Design of an ultra compact distribution substation

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Abstract: This paper presents a new architecture of distribution substation allowing reducing 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 new types of medium voltage (MV) and low voltage (LV) connections, and a transformer with integrated protection and switching.

1. 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, reliability, and remote control.

The equipment of a ground-mounted distribution substation includes one distribution transformer directly connected to the MV network or 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.

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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 find 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.

The proposed substation allows cost reduction for utilities, offers more safety for people and property, and includes a new device for remote monitoring and control. This substation is designed for underground ring networks. The substation is designed for power up to 630 kVA and for MV network voltage up to 22 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.

This new architecture also brings other advantages, such as safer transformer due to the integrated protection and switching, reliability improvement and reduction of electromagnetic radiation.

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 2 gives details on substation compactness, Section 3 describes the substation safety and Section 4 presents the architecture of the substation monitoring and control system. Finally, Section 5 concludes the paper.

2. COMPACTNESS

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

2.1 Current Situation

The indicator of the substation compactness is its footprint. 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 the kiosk.

Today substations require about 1 m of free space for door access. 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 big since it consists of two switches and one fuse-switch. Moreover, due to their large curve 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).

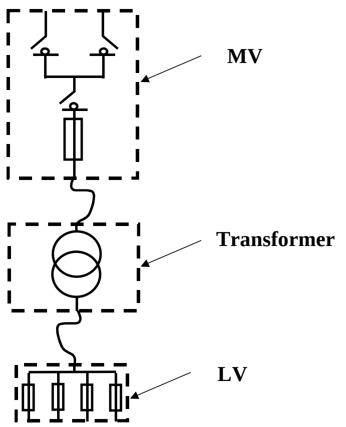

Fig. 1: Typical substation design.

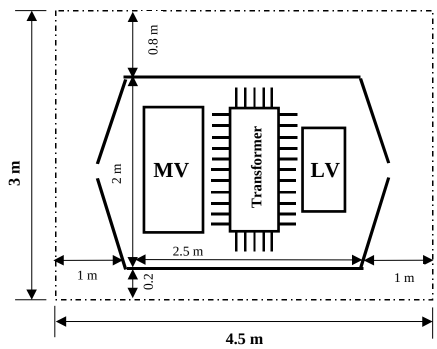

Fig. 2: Footprint of a typical 630 kVA substation.

2.2 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).

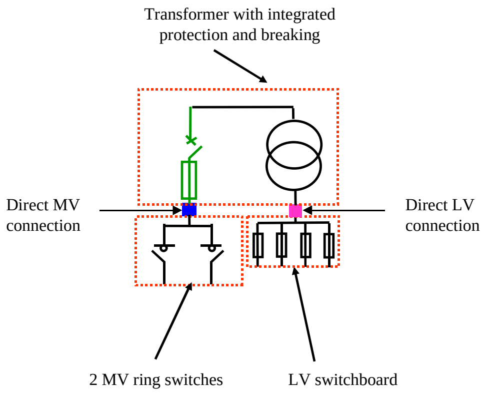

Fig. 3: Proposed substation design.

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 (Fig. 4). For example, one 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).

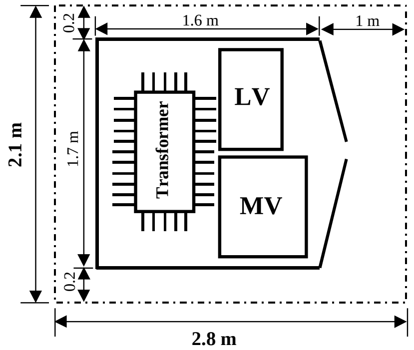

Fig. 4: Footprint of the proposed 630 kVA substation.

2.3 MV Network Switches

MV network switches comprise 2 integrated, compact functional units. This integrally insulated self-contained assembly comprises (a) a sealed for life stainless steel enclosure that includes the active parts, the disconnector and the earthing switch, (b) two cable compartments for the MV network connection, (c) one LV compartment, and (d) 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 position 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 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.

2.4 MV Connection System

A direct factory-built MV connection between the MV switchgear and the transformer enables to put 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 set.

In case of factory-installed, the MV connection (called block type MV connection) comprises three bi-conical sleeves made from over-moulded elastomer on copper braids. These assemblies provide the electrical connection between the MV network switch and the transformer. A mechanical positioning system ensures perfect position with each of the bushings.

In case of on-site-installed, the MV connection (called kit type MV connection) comprises three 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.

2.5 LV Connection System

The connection of the transformer and the LV fusegear is achieved using a factory-built direct LV connection. This connection comprises a single component fixed with two bolts.

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

3. 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 [1]. Avoiding damage to distribution transformers is vital, otherwise continuity in power system delivery may be seriously disrupted. Furthermore, repair or replacement is expensive and time-consuming [2]. Consequently, it should not come as a surprise that transformer protection forms a subject of a permanent research effort [1-7].

In the distribution substation, the faults downstream the substation (LV network) are eliminated by the LV fuses and they don't include any risk concerning safety. Internal arc test in MV switchgear enables to assure safety in case of fault in this equipment.

On the other hand, in the substation transformer, current protection solutions are not able to assure total safety. Two types of solutions are currently used:

- MV fuses with strikers that are tripping the transformer switch
- Current relay that is tripping the transformer circuit breaker.

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 interrupt currents only 8 times higher than the nominal current of the transformer, or with strikers that are tripping the transformer switch it can be interrupted by the switch a current that is 5 times higher than the transformer nominal current. As a result, in case of weak fault current, the transformer tank can be exploded 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. Moreover, for high fault current, the time necessary to interrupt this fault is approximately 80 ms, so there is a risk of explosion of the transformer tank.

From the first 3 columns of Table 1, which summarize the current practice for the protection of the substation transformer, it can be concluded that the transformer safety is not satisfactory.

Table 1: Current Protection Practice

Fault	Fuse protection	Circuit breaker protection
High level MV short circuit	OK	Risk of explosion
Low level MV short circuit	Risk of explosion	OK
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

3.1 Transformer Protection Objectives

The objective of this paper is to propose a low-cost and small in volume device for integrated transformer protection. This device 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.

3.2 Proposed Transformer Protection Technique

In order to achieve the transformer protection objectives, a protection device (immersed in the dielectric oil) is proposed, which device is connected to the primary circuit and comprising a circuit breaker controlled by tripping means and fuses (Fig. 5). The fuses are arranged between a bushing of the tank and the CB. The fuses, CB and tripping means are associated in such a way that under conditions corresponding to a short-circuit at the terminals of the secondary circuit, the CB contact means separate and interrupt the current without the fuse starting to melt, and that there exists a threshold value of the current intensity flowing in the fuse, lower than the breaking capacity of the corresponding pole of the CB and above which melting of the fuse has taken place before a separation order of the contact means given by the tripping means has been able to cause separation of the contacts.

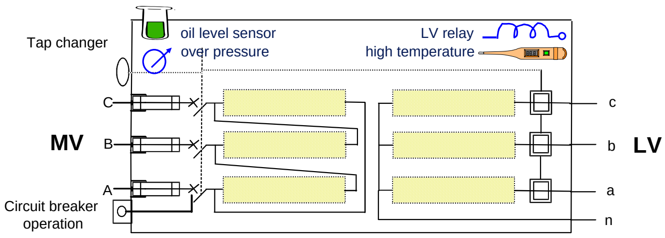

Fig. 5: Principle schema.

Fuses interrupt high fault current avoiding any risk of explosion.

Circuit breaker tripped by an overpressure relay (Fig. 5) interrupts weak fault current without any risk of explosion since the relay interrupt the current as soon as the pressure of the tank exceeds its normal condition.

Since the circuit breaker 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 (Fig. 6).

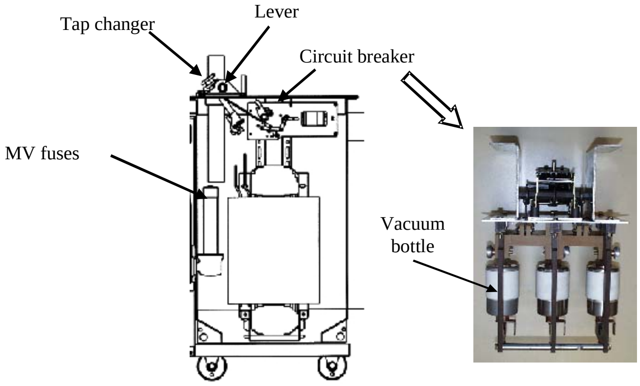

Fig. 6: Practical realization.

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 manoeuvre the circuit breaker.

After having total safety for people it is interesting to protect equipment against deterioration, notably the transformer.

An oil level sensor (Fig. 5), which trips the circuit breaker in case of oil leakage, enables to avoid destruction of the transformer or to avoid pollution by oil.

An over-temperature sensor (Fig. 5), which trips the circuit breaker 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 change MV fuse with fuse-switch combination
- To close circuit breaker if there is an MV relay.

With the solution within transformer tank associating MV fuses and circuit breaker tripped by overpressure relay, it is proposed to have a system enabling to trip the circuit breaker without damaging the MV fuses, when a fault occurs in the LV switchgear. This system is called LV relay (Fig. 5) and is installed inside the transformer tank close to the LV bushing because it must detect overcurrent on the LV side. With this LV relay, it is not useful to be able to change MV fuses since they act only if a fault occurs within the transformer tank (in that case, the transformer is destroyed and must be changed).

The fourth column of Table 2 shows that the proposed technique protects the transformer against all types of faults.

Table 2: Proposed Protection

Fault	**Proposed protection**
High level MV short circuit	OK (fuses blow up)
Low level MV short circuit	OK (overpressure relay trips; CB opens)
Short circuit on the LV switchboard	OK (LV relay trips; CB opens)
Oil leakage	OK (oil level sensor trips; CB opens)
Over temperature	OK (over temperature sensor trips; CB opens)

4. REMOTENESS

In today's deregulated marketplace, simply delivering power to customers is no longer sufficient; utilities must deliver the commodity safely, reliably, and cost-effectively. Moreover, information traditionally used only within a given utility now becomes desired by many players [1]. Exponential advances in hardware, software, and communication equipment allow the transportation, storing, and manipulation of vast quantities of data at blinding speed relative to just a few years ago [2]. As a result, utilities have shifted their focus to information technology and automation to optimize operations and improve the bottom line [3-5].

This paper presents an architecture and a communication system dedicated to substation remote monitoring and control.

4.1 Hardware Architecture

The system comprises a device (called W200 enclosure in the sequel) in each distribution substation and a WEB server situated on the user's Intranet which concentrates information access. The WEB server and the enclosures are linked via the GSM network. The server has a telephone modem. This architecture (first phase) allows access to data in the client Intranet. Moreover, a second phase involves placing the server on the Internet. The aim is to provide data access for different correspondents and to enhance the service provision. The architecture for the second phase will be similar to that of the first phase, however the server will be hosted by a service provider and must integrate data access security.

The W200 enclosure (depicted in Fig. 5) is situated in the LV enclosure of the distribution substation (S/S).

The WEB server is a personal computer (PC) or an equivalent tool of the market. It is exclusively used as a data concentrator, so a PC without screen and a keyboard may be sufficient. The server is connected to the Intranet network via a standard Ethernet link. It communicates with the enclosures via a telephone socket. The maximum number of W200 enclosures used with a single server is 8000.

The system, thanks to new web and GSM technologies that are becoming less and less expensive, makes possible to:
- have access to pertinent information from anywhere, via communications standards (GSM, web browser)
- propose a delocalized maintenance service to utilities or infrastructures (asset management)
- provide utilities with information about measurements, energy quality [6] and substation equipment characteristics.

From his/her PC, the user can access information using a simple navigator. If an alarm occurs, the user receives an e-mail. Fig. 7 presents the whole communication system.

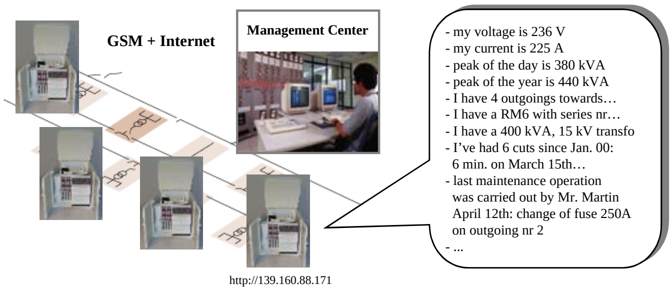

Fig. 7: Communication system.

In remote mode, the information is displayed via a WEB Browser. A WEB server is therefore placed in the user's network (Intranet or possibly Internet). For each substation, it is possible to display the following pages:
- Substation information page (e.g. physical location of substation, type of equipment, maintenance operations, etc)
- Substation status page (the status of the substation on the date of the last telephone connection with the substation)
- Event history page (any change of status of one of the digital inputs, and any exceeding of thresholds)
- File loading page (to download files contained in the enclosure to the PC, using FTP)
- Configuration page (to configure the W200 enclosure).

In local mode, a connector providing a link to a laptop PC is sufficient and the local display is the same as the remote one.

4.2 Architecture Evaluation

The proposed architecture, dedicated to substation remote monitoring and control, has the following advantages:
- optimizes transformer maintenance and change operations (the situations where the transformer is overloaded are known, so premature aging can be avoided)

- facilitates substation maintenance operations and manages the equipment inventory without site visits
- optimizes intervention time (the cause of the problem and its location are known; the relay dates and records service cuts so as to quantify their number and duration)
- offers the possibility to connect inputs-outputs for remote alarms adapted to client needs: fault indicator, door sensor, etc
- besides traditional distribution substation control methods, it provides the operator (in a simple and economical manner) with all the information concerning the installations on his network (substation equipment, installation status, load curves, etc.) and in this way it notably contributes in the improvement of the quality of service.

The proposed architecture has the following advantages compared with an architecture where a server is integrated into the enclosure:

- rapid connection: data access is faster with an intermediate server because the pages have been saved. In addition, the server takes care of the telephone connection.
- no security problems: access is secured by the client's Intranet.
- simpler configuration: configuration of parameters common to all enclosures is undertaken by the server in a transparent manner (i.e. the e-mail configured to receive alarms does not have to be updated in each W200 enclosure).

5. 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 simpler, more economical, and safer than other currently existing substation solutions.

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