use overvoltage relays to trip long transmission lines as a last resort to control overvoltages before tripping equipment such as transformers with their associated loads.

Also, because overvoltages in the region 3 must be controlled with times less than one minute, shunt reactor switching must be accomplished even more quickly than the line tripping.

It is recommended that the automatic insertion of the reactors be made before Region 3.
So the criteria to set the overvoltage relays in the Peruvian Power System are the following:

- **Shunt Reactor Insertion:**
  The insertion of shunt reactor must be made with voltages less than 1.1 p.u., and the delay of this must be shorter than line tripping by overvoltage relays.

- **First Step of line overvoltage tripping.**
  The first step of overvoltage must be set between 1.15-1.20 pu, the delay of this step must be set between 1 to 30 sec. This step must be coordinated with the shunt reactors insertion and the first step of tripping the other lines.

  \[ U > 1.15 \text{ – } 1.20 \text{ pu} \]
  \[ t > 1 \text{ – } 30 \text{ seconds} \]

- **Second step of line overvoltage tripping**
  The second step must be set between 1.20 to 1.30 p.u., the delay of this step must be set between 0.1 to 10 sec. This step must be coordinated with the overvoltage relays of other lines

  \[ U >> 1.20 \text{ – } 1.30 \text{ pu} \]
  \[ t>> 0.1 \text{ – } 10 \text{ seconds} \]

- **Backup Step for Power Transformers.**
  If it is necessary, and the owner or the manufacturer recommends overvoltage protection of the power transformer, this step must be set to operate after the first and the second step of the line relays, and the point of operation must be under the temporary overvoltage limit.

Additionally the following restrictions are also important:

### 4.1 Ground faults restriction.

During single phase to ground faults in the lines, the phase to ground voltage in the faulted phase drops, while the voltage in the healthy phases are increased. These overvoltages can reach values up to 1.73 p.u. depending of the effectiveness of the system grounding. In HV and EHV transmission systems, the grounding is usually effective enough to limit the voltage rise in healthy phases to less than 1.3 per unit.

The voltage in the healthy phase can be calculated using conventional fault studies.

If the overvoltage protection uses positive sequence voltage or a criterion that all three phase voltages must be high, the healthy phase voltage rise during a single line to ground fault will not be a concern.

### 4.2 Ferranti effect restriction.

When a long line is energized in one end, the voltage in the opposite end can reach values that go from 1.05 to 1.16 p.u, this condition can cause the overvoltage relays to trip. So this voltage must calculate and then considered during the overvoltage setting.

The voltage at the open end is calculated using conventional power flow or fault studies with proper representation of the shunt capacitances:
5. Advantage of the application of overvoltage relays in lines

In this new application, the overvoltage relays were implemented in the lines, in order to trip lines before tripping power transformers. The intent is to halt the aggravation of the overvoltage condition before the health of the connected transformer is threatened. The difference between the old and the new methodology is explained using Figure 3. as an example.

Figure 3. Proposed disconnection scheme.

Figure 3 shows a system were a sudden contingency causes a temporary overvoltage in the substation B-1. This causes a local problem in the substation.

With the old methodology the overvoltage relays of the substation trip the power transformer connected to B-1, shedding the load C-1, stressing generator G-1 even more. If the overvoltage remains and it is not controlled by the generator, the substation B-2 is going to have overvoltage too, so the power transformer connected to B-2 is going to trip, exacerbating the overvoltage in all the system.

With the new methodology the scheme of overvoltage control is as follows:

Under the condition of overvoltage in substation B-1

First step, the overvoltage relay of line L-1 trips, sending a transfer trip to the opposite end. Since lines L-1 and L-2 are long and lightly loaded, system security is lightly threatened, by loss of the line, but reactive power injection is significantly reduced. Tripping this line, the overvoltage will be mitigated. However if the overvoltage is not fully controlled, the second step will occur.

Second step, Shed generation of the generator G-1. This increases the power flow in line L-2., Increased power flow in Line L-2 increases reactive power consumption in the transmission system, thereby reducing the overvoltage at substation B-1 even further. If after all these disconnections, there is still an overvoltage, the power transformer of the substation B-1 is tripped interrupting the load C-1. After this the line L-2 is tripped in order to not propagate the overvoltage problem to substation B-2.

These overvoltage schemes must be analyzed using power flow simulation programs. In the Peruvian power system the studies were made using a commercially available power system analysis program.
6. Overvoltage coordination in the peruvian power system

This methodology of overvoltage coordination was applied in the northern area of the Peruvian power system. This is a 220 kV transmission system with long lines and (sometimes) light loads. The system is shown simplistically in Figure 4.

Firstly, for this area the ground faults restrictions were calculated for the lines which are shown in Table 1

<table>
<thead>
<tr>
<th>Substation</th>
<th>Vph he (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zorritos</td>
<td>0.98</td>
</tr>
<tr>
<td>Talara</td>
<td>1.07</td>
</tr>
<tr>
<td>Piura</td>
<td>0.97</td>
</tr>
<tr>
<td>Chiclayo</td>
<td>0.99</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>1.01</td>
</tr>
<tr>
<td>Trujillo</td>
<td>0.96</td>
</tr>
<tr>
<td>Chimbote</td>
<td>0.98</td>
</tr>
<tr>
<td>Paramonga</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Table 1: Voltage in the healthy phases during single phase to ground faults
The Ferranti effect for each 220kV line was calculated too. These values are shown in Table 2. The sending voltage in each case of Table 2 was considered as 1.05 p.u. of the nominal voltage.

<table>
<thead>
<tr>
<th>Line</th>
<th>Length (km)</th>
<th>Us (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-2249</td>
<td>137.0</td>
<td>1.07</td>
</tr>
<tr>
<td>L-2248</td>
<td>103.8</td>
<td>1.06</td>
</tr>
<tr>
<td>L-2238</td>
<td>211.2</td>
<td>1.09</td>
</tr>
<tr>
<td>L-2236</td>
<td>83.6</td>
<td>1.06</td>
</tr>
<tr>
<td>L-2234</td>
<td>103.2</td>
<td>1.06</td>
</tr>
<tr>
<td>L-2232</td>
<td>134.0</td>
<td>1.07</td>
</tr>
<tr>
<td>L-2233</td>
<td>134.0</td>
<td>1.07</td>
</tr>
<tr>
<td>L-2215</td>
<td>221.2</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Table 2: Voltage in the open end of the lines

Finally the settings calculated for the overvoltage relays are shown in Table 3.

<table>
<thead>
<tr>
<th>Line</th>
<th>Step 1</th>
<th>Step 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U&gt; (p.u)</td>
<td>t&gt; (seg)</td>
</tr>
<tr>
<td>L-2280</td>
<td>1.15</td>
<td>1.0</td>
</tr>
<tr>
<td>L-2249</td>
<td>1.15</td>
<td>1.5</td>
</tr>
<tr>
<td>L-2248</td>
<td>1.15</td>
<td>2.0</td>
</tr>
<tr>
<td>L-2238</td>
<td>1.15</td>
<td>2.5</td>
</tr>
<tr>
<td>L-2236</td>
<td>1.15</td>
<td>3.0</td>
</tr>
<tr>
<td>L-2234</td>
<td>1.15</td>
<td>3.5</td>
</tr>
<tr>
<td>L-2260</td>
<td>1.15</td>
<td>3.8</td>
</tr>
<tr>
<td>L-2233</td>
<td>1.15</td>
<td>2.5</td>
</tr>
<tr>
<td>L-2232</td>
<td>1.15</td>
<td>4.2</td>
</tr>
<tr>
<td>L-2215</td>
<td>1.15</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 3: Some overvoltage settings for the northern area of the Peruvian Power System

It can be seen from the table 3 that the lines nearest the end of the transmission chain (most remote from the strong system) are tripped in the shortest time. These lines are most likely to suffer overvoltage and also their loss has the least impact on system security. Also, where parallel lines exist, one of the two lines is tripped significantly earlier than the other, to try to maintain the transmission path.

Figure 5. shows a simulation of cascading loss of the system using old protection methodology of tripping loaded transformers to protect them from overexcitation damage. In this simulation, a shunt reactor is disconnected from Talara Substation at time t=0. The figure shows how the power transformers with their loads connected tripped, exacerbating the overvoltage problem. The increasing disconnection of load converted a local problem to a wide area system problem.
In Figure 6, the same disconnection of a shunt reactor at Talara was simulated but this time with the new scheme implemented. The overvoltage produced by this disconnection is controlled tripping only one line L-2280.

In some cases where the security of a direct transfer trip needs to be enhanced, additional supervision may be advisable. For instance, Figure 7. shows how a medium set voltage level detector at the receiving terminal may be used to supervise a received direct transfer trip signal from a higher set voltage detector at the remote terminal.
7. Conclusions

7.1 In power systems where temporary overvoltages are present, it is necessary to implement protection schemes against such overvoltage in order to prevent damage to the power equipment.

7.2 The application of overvoltage relays to power transformers protects only the equipment, but not the system.

7.3 The arresters of the substations are not designed to support high temporary overvoltages. If arresters fail due to temporary overvoltages, system restoration times will be increased.

7.4 In setting of the pickup and delay values of a line overvoltage relay, the following must be considered.

- Ferranti effect
- Healthy phase voltage rise during single line to ground faults (depending on the type of sensing applied)
- Reset ratio of the measuring device (depending on the type of relay used)
- Coordination with equipment capability
- Coordination with system voltage controls such as reactor switching
- Coordination with other line overvoltage relay settings to minimize impact on the power system security

8. Acknowledgement

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9. References