1. INTRODUCTION

A mobile substation is a fully equipped electrical substation that can be easily moved due to the fact that it is completely mounted on a semi-trailer. The design and installation of a mobile substation have specific restrictions, which are not present when dealing with conventional substations: restrictions due to transport such as dimension and weight of the trailer, road regulations, electric clearances in particular for equipment higher than 100 kV, the need for a quick installation in places with no lifting equipment available and finally the specific problems of connection and integration of the substation to the existing network. All these constraints make the manufacturer of mobile substations face a much more complex task than just placing the equipment of a normal transformer bay on a semi-trailer.

This paper intends to review some of the most relevant technical considerations regarding mobile substations and to present the practical approach to deal with them at the design stage.

2. DESCRIPTION AND APPLICATION OF MOBILE SUBSTATIONS

Mobile substations can be defined as completely equipped electrical substations. The following sections can always be distinguished: HV equipment, Power transformer, MV equipment and Control, metering & protection equipment. All this equipment is mounted on a semi-trailer, factory pre-tested and ready for use. Mobile substations are designed to allow rapid integration in different places in the network (Figure 1)
In practice the maximum voltage is generally limited up to 245kV (with a full BIL) because of increasing dimensions: phase-to-phase distance, phase-to-earth distance and the length of the bushings. A more compact design can be achieved by reducing the BIL level (IEC guide 71) or in certain cases by using gas insulated switchgear for voltages of 245kV. The rated power is generally limited because of the weight. A power transformer of 50MVA with a conventional design will usually already imply an unacceptable weight. Using hybrid insulation for the power transformer will bring the maximum well beyond this limit while improving the mobility and manoeuvrability of the mobile unit [1].

Mobile substations can minimize the duration of unexpected power outages. The equipment can bypass a complete substation or a part thereof following failure of any major equipment in the substation due to: equipment failure, weather related system problem, natural disaster or other external influences.

This equipment can also assure service during programmed works by bypassing a complete substation or a part thereof allowing: maintenance operations, repair works, expanding or changing the substation configuration.

Mobile substations can also temporarily increase or provide capacity while permanent substations are being build. They can handle seasonal peaks due to air conditionings, increased electricity consumption in tourist areas, as well as temporary peaks due to large events such as carnivals and major sports events.

Other applications of mobile substations include their operation as standby unit for power transformers that are operating near or above their rated output, providing redundancy for critical customers (N-1 criterion). The units can also serve as electrical power source in isolated areas and are used in oil & gas exploration, irrigation and mining industry. Mobile substations are used as back-up unit in countries exposed to natural disasters or war. In cold areas they are used as power source for de-icing of MV lines.

Utilities around the world are using mobile substations to reduce downtime with associated revenue loss and fines. It is generally accepted that mobile units can reduce overall capital costs as well as system maintenance cost. Mobile substations can increase flexibility in scheduling maintenance or repairs, improve operational flexibility of the network and consequently increase reliability of power supply.

![Figure 1. Mobile Substation in service](image-url)
3. MOBILE SUBSTATION ARCHITECTURE

From an electrical point of view there is little difference between a mobile substation and a transformer bay in a fixed substation. In the mechanical lay out and the choice of equipment however there are essential differences due to the limitations in the dimensions and weight of the trailer and to the manoeuvrability of the unit.

The limitations on the dimensions and weight of the trailer will be given by the specific road and vehicle regulations in each country. Those will determine the maximum height, width and length of the trailer which may vary from country to country between 2.6 and 3.5 m width, 4.4 and 4.8 m height and 14 to 25 m length.

The maximum weight depends on the type of trailer. In practice the maximum road pressure on the axles and the maximum load on the kingpin (coupling between semi-trailer and tractor) are defined. This can be estimated by a simple static calculation. Typical values of pressure on the axles go from 8 to 12 tons depending on countries and it can be doubled if using double axles.

The load on the kingpin depends on the type of tractor used to move the mobile substation. Assuming a tractor with three 12 tons axles and taking into account that the own weight of the tractor is divided in 6 tons on the front axles and 2 tons on the rear axles about 22 tons remains as possible load on the kingpin.

A way to increase the admissible weight on the trailer is increasing the number of axles. Trailers with more than 3 axles should have additional hydraulic steerable axles. To increase the load on the kingpin extra axles on the gooseneck by means of a dolly can be used. This will of course increase the length and the price of the trailer.

Once the transport restrictions and the specifications to fulfil by the equipment of the substation as maximum voltage and power are known, the designer must consider the space and weight distribution limitations to allocate all the substation components following the electric single-line diagram required. The designer must keep as well the electric clearances as the accessibility to the different components in mind.

As the heaviest element of the mobile substation, the relative position of the transformer to the axles and kingpin will basically determine the weight distribution of the trailer. This is the first element to consider in the design. It is not difficult to calculate the optimum position of the transformer that can fulfil the weight distribution limitations and optimise the length of the semi-trailer and the number of axles. However this position has to be compromised with the space available for the other components as switchgear, cables, control and protection panels etc. It is important as well to consider the limitation to pass cables through certain surfaces of the trailer such as the gooseneck or the axles. Then, at the end the designer has to try many different arrangements and consult continuously with the manufacturer of the equipment and the trailer until finding the optimum lay out which fulfils all transport and substation requirements with the most economical trailer design. This makes of every mobile substation a unique design.

The width limitation of the trailer imposes serious technical constraints to the high voltage part of the mobile substation. This is due to the minimum air clearances to keep between live and earthed parts. The mobile substation must guarantee the same insulating distances as indicated in the relevant standards and taking into account the maximum height where the substation may be placed. For instance a maximum width of 3.2 m would limit the HV equipment to a maximum BIL of 450 kV. For a BIL of 900kV an overall width of the trailer of 6.2 m would be necessary. It is impossible of course to manoeuvre a trailer of such width.

This problem can be overcome by the use of rack-out mechanisms for the supports of the HV switchgear, arresters, measuring transformers and insulators. Those structures are retractable while transporting the mobile substation and moved out to put the substation in service.
The design of support structures in the conventional substation being something that can easily be normalised, the support structures of the equipment of the mobile substation will have to be designed individually for each case. Many designs of rack-outs have been used and several patents exist. In figure 2 can be seen some examples.

Figure 2. Example of extensible mechanisms used to transport HV equipment with insulation clearances exceeding the limits of the trailer: dead tank breaker in service (a1) and transport position (a2), extensible horizontal support with rollers for circuit-switchers (b1,b2), portable gantry folded (c1) and rotating arm for support insulators in transport position (d1)
When designing such mechanisms it is important to bear in mind:

- Guaranteeing an easy extension of the structure to place the equipment into service position in short time and without the need of any lifting equipment.

- The same has to be applied for the operation of retracting the structures for transport when taking the unit to storage or to another location after having been for years in service position.

- Mechanical stresses during transport which can damage the structures or loose the connections. The relative movements of the different parts that are needed for the extension-retraction operation have to be properly blocked during transport to avoid vibrations.

- Guaranteeing the mechanical integrity during service conditions. The mechanical stresses in service considered for the design of those structures are the same as for supports in conventional substations such as:
  
  o Normal loads: dead load, tension load (for supports with flexible conductors), erection load, wind and ice if applicable.
  
  o Exceptional loads: Switching forces in circuit breakers supports (those are commonly the most important stresses for those mobile extensible structures), Short-circuit forces (maximum possible value of short-circuit for the possible locations has to be considered), loss of conductor and seismic load (again considering worse position

Another way to guarantee the insulation clearances is to mount the equipment on the trailer in a triangle. In the case of life-tank circuit breakers this special mounting has as consequence that the mechanical link between the poles is impossible. Hence, in these cases, the use of a single pole operated breaker mechanism is required.

In the case that this type of breaker cannot be employed or if a dead-tank breaker is used, installing the circuit breaker on a rotating platform over the trailer as in figure 2a is a solution for keeping the pole alignment during transport and service.

For voltages higher than 170 kV the GIS option may become acceptable and the advantages on higher compactness and manoeuvrability of the mobile substation may compensate for the serious difference of cost in the HV switchgear.

By using GIS technology it is possible to design 230 kV mobile substations on trailers of 2.5 m width. To simplify the high voltage dielectric test to check the GIS integrity, the voltage transformer of the same GIS (considering that a mobile GIS will have normally a low capacitive load: about 1 nF) can eventually be used.

The transformer cannot benefit of using extractable parts. A special transformer design for each mobile substation is necessary. There are different ways to reduce the dimension and weights of the transformer as reducing the BIL, using aluminium tanks, ODAF cooling and allowing higher winding temperatures thanks to the hybrid insulation application [1].
4. MOBILE SUBSTATION INSTALLATION

4.1 Planning of accessibility of the mobile substation and connection to the grid:

Prior to installing the substation a careful planning has to be done regarding the accessibility and the manoeuvrability of the mobile substation in its new sites. The length and type of the trailer (number of steering or follower axles etc) has to be considered. To accommodate the installation adequate space has to be available to manoeuvre and connect the mobile. This is especially important if the mobile will be integrated in an existing substation. Insulation clearances have to be checked and adequate fencing has to be provided. It is important to consider that for mobile substations there are cases where it is not possible to place the live equipment at a safety height from personnel and then those areas must have restricted access by proper fencing. It may be impossible to use larger units in some locations without substantial modifications because the lack of sufficient space.

Figure 3 shows a plan of access of a mobile substation consisting of 2 trailers to be installed in an existing substation.

The connection of the mobile substation to networks 66 kV or higher is generally done by overhead lines, for lower voltages both cable and overhead lines are commonly used. Cable drums can be transported on the trailer. The overhead connections from the support insulators to the HV lines have to be made as short as possible due to the increase of the sagging and tensions with the connection distance. If it is not possible to guarantee the insulation distances or a long connection may produce too high stress on the support insulators, a folding portable gantry can be placed on the trailer as it appears in Figure 2c.
4.2 Grounding of the mobile substation

Above ground earthing:

The transformer and switchgear equipment on the trailer are grounded by a copper conductor of adequate size. The dimension of this conductor has to be able to carry the highest earth-fault current in the possible mobile substation locations. Each of the earthing leads from the equipment (except the Surge arresters and the transformer neutral which had a direct connection to the earth grid) are collected in a grounding copper bar that runs all along the trailer on one of the longitudinal beams.

Below ground earthing:

If the mobile substation is placed in an existing substation, the existing earth grid will be used for the mobile substation with a minimum of 2 connections to the general grounding bar on the trailer. If the mobile substation is placed close to an existing substation, the existing earth grid will be used as well. A new earthing mesh will be built below the mobile site and connected to the existing grid. The connection of both grids will reduce the earthing resistance. Figure 4 presents a good example of this interconnection. In the mobile substation site of the Figure 3 a new earthing grid has been built. The calculation of the new touch voltages represented in colours shows that same touch voltage protection levels as in the existing substations are guaranteed in the mobile. If the mobile substation is placed not near an existing earthing grid, several methods to provide a safe step and touching voltages for the personnel are possible. First of all it is important to have an estimation of the soil resistivity in the chosen site. A copper loop around the mobile substation at the soil surface fixed by earth rods can already make a big difference [2]. A temporary solution can be a portable ground mat installed on the soil surface on the areas where personnel need to access.

Figure 4. Results of calculation of touch voltages distribution on the grounding of the existing substation (figure 3) and the new grounding built for the mobile substation.
4.3 Lightning and Surge protection:

In general the probabilities of direct lightning strokes to mobile substations are lower than for permanent substations. This is due to the generally shorter working period of time of the mobile substations, its smaller footprint and low profile [2]. However in areas of high keraunic activity or long duration it is prudent to provide direct stroke shielding for the installation. A solution as shown in figure 5, is the use of lightweight electrical-grade aluminium masts that can be transported on the trailer and erected, bracketed to the trailer structures during service.

For surge protection conventional metal oxide arrester are used. Care must be taken when selecting the arrester rating trying to achieve the maximum protection coverage considering the different possible voltages and neutral earthing in all the applications. In cases of big voltage differences from one to another application arresters with several voltage taps are used.

5. SUMMARY

The experience with hundreds of mobile substations built in the last 20 years has been positive and brought the expected benefits with respect to reduction of down time, capital and maintenance costs and increase of flexibility and reliability of the power networks.

The specific characteristics and application of mobile substations makes them unique designs where a combination of technical restrictions has to be resolved case by case.

6. REFERENCES