# DESIGN OF AN ULTRA COMPACT DISTRIBUTION SUBSTATION

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*Summary — This paper presents a new architecture of distribution substation allowing the reduction of global cost and size of substation. Moreover, safety and reliability are improved. The substation is designed as a global product (turnkey solution). The main innovations are the new types of medium voltage (MV) and low voltage (LV) connections, and the transformer integrating protection and switching.*

## I INTRODUCTION

The process of restructuring, privatization, and deregulation has created a competitive, global marketplace for energy [1]. Early preparation to market competition and best use of technology will drive success in this new and challenging environment [2]. The utilities of the future will be focused on their expertise in order to do what they do best [3]. Moreover, twenty-first century utilities will try to further improve system reliability and efficiency by upgrading and modernizing the network's infrastructure, while simultaneously being cost effective.
The increased competition has led utilities to think thoroughly about how to optimally satisfy their needs for distribution substations in terms of global cost optimization, easy and fast installation, easy operation, safety for operators and public.
The equipment of a ground-mounted distribution substation includes one distribution transformer connected to the MV network through a MV switchboard, a LV switchgear and accessories. For indoor substations, all equipment is usually located in a separate (electrical) room, while outdoor substations are located outside. For underground cable networks, the main types of outdoor distribution substations are the "bricked up", which are done and tested on site, and the "prefabricated" substations, which are assembled and tested by the manufacturer.
The outdoor ground-mounted prefabricated substations (also called kiosks in the sequel) started to be industrial products by the end of the 1970's with a new generation of MV switchgear using $SF_6$ switching technique. Then, ring main units using the same medium both for switching and insulation gave reduction of substation dimensions, safety and insensibility to the environment [4]. Type tested enclosure is one guaranty for reliability. The kiosks became, and remain, the European and worldwide best substation solution for the underground cable networks [5], in the context of the different power distribution practices [6] that are followed around the globe.
Without technological breakthrough concerning the substation equipment (MV and LV switchgear, transformer, cables, etc), the current solutions have reached a limit regarding cost reduction, so the breakthrough can only be done regarding global substation. That is why this paper proposes a novel ultra compact substation architecture leading to a global product (turnkey solution).
The new ultra compact substation significantly contributes in the global cost reduction for the utilities as well as for the industrial users because of three main reasons. First, the reduced surface area required to install the substation generates cost-savings, especially in urban areas where space is hard to be found and also expensive. Second, the substation needs less labor installation costs, since it is delivered as a ready-to-install assembly. Third, the procurement of the substation as a complete assembly facilitates purchasing, management, storage and handling operations.
This substation is suitable for underground ring networks. It is designed for power up to 630 kVA and for MV network voltage up to 24 kV. However the range is going to be extended in the near future. This new substation includes three main components: a module comprising two MV network switches, a transformer integrating a protection and switching system, and a LV fusegear. These three components are connected using factory-built and enhanced-reliability connections.
The substation can be supplied without an enclosure for indoor use, or with an enclosure for outdoor use. Moreover, this turnkey substation is available in two types: bloc and kit. The bloc type substation is fully assembled and tested in the factory. The kit type substation is delivered in sub-assemblies, which are to be connected on-site using factory-built connections.
The paper is organized as follows: Section II gives details on substation compactness, Section III describes the substation safety. Section IV presents the standards and tests that are done to the proposed substation. Finally, Section V concludes the paper.

## II COMPACTNESS

Compactness is a very important value for customers because ground surface is expensive (especially in building) and it is very difficult to find free area (particularly in building if customers require front access). Moreover, a very compact kiosk has less impact on the landscape and is more acceptable by the public.

**Current Situation**

The indicator of the substation compactness is its footprint [5]. The footprint of the equipment is the total required surface area (in $m^2$) that is covered by the substation equipment. The footprint of the kiosk is the total surface area that is necessary to operate or check the included equipment.

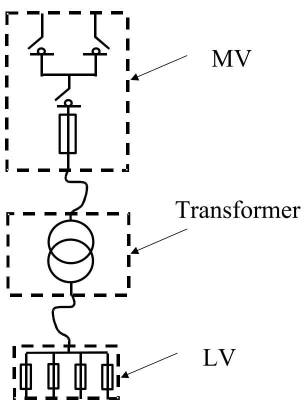


Fig. 1. Typical substation design.

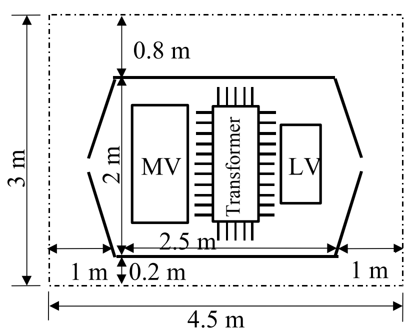


Fig. 2. Footprint of a typical 630 kVA substation.

Today, substations require about 1 m of free space for door opening. If the kiosk has access doors on two faces (one for MV and one for LV), the footprint requires in addition a free way of 0.8 m to join the two faces. Moreover, it is necessary to let 0.2 to 0.5 m of free space in front of the ventilation.

In the traditional substation design (Fig. 1), the MV switchgear compartment is not enough compact since it consists of two switches and one fuse-switch. Moreover, due to their large bending radius, the MV and LV cables require to install MV switchgear, transformer and LV switchboard with large space in between. For example, one 630 kVA substation with an equipment footprint of 5 $m^2$ (2m*2.5m; Fig. 2), with two access faces and ventilation on the other sides requires a kiosk footprint of 13.5 $m^2$ (3m*4.5m; Fig. 2).

**Compactness Improvement**

In order to reduce the equipment's as well as the kiosk's footprint, it is proposed to integrate the protection and switching within the transformer tank (Fig. 3). Another way to optimize the dimensions of the substation is to use direct connections between the MV switchgear and the transformer as well as between the LV switchgear and the transformer (Fig. 3).

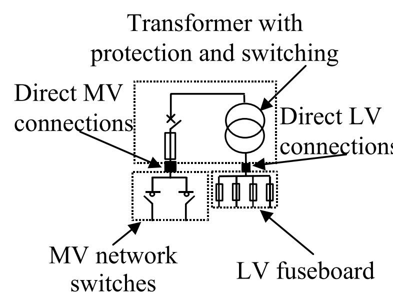


Fig. 3. Proposed substation design.

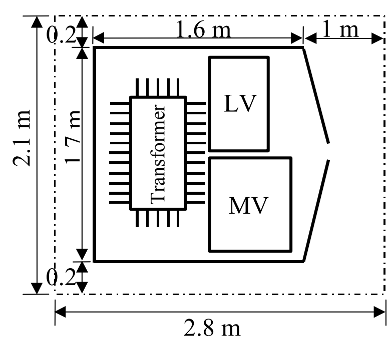


Fig. 4. Footprint of the proposed 630 kVA substation.

In the proposed design, the integration of protection and switching in the transformer enables to reduce the size of the MV switchgear and then to be able to design an optimized kiosk in terms of dimensions with only one operating face for MV and LV switchgear (Fig. 4). For example, a 630 kVA substation of the proposed design (Fig. 3) has an equipment footprint of 2.72 $m^2$ (1.6m*1.7m; Fig. 4) and requires a kiosk footprint of 5.88 $m^2$ (2.1m*2.8m; Fig. 4). For the specific example of the 630 kVA substation, the equipment footprint is reduced by 46% (from 5 $m^2$ to 2.72 $m^2$) and the kiosk footprint is reduced by 56% (from 13.5 $m^2$ to 5.88 $m^2$).

**MV Network Switches**

MV network switches comprise 2 integrated, compact functional units. This integrally insulated self-contained assembly comprises a sealed for life stainless steel enclosure that includes the active parts, the switch disconnectors and the earthing switches, two cable compartments for the MV network connection, one LV compartment, and one control compartment.
The MV network switches ensure safety of people due to internal arc withstand in conformity with IEC 60298 standard, visible earthing, 3 positions switch providing natural interlocking, and reliable switch position indicators.
The performance levels obtained with MV network switches meet the definition of sealed pressure system, in line with IEC recommendations. The switch disconnector and the earthing switch offer full operating guarantees for the operator. The enclosure is filled with $SF_6$ at a relative pressure of 0.2 bars. Once filled, it is sealed for life. Its sealing is systematically checked in the factory, giving a service life of 30 years. Therefore the ring switch does not require any maintenance of its active parts. Electrical arc extinction is achieved using the puffer technique in $SF_6$.

**MV Connections**

A direct factory-built MV connection between the MV switchgear and the transformer enables to place them directly one against the other. In addition to the footprint reduction, this solution can improve the reliability if the MV connection is installed in the factory, since the MV switchgear and the transformer can be tested as a complete unit.
In case of factory-installed (bloc type substation), the MV connection comprises three bi-conical sleeves made from over-moulded elastomer on copper braids (Fig. 5). These assemblies provide the electrical connection between the MV network switches and the transformer. A mechanical positioning system ensures perfect position with each of the bushings.
In case of on-site-installed (kit type substation), the MV connection comprises three flexible cables, which are pre-equipped with over-moulded connectors at both ends. When installing the substation on-site, these cables are to be connected to the transformer and to the MV network switches. A set of flanges fixes them at both ends. Thanks to the flexibility of cables, the MV switches can be positioned closed to the transformer, then reducing the footprint.

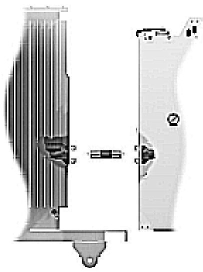

Fig. 5. MV connection for bloc type substation.

Fig. 6. MV connection for kit type substation.

**LV Connections**

The connection of the transformer and the LV fusegear is achieved using a factory-built direct LV connection (Fig. 7). This connection comprises a single component fixed with two bolts. Thanks to this connection, the LV switchgear can be positioned next to the transformer with the integrated protection and switching since there are no longer any cable bending radius to take into account.

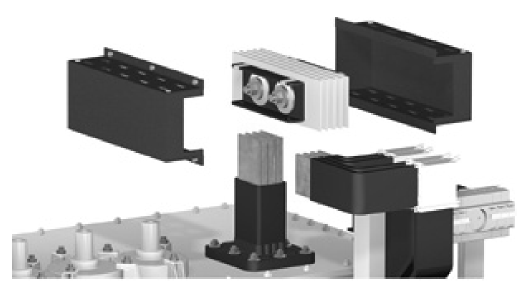

Fig. 7. LV connection.

The proposed LV connection reduces the distance between the LV fusegear and the transformer. Moreover, it is easy and quick to install the LV connection, since no cables are needed and the fitting of the connection takes less than five minutes.
For traditional substations, the LV cables between the

transformer and the LV switchgear are the main source of magnetic radiation [7]. Their replacement by a connector plate drastically reduces emissions of magnetic radiation by acting to significantly reduce the length of conductors and by acting on the proximity of the phases to generate opposing magnetic fields, thus canceling out the effect.
Fig. 8 shows the layout of the proposed substation.

Fig. 8. Layout of the proposed substation (bloc type).

## III SAFETY

Safety of property and persons, respect for the environment and improvement of operating conditions are gaining in importance daily. As the ultimate element in the electricity supply chain, the distribution transformer is one of the most widespread items of equipment and, being located nearest to the user, it is therefore one of the most sensitive [8]. Avoiding external consequences (explosion, oil pollution, etc), when a transformer fault occurs, is vital [9]. In addition, limiting outages at their minimum is an important target for utilities. Therefore they are very keen to avoid outages on upstream MV network in case of transformer fault. Consequently, it should not come as a surprise that transformer protection forms a subject of a permanent research effort [8-19].
In the distribution substation, the faults downstream the substation (LV network) are eliminated by the LV fuses and they do not include any risk concerning safety. Internal arc test in MV switchgear enables to assure safety in case of unlikely fault in this equipment.
On the other hand, in the distribution transformer, current protection solutions, if used alone, are not able to assure total safety. Two types of solutions are currently used:

- MV fuses with strikers that are tripping the transformer switch, which is most common choice, due to its historical use
- Protection overcurrent relay that is tripping the circuit breaker (CB) of the transformer at an affordable similar price level.

Fuses are very effective for high fault current (internal arc within transformer tank) because they limit and interrupt the current in approximately 5 ms. On the other hand, in case of fault in the winding (short circuit between turns causing weak fault current with gas build up), there is a risk for fuses to not act. The reason is that fuses can only interrupt currents higher than 8 times the nominal current of the transformer, or with strikers (that are tripping the transformer switch), currents higher than 5 times the transformer nominal current. As a result, in case of weak fault current, the transformer tank could be teared due to the overpressure and there is a risk for safety and pollution of the environment by oil.
Circuit breakers with current relay are more effective against weak fault current because the threshold is generally set at 1.5 to 1.8 times the nominal current of the transformer. However, for fault current weaker than this threshold, the risk of explosion is still present.
In such cases, and whatever the over-current protection, a pressure or gas relay provides a convenient way to deal with the fault before it can evolve towards higher current values. It is sometimes provided as an extra feature on current solutions.

TABLE I
CURRENT PRACTICE FOR TRANSFORMER PROTECTION

| Fault | Fuse protection | CB with electronic relay |
|---|---|---|
| Low level overcurrent ( i.e. MV or LV winding faults) | Risk of explosion | OK |
| High level overcurrent (i.e. short circuit on the LV switchboard) | OK, but necessary to replace fuses | OK |
| Oil leakage | Destruction of transformer and risk of explosion | Destruction of transformer and risk of explosion |
| Over temperature | No action | No action |

From Table I, which summarizes the current practice for the protection of the substation transformer, it can be concluded that the transformer safety is not perfect.

### Transformer Protection and Switching Objectives

The transformer protection objective is to propose an optimised-cost and small in volume system for integrated transformer protection and switching. This system is going to be able to deal both with internal faults and faults on the secondary terminals. Let us recall that the operating safety requirement of a system implies that the following must be taken into account simultaneously:

- the safety of the system, i.e. its ability to prevent a catastrophic event;
- its reliability, i.e. its probability of not failing over a given time;
- its availability, i.e. its probability of operating at

a given moment.

**Proposed Transformer Protection Technique**

In order to achieve the transformer protection and switching objectives, a system (immersed in the dielectric oil) is proposed, which system is connected to the primary circuit and comprising a high performance switch (HPS) controlled by tripping means and fuses (Fig. 9).
In brief, the philosophy of the proposed transformer protection and switching is as follows: the fuses interrupt high fault current, thanks to current limitation, avoiding any risk of transformer explosion. HPS tripped by an overpressure relay (Fig. 9) interrupts weak fault current without any risk of explosion since the relay interrupts as soon as the pressure of the tank exceeds its normal condition. An oil level sensor trips the HPS before its destruction in case of oil leakage. An over-temperature sensor trips the HPS when the oil exceeds its normal temperature, enables to save the expected life of the transformer. A LV relay coordinated with MV fuses trips the HPS when a fault occurs on the LV switchboard without damaging the MV fuses.

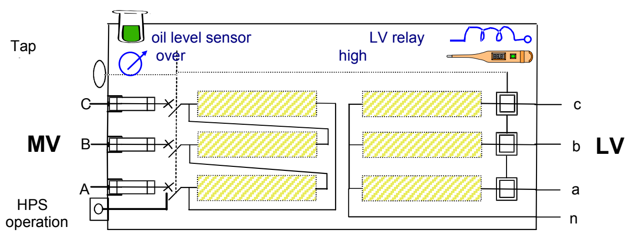


Fig. 9. Principle schema.

Since the HPS is within the transformer tank, tripping by overpressure is very reliable thanks to a mechanical direct connection between the relay and the mechanism.
Concerning interruption of the current, it is dangerous to break the current in transformer oil because making an arc in oil is not advisable and will damage oil quality with a risk to lead to a fault. Therefore it is necessary to make another tight tank within the transformer avoiding interrupting the current in oil. A good solution is to interrupt the current in a vacuum bottle.
In order to keep the possibility to put out of voltage the transformer, it is necessary to have means so as an operator to be able to operate the HPS.
After having total safety for people it is interesting to protect equipment against deterioration, notably the transformer.
An oil level sensor (Fig. 9), which trips the HPS in case of oil leakage, enables to avoid destruction of the transformer and to avoid pollution by oil.
An over-temperature sensor (Fig. 9), which trips the HPS when the oil exceeds normal temperature, enables to save the expected life of the transformer or to avoid its destruction.
When a fault occurs it is interesting to put out of power only the part of the network, which is in fault.
If a fault occurs on the LV network downstream the substation, the LV fuses interrupt the current only on faulty phase of the feeder.
If a fault occurs within the LV fusegear, with traditional solution it is necessary:

- To replace the MV fuse which is located in the fuse-switch combination
- To close CB if there is a protection relay.

With the solution within transformer tank associating MV fuses and HPS, it is proposed to have a system enabling to trip the HPS without damaging the MV fuses, when a fault occurs in the LV switchgear. This system is called LV relay (Fig. 9) and is installed inside the transformer tank close to the LV bushing because it must detect overcurrent on the LV side. The protection curve of the LV relay is totally coordinated with the relevant curve of the MV fuse. This means that the MV fuses will act only if a fault occurs within the transformer tank (in that case the transformer is destroyed and must be changed), so there is no necessity to replace the MV fuses.

TABLE II
PROPOSED SYSTEM FOR TRANSFORMER PROTECTION AND SWITCHING

| Fault | Proposed protection |
|---|---|
| High level MV short circuit | OK (current limitation) |
| Low level MV short circuit | OK (overpressure relay trips; HPS opens) |
| Short circuit on the LV switchboard | OK (LV relay trips; HPS opens) |
| Oil leakage | OK (oil level sensor trips; HPS opens) |
| Over temperature | OK (over temperature sensor trips; HPS opens) |

Table II shows that the proposed technique protects the transformer against all types of faults.

## IV STANDARDS AND TESTS

Conformity to standards is a guarantee of the proposed substation functional aptitudes. The substation has been put through a whole series of tests, in reference to international standards:

- MV network switches : IEC 60298, IEC 265-1
- High performance switch : IEC 60265-1, IEC 62271-100
- Fuses : IEC 60282-1
- Transformer : IEC 60076
- Prefabricated substation : IEC 61330

In addition, several tests have been made to prove the total safety of transformer protection system:

- internal arc in the transformer tank (eliminated by fuses)
- short circuit between MV turns or LV turns (overpressure relay trips HPS)
- oil leakage (oil level sensor trips HPS before any risk of explosion).

During manufacturing, each substation is subject to routine testing, with the aim of checking quality as well as conformity with drawings and diagrams.

In particular, the tests of the protection and switching integrated within the transformer, it should be mentioned that each transformer passes all the tests that are defined by the international standards. Moreover, the vacuum units of the high performance switch undergo pressure measurement based on the proven "magnetron discharge" method. This sophisticated process gives very accurate measurement and does not require access inside of the vacuum unit, thus not affecting sealing.

Regarding the tests of the MV network switches, a meticulous series of tests and measurements is carried out on each unit. The obtained results are recorded and signed by the quality control department on the test certificate of each device. This therefore guarantees traceability.

In case of substation architecture of the bloc type, the testing of the complete substation is allowed and additional tests are carried out, i.e. partial discharge and dielectric withstand. These tests are impossible to be carried out with a traditional substation configuration.

## V CONCLUSIONS

In this paper, a new ultra compact distribution substation is proposed for underground ring networks. This new substation architecture includes two MV network switches, a transformer with integrated protection and a LV fusegear. These three components are connected using factory-built and enhanced-reliability connections. This substation is more economical, safe and simple to install than any other currently existing substation solution.

## REFERENCES


[1] P.S. Georgilakis, N.D. Doulamis, A.D. Doulamis, N.D. Hatziargyriou, and S.D. Kollias, 2001, "A novel iron loss reduction technique for distribution transformers based on a combined genetic algorithm-neural network approach," *IEEE Trans. Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 31, n°. 1, 16-34.

[2] C. Lewiner, 2001, "Business and technology trends in the global utility industries," *IEEE Power Engineering Review*, vol. 21, n°. 12, 7-9.

[3] R.K. Green, 2001,"Twenty-first century utilities," *IEEE Power Engineering Review*, vol. 21, n°o. 12, 4-6 & 12.

[4] R.P. Leeuwerke, A.L. Brayford, A. Robinson, and J.C. Tobias, 2000, "Developments in ring main unit design for improved MV network performance," *Power Engineering Journal*, vol. 14, n°. 6, 270-277.

[5] M. Bidaut, 2000, "MV/LV substations, developments for increased satisfaction of requirements," in *Proc. EMSO 2000 Int. Conf.*

[6] A.P.S. Meliopoulos, J. Kennedy, C.A. Nucci, A. Borghetti, and G. Contaxis, 1998, "Power distribution practices in USA and Europe: impact on power quality," in *Proc. IEEE Int. Conf. Harmonics and Quality of Power*, 24-29.

[7] W.K. Daily and F. Dawalibi, 1994, "Measurements and computations of electromagnetic fields in electric power substations," *IEEE Trans. Power Delivery*, vol. 9, n° 1, 324-333.

[8] M. Sacotte and J. Wild, 1997, "Transformer faults and protection systems," in *Proc. CIRED Int. Conf. and Exposition on Electricity Distribution*, IEE Conf. Publ. N°. 438.

[9] Zhiqian Bo, Geoff Weller, and Tom Lomas, 2000, "A new technique for transformer protection based on transient detection," *IEEE Trans. Power Delivery*, vol. 15, n° 3, 870-875.

[10] M.A. Rahman and B. Jeyasurya, 1998, "A state-of-the-art review of transformer protection algorithms," *IEEE Trans. Power Delivery*, vol. 3, n° 2, 534-544.

[11] M.R. Zaman and M.A. Rahman, 1998, "Experimental testing of the artificial neural network based protection of power transformers," *IEEE Trans. Power Delivery*, vol. 13, n° 2, 510-517.

[12] Mladen Kuzenovic and Yong Guo, 2000, "Modeling and simulation of the power transformer faults and related protective relay behavior," *IEEE Trans. Power Delivery*, vol. 15, n° 1, 44-50.

[13] A. Guzmán, S. Zocholl, G. Benmouyal, and H.J. Altuve, 2001, "A current-based solution for transformer differential protection – Part I: Problem statement," *IEEE Trans. Power Delivery*, vol. 16, n° 4, 485-491.

[14] G.W. Swift et al., 2001, "Adaptive transformer thermal overload protection," *IEEE Trans. Power Delivery*, vol. 16, n° 4, 516-521.

[15] R.W. Blower, D.W. Klaus, and M. Adams, 1990, "Trends in distribution transformer protection," in *Proc. 3rd Int. Conf. on Future Trends in Distribution Switchgear,* 7-11.

[16] G. Bruggemann, J.E. Daalder, R. Heinemeyer, and R.W. Blower, 1991, "Protection contre les defauts dans les transformateurs de distribution MT/BT," in *Proc.* CIRED Int. Conf., paper n° 1.14.

[17] C. Raux, C.-J. Leconte, and T. Gibert, 1989, "Resistance of transformers to internal faults: synthesis of experimental results," in *Proc. CIRED Int. Conf. on Electricity Distribution*, vol. 1, paper n° 1.77, 71-75.

[18] S.D. Kaminaris, A.V. Machias, and B.C. Papadias, 1991, "An intelligent tool for distribution substations troubleshooting and maintenance scheduling," *IEEE Trans. Power Delivery*, vol. 6, n° 3, 1038-1044.

[19] Wen-Hui Chen, Chih-Wen Liu, and Men-Shen Tsai, 2000, "On-line fault diagnosis of distribution substations using hybrid cause-effect network and fuzzy rule-based method," *IEEE Trans. Power Delivery*, vol. 15, n° 2, 710-717.