INTRODUCTION

Over the last 30 and 40 years the Transformer Substations (TS) have had a great evolution, progressing from classic assembly in open bays, partition walls and outdoors, to the existing model, in order to increase the human safety and material reliability as well as the assembly and space reduction. New outcomes such as metallic bays, prefab buildings, compact transformer substations and eventually pad-mounted substations are also revolutionary.

Given the increasing concern of society about environment, the industry in general is reconsidering both the design and the materials that may mean contamination, trying as much as possible to replace them for environment friendly ones. The inevitable society advance should not and must not cast out the Earth’s future. It is time for a sustainable development.

Therefore our work here today is a contribution in this sense.

BACKGROUND

It is in 1995 when the first steps are performed in Spain in the use and design of pad-mounted substations. The origin of these substations is the search of a smaller place to an indoor installation.

During those years the wide dimensions necessary for building and access these transformers (±20 m²), the conditions for Low Voltage (LV) local regulation, the use of them meant an enormous cost for the properties developers and therefore a conflict between them and the utilities. So the premises were scarce and hardly ever in good conditions. Thanks to expansion of pad-mounted transformers the space required dropped from the required 20 m² to 5m² to installed powers under 630 kVA. At the same time there was a reduction in the overall owning cost of a 50%. Moreover, the transformer substations exhibited an important improvement both in quality and reliability of the installation, and they are delivered fully connected and tested from the factory. To set it, it just needs to be connected to the inlet wire of Medium Voltage and the Low Voltage outlet. The works in the building are simplified too.

The first transformer was initially established by UNION FENOSA on its own headquarters in La Coruña in 1997. This pad mounted system meant an utter revolution within transformers, and even the Spanish regulations were modified in order to allow the installation to meet the standards. It was the running start of all the different pad-mounted substations available in our company.

Once achieved the original main goal of reducing the space, we decided to work in an environmental transformer under the following viewpoints:

- Use of recycle and/or biodegradable materials.
- Contaminating or toxic elements disposal.
- Losses reduction (better energy efficiency)
- Vibration and sound reduction (acoustic pollution).
- Maximum use of power supply (enhanced protections)

All these aspects were considered in the running design of integrated new environmental transformer substation.

BUILDING FEATURES

Pad-Mounted Transformer vs. Conventional Assembly

The most common and extended transformer substation in Europe consists of three SF₆ bays (inlet, outlet and transformer protection), the transformer itself and a low voltage control panel with its corresponding LV protections.

The security system in case of short-circuit in the transformer consists on a current-limiting fuse-link, and the protection for overloads is operated by a thermometer that measures the cooler temperature and, in case of over limited heat, the switch reacts shutting itself automatically. This typical scheme is shown in Picture 1.

Every functional set (disconnector, transformer and LV panel) is an independent unit. The switch-disconnectors are connected with the transformer by insulating cable and plug-in terminations. The same applies for the connection between transformer and the LV panel. This extends the space provided as well as possible fault points.

Metallic Pad-Mounted Transformer

In 1995 UNION FENOSA was the first to introduce in Spain these kind of transformers, already well known in The U.S.

These transformers consist of an oil tank containing the transformer, protection devices and switches.

The design includes a loop feed configuration with two three-position switch-disconnectors, MV/LV transformer and LV distribution panel with fuse protection for low voltage lines. The main difference is the use of a common metallic enclosure for all the elements; this eliminates bushings, terminals and connection cables among them. The insulating element used in the process comes from vegetable oils with the characteristics described bellow.
The basic components of this design are (Pictures 2 and 3):

1. Loop switch: Three positions, (open-close-earth) switch-disconnector
2. Transformer switch: Two positions, (open-close) switch-disconnector
3. Thermo-magnetic protection.
4. ELSP Back-up current limiting fuse-links
5. Tap Changer
6. Pressure vacuum gauge
7. Thermometer
8. Liquid level gauge
9. Screened Middle voltage bushing.
10. LV distribution panel

This latest model eliminated all the external MV and LV connections to the various components from the conventional transformers such as switch, transformer connecting cable, bushing, plug-in termination, wires between transformer and LV panel, etc. resulting a more simple and reliable equipment fully tested and installed in the supplier factory.

**New Design: Radial Pad-Mounted**

Over 9 years of experience using Loop Feed configuration we have developed a new TS by adapting the underground distribution networks both in rural and semi-urban areas. This allows the use of Radial Pad-Mounted Transformer instead of conventional pole one, those areas where new overhead lines are not possible.

The design is similar to that in loop feed transformer with likewise protection devices (thermo-magnetic switches and backup current limiting fuses). The transformer operation has a three-position switch: open, close and earthing of the feeder. The powers in the models are 100, 160 and 250 kVA and tensions 15 and/or 20 kV.

This new model allows to extend the line to a second transformer (Picture 4), disconnects and parks outside the feeder.

**Transformer Protections**

The load limit depends on two considerations:

**Thermal limits.** Amount of load that increases the temperature over a critical point, causing an early ageing in the insulating materials and reduces the transformer lifetime. The protection elements are in the charge of controlling that the temperature does not exceed the critical point, so in case of this overload reach that point the supply must be automatically interrupted.

**Economic Limits.** A more powerful transformer is recommended when the cost due to load losses is profitable.

The critic characteristic of the transformer is represented by a curve. This curve shows the maximum time at which the device can operate at a certain overload rate, before exceeding the critical point, at which a rapid ageing in lifetime would occur.

The curve varies according not only to the particular transformer characteristics but also depend on other conditions, being the most important:

- Ambient temperature
- Load conditions previous to overload

**Ambient temperature.** When the temperature decreases the transformer will admit more overload conditions, so the curve will move rightwards.

On the contrary, when the ambient temperature increases the overload permitted will be lower than before, so the curve moves to the left.

**Previous load conditions.** If the transformer was unloaded before the overload situation it will permit a superior overload rate. But if it was loaded the overload admitted will be minor. According to this information the protection for overload must be adapted to the variations of the critical curve caused by various factors simultaneously observing two conditions:

- Always disconnect the transformer when the temperatures are close to critical limit.
- Never disconnect if the transformer can stand this load.
Conventional Transformer Protection

The protection in distribution transformers has always been based mainly in fuseable elements, both for faults in the primary as well as for overloads.

This sort of protection is only current sensitivity; therefore not considering room temperature nor load conditions.

The fuse-link replacement needs a suitable fuse-link for each equipment, that have to be carried by the maintenance teams. Given the variety of transformers in the market, each with different voltage and power levels, many specific fuse-links become also necessary, which means an extraordinary expense on investment, and higher cost of repairing breakdowns.

The new contact thermometer turned into an advantage for overload protection but on the other hand it has an important delay in case of serious shortcuts in the LV side, forcing the MV fuses to operate; so the access to them must be trouble free.

Thermo-Magnetic Switch Protections Operating

The Thermo-Magnetic Interrupter (TMI) is an over-current protective device that protects distribution transformers from damages caused by overloads and secondary faults.

There are now two versions available: single-phase and three-phase.

The TMI is mounted under-oil in the primary side of the transformer. It disconnects the transformer to prevent a damage in the insulating materials caused by high temperatures. The TMI is activated by a sensor that operates in case of a combination of two conditions occur:

- The heat (R²) produced by the current in the primary
- The oil temperature in which is immersed.

An excessive temperature forces the sensor to change from a ferromagnetic to a paramagnetic state, decreasing its magnetic attraction capability which causes the switch to activate. Under fault conditions, the sensor suffers the main effect of the current heat, causing a sudden reaction of the TMI as a fuse-element would do. In fact, the time-current characteristic curves of the magnetic actuation are very similar to the fuse-link ones.

A suitable sensor should be determined for each kVA range and Voltage.

However, this sensor reacts to an oil temperature increase during long overload period, which did not happen with the fuse-links.

Coordination of TMI Protection

The limiting fuse-links have largely proved to be inefficient during serious transformer faults. However, the TMI and the fuse-link working together cover this case.

The distribution of protective functions for the transformer is:

- The fuse-link operates in case of short circuits in the Medium Voltage level, therefore only when the transformer has an internal failure. Under different circumstances is the TMI the one that trips.
- This simple plan permits an optimum use of the transformer in case of overloads.

The TMI trips the transformer when overloads and/or short-circuit occurs in LV side.

When a Low Voltage distribution panel with fuse-links is installed in order to protect the output lines, the TMI is coordinated with them, so, in case of a fault in the LV network the fuse-links act before the TMI does.

By doing this, a total disconnection is avoided in case of a fault in one of the LV output lines.
LOSSES REDUCTION

First Step: Urban Transformers

Following our saving and efficiency policy, it was very important for us to reduce the losses in the Pad-Mounted Transformer Substations. The reduction in both cost and size in the transformers had several results:

- Transformers became closer to customers.
- Shorter Low Voltage network
- Losses and Fault rates reduction in LV network.

On the other hand, given the MV/LV transformers characteristics and the increasing number of appliances existing, any unitary saving means an eventually multiplied saving.

In 1998 there was a great reduction in losses for the urban Pad-Mounted TS (250, 400, 630 kVA). Table 1 shows the magnetic losses rates as well as the different powers before and after 1998.

<table>
<thead>
<tr>
<th>kVA</th>
<th>Before 1998</th>
<th>1998 - 2005</th>
<th>Unitary Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Po</td>
<td>Pcu</td>
<td>(W)</td>
</tr>
<tr>
<td>250</td>
<td>650</td>
<td>3250</td>
<td>480</td>
</tr>
<tr>
<td>400</td>
<td>930</td>
<td>4600</td>
<td>730</td>
</tr>
<tr>
<td>630</td>
<td>1300</td>
<td>6500</td>
<td>1050</td>
</tr>
</tbody>
</table>

TABLE 1: Losses Rates in UNION FENOSA Transformers

This losses reduction did not mean an increase in the Urban Transformers cost because it came along with the revolutionary development in Spain of Pad-Mounted TS, transformers which according to the previous information, have an important decrease in dimensions, manufacture and installation costs.

To see the energy saved thanks to this losses reduction, we must remember the effect of them in the machine performance. The magnetic losses occur in a permanent way throughout the machine's life, which means that the transformer is permanently connected for 8760 hours a year. For load losses, we consider that most of the transformers work at a 60% of nominal load during 4000 hours a year.

In Table 2 we can see the number of transformers installed from 1998 to 2003, as well as the annual losses reduction by UNION FENOSA for this period.

In order to continue the research started in 1998 with the losses reductions in urban transformers, we decided to extend these treatment within the rest of transformers to be assembled into the network, specially in the recent Radial Pad-Mounted for underground network in semi-urban and rural areas, having as a result an important reduction in the losses compared to the present transformers

In transformers of 100, 160 and 250 kVA we emphasise the reduction in the no-load losses, because this transformers work usually with lower load levels.

<table>
<thead>
<tr>
<th>kVA</th>
<th>Normal</th>
<th>Reduced</th>
<th>Unitary Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pn</td>
<td>Pr</td>
<td>(W)</td>
</tr>
<tr>
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<td>730</td>
<td>3650</td>
<td>600</td>
</tr>
<tr>
<td>630</td>
<td>1050</td>
<td>5250</td>
<td>850</td>
</tr>
</tbody>
</table>

TABLE 2: Annual Losses Saving during First Step

Second Step: Semi-Urban and Rural Transformers

In order to see the losses reduction we have applied this to the existing transformers in the company. The reference is included in the Harmonised European document HD428. A 50% of the working transformers are estimated to have a normal loss rate (normal in UNESA transformers) and the remaining 50% we consider 1.3 times this losses due to they are obsolete transformers.

The study in Table 4 includes the present working transformers but not the ones on Table 2 which were installed from 1998 on (already exhibiting an under 40% load rate).

<table>
<thead>
<tr>
<th>kVA</th>
<th>Normal</th>
<th>Reduced</th>
<th>Unitary Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pr</td>
<td>PR</td>
<td>(W)</td>
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<tr>
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<tr>
<td>630</td>
<td>1050</td>
<td>5250</td>
<td>850</td>
</tr>
</tbody>
</table>

TABLE 3: Second Reduction of Losses in UNION FENOSA

Table 3 shows the losses reduction in the new units starting from the regular rates (UNESA) and including the present specified rates.

The second reduction is also included for the urban transformers, strengthen the no-load losses more than the load losses.
To sum up, these new transformers are a 39% energy reduction compared to the existing ones, 35% for rural and 41% to urban transformers. The overall losses reduction in this case would be 82387 MWh per year. This saving is like a power plant of 9.5 MW operating at maximum load during 8760 hours a year, and reducing 15 MVA in the installed load (a small substation). The energy cost in the energy market is about 3,050,000 euros a year.

In environmental terms, if the older transformers were to be replaced, the CO₂ annual emission into the atmosphere would be reduced in 32,000 tons, the NOₓ and 480 for the SO₂.

<table>
<thead>
<tr>
<th>kVA</th>
<th>Num. Trfs</th>
<th>Losses (MWh)</th>
<th>Real Saving</th>
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</thead>
<tbody>
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<td></td>
<td></td>
<td>Normal</td>
<td>Reduced</td>
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<td>28175</td>
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<td>4051</td>
<td>23799</td>
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<td>290</td>
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<td>84395</td>
<td>51004</td>
</tr>
<tr>
<td>TOTAL</td>
<td>21612</td>
<td>211793</td>
<td>129406</td>
</tr>
</tbody>
</table>

saving of global losses 39% 

TABLE 4: Potential Annual Losses Saving in UNION FENOSA

Enhanced Use of Transformers Load

Another important advantage of new TS is related to the protection system. The protection system based on TMI allows the transformer to work under overload conditions, but still this does not increase ageing nor permanent failure. Given that the loads vary widely during the day and have short peaks, a less powerful transformer is possible with important saving in the no-load losses.

Otherwise, if we have a 200 kW peak during three hours a day, we would install a 250 kVA transformer with an overall of 400 W magnetic losses a year. If we install a 160 kVA transformer this permanent losses would be 320 W. The load losses would be more with this transformer, but given the load conditions it does not affect much the annual figures, eventually producing a loss reduction.

If we decide to install less powered transformer in 5000 devices with new protection, we would have an additional 5000 MWh per year reduction, which in other terms it is 600 kW generator working at a maximum load throughout the year, as well as a 2000 CO₂ tons, 12 NOₓ and 36 SO₂. Or a cost in the energy market of 18,520,000 euros per year.

DIELECTRIC COOLANT

The coolant used in this design is FR3, a product developed by Cooper Power Systems and manufactured from food graded vegetable oils, and additives to minimize environmental impact. The commodities seeds oil comes from common crops, being a renewable source. According to the OECD G.L. 203, one of the most sensitive tests for toxicity, FR3 fluid exhibited exceptional performance with zero mortality. It also meets EPA standards for ultimately biodegradable product on water and soil. The thermal decomposition produces CO₂ and H₂O but it can not produce Furanic nor Dioxin compounds. It is readily biodegradable, and in case of excess purchase it can be used as bio-diesel for fuel oil.

Given its special characteristics in the U.S., it is regulated by the edible oil federal laws. In order to difference them from other liquids and enhance its environmental properties it is given a greenish tint. Table 5 shows the features of dielectric coolant fluid in Transformers compared to FR3.

Fire Safety

In FR3, both the FIRE POINT (360º) and the FLASH POINT (330º) have been proved superior to in other fluids such as silicone, synthetic esters, or conventional oils. This features eliminate the necessity of fire extinguisher in Pad-Mounted Transformers complying with the 4.1 MIE-RAT 14 (Spanish High Voltage Regulation). Thanks to its non contaminant and ultimately biodegradable attributes, the built of an oil pit becomes unnecessary complying with 5.1 MIE-RAT because accidental spills would not cause earth nor water pollution. And it can be installed at any ambient or placement.

Caloric Transfer

The POUR POINT (PP) and Viscosity are very important in a coolant fluid. The PP indicates the minimum temperature at which an oil can be used and still operate. The viscosity helps the heat dissipation in a transformer especially in a natural refrigeration one (as in distribution transformers). The FR3 has a quite high PP, -21º C (standard is between –30 and –40) and a higher viscosity than other natural conventional oils. This means a slower liquid flow compensated by a better thermal conduction and specific heat, though.

The expansion coefficient is also lower than in other oils. This particular attributes of the FR3 permits its use on existing transformers, without changes in design, both magnetic core nor oil tanks, including integral retrofitting of distribution transformers.
Chemical Compatibility

The chemical structure consists of vegetable oils. It is perfectly compatible with the insulating materials and other components used in oil for transformers. The FR3 has been proved to minimize paper ageing caused by high temperatures. Along several accelerated ageing tests in insulation paper, submerged in different coolants, this fluid has showed to enhance the life expectancy of insulating and allows a higher overload capability. Totally miscible with conventional mineral oils, maintaining the characteristics even in highly contaminated situations. A conventional transformer can be retrofitted with FR3 and it is not necessary to clean up the remaining mineral oil, which means a maintenance saving.

![Picture 11. Biodegradability](image1)

Dielectric Strength

FR3 presents a superior dielectric strength compared to conventional coolant oils and other high qualified coolants such as R-Temp or silicone oils. Even with high moisture contents, which is not possible with conventional oils, these attributes still remain the same. A 220 ppm moisture in this oil is equivalent to a 10 ppm for mineral oil. This factor makes it suitable for transformers with air chamber. FR3 works as a drying agent for the paper and other insulating, absorbing the moisture and giving a longer life to the transformer. Due to its coke sludge decrease and gassing tendency it is ideal as an insulating and arc extinguisher transformer. Due to its coke sludge decrease and gassing tendency it is ideal as an insulating and arc extinguisher (load-break switch-disconnector) and, at the same time, it permits the transformer and feeder disconnecter to be installed in the same tank.

![Picture 12. Dielectric Strength](image2)

Acoustic reduction

The metallic enclosure transformer uses the oils as an insulating fluid. It must comply with American (ANSI-NEMA) and European (CEI) noise regulations. The origin of noise in Pad-Mounted Transformers is mainly the magnetic field. The noise is produced in the transformer core due to the iron particles’ vibration when changing direction during magnetic flow changes. The noise rate varies according to the core flow rate, which also depends on its design and voltage applied. In order to see the noise produced in the transformer we must apply the nominal voltage in the coil and see the result when increasing from 110% to 120%. Also, the oil around the transformer core works as a sound insulator. As a consequence, these transformers are quieter because they have more oil volume than conventional ones. According to international regulations the noise rate limit in a transformer depends on its power, the applied tension and its testing method.

NEMA and CEI specify a limit of 55dB in transformers from 101 to 300 kVA, and 56dB for over 300kVA. In Spain a 70% of the population suffer from noise level over 65dB, being this the limit of acceptable noise. The noise rate for these transformers operating in UNION FENOSA’s network at present have a percentage of 20% below the values established by NEMA and CEI. On the other hand, to obtain the maximum level permitted the supply voltage required would be a 21% over the nominal voltage, therefore far above the quality supply limit. Several studies in particular devices have proved the noise levels to be accurate.

CONCLUSIONS

This document summarizes the criteria followed in the design of these new transformers based on many years of development and experience in the electric industry, including new demands such as environmental concerns and enhanced energy efficiency.

These improvement criteria are successfully operating in our Pad-Mounted Transformer Substations network.

According to the demand for diversification and the use of different suitable technologies in the transformer substations, UNION FENOSA, in collaboration with Spanish manufacturers has motivated the evolution of Pad-Mounted Transformers, with the same or at least quite similar benefits, in two different ways, both metal-clad and concrete-clad Pad-Mounted.

At present these Transformer Substations are in its final phase of design and testing, and in a few months a serial production will be possible.

Including all features:

- Recycle materials → commodities saving → **Energy Saving**
- Biodegradable and non-toxic coolant → Disposal saving → **Energy Saving**
- Fire security
- Loses reduction → **Energy Saving**
- Noise reduction → correction measures saving → **Energy Saving**
- Reduced space.