

Design aspects of medium voltage capacitor banks

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Abstract—Reactive power compensation is commonly used to increase network capacity, extend plant life, reduce and delay capital expenditure, provide voltage support and improve power quality.

Designing medium voltage capacitor banks balances the potentially conflicting requirements of minimised cost, long life, infrequent maintenance, ease of operation and fitness for purpose.

This article describes an approach that provides such a balance in the context of mobile, outdoor enclosed capacitor banks for medium voltage networks. The approach acknowledges the complex interaction between environmental demands, electrical design and mechanical constraints.

Acknowledging the realities of site conditions and field operations and adhering to established design requirements for all components result in durable, reliable equipment that provide the necessary functional performance while reducing the lifetime cost of equipment. Site conditions include the actual climatic and atmospheric conditions such as tropical temperatures, dust and humidity and field operations include operators that expect robust, simple operation and easy access for maintenance purposes.

The outcome of the design approach is a novel but sensible solution that is easy to transport and install and is based on readily available core components that will guarantee a long service life.

I. BACKGROUND

How are enclosed capacitor banks procured? The end user has a requirement for a solution that requires a combination of engineering, commercial and project requirements. For example, a solution that must be delivered within a certain time frame, will fit into a specific available footprint on site, and must satisfy cost/performance measurements that will ensure it is feasible.

The ideal cycle proceeds as shown in figure 1.

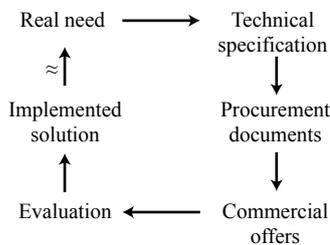


Fig. 1. The ideal project procurement cycle

A need for compensation is identified on a project. The technical performance requirements are captured accurately and concisely by the responsible engineer, and the procurement department combines these requirements with the commercial and other project expectations into a tender document. Suppliers review the requirements, and offer exactly what has been specified, with a limited number of clearly identified deviations from the tender documents. An unbiased, analytical evaluation is performed and the successful supplier delivers a solution that nearly exactly matches the original requirements. Operations and maintenance staff have no problems with the equipment for the expected life of the project.

Actual life is somewhat different, as shown in figure 2. The real need may not be understood or identified clearly. The engineer may have specific preferences for an outcome, or may pre-empt and therefore try to compensate for deficiencies in suppliers' offers. The

technical specification therefore may not capture the actual needs. Procurement typically create tender packages to ensure all equipment on a project are aligned with the project requirement, and adds volumes of requirements to the technical specification that may or may not be relevant to the real needs. Suppliers have their own baggage, and prefer to offer something they have already developed. Suppliers with some experience will understand that there has been some communication loss between the real needs and the tender package, and may offer what they believe to be the real needs. Given the sometimes vast package of tender documents, listed deviations from the specification may be restricted to what is thought to be key areas. Evaluation is often influenced by incorrect assumptions of the true cost of offers, preferences for suppliers based on previous experience, or emphasis is placed on aspects that are not key to the real needs. The result is an implementation that may not match project expectations, is not reliable or cannot be operated or maintained with ease.

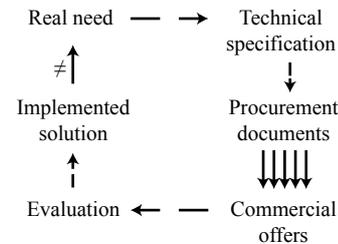


Fig. 2. Real world project procurement cycle

These complications take place across several departments and business entities, and cannot be resolved by any single party. The intention in this note is to illustrate one supplier's specific approach to the design of enclosed capacitor banks and how this addresses the key needs of projects.

II. REAL NEEDS

Each project or application may have slightly different requirements and some aspects may be more important than others. We believe the following are the most important needs for enclosed capacitor banks:

- 1) Do the job:
 - a) Deliver reactive power in an environment or situation where outdoor or indoor open type equipment is not desirable or practical. Enclosed solutions are required in case where the physical environment may not suit open type solutions, or where there is a need for rapid deployment with minimal site work, or where space constraints make open type solutions impractical.
 - b) Control the amount of reactive power delivered on the basis of network conditions such as power factor, harmonic levels, or any number of other factors such as voltage level, load level and operator instructions.
- 2) Do it safely:

- a) Ensure installers, operators, and maintenance personnel are not placed at any risk when working on or near the equipment.
 - b) Protect the equipment itself against internal failures and external network events.
- 3) Endure the environment:
- a) Operate continuously under the worst case ambient conditions in terms of temperature, solar radiation, wind and seismic loading and atmospheric pollution.
 - b) Withstand electrical conditions that may exist continuously or for short durations according to the local network code.
 - c) Facilitate storage conditions that may be more extreme than continuous operating conditions.
 - d) Withstand mechanical stresses that may occur during transport.
- 4) Be easy to use:
- a) Present a simple operator interface that makes working easier on site.
 - b) Provide flexible controls based on internal, local grid and remote conditions.
- 5) Be easy to maintain:
- a) Extend the time between maintenance periods as much as possible.
 - b) When work needs to be done on the equipment, provide easy access.
 - c) Standardise replacement parts as much as possible to reduce maintenance spares.
 - d) Plan the complete equipment life cycle from manufacturing to removing from service.

These topics will be discussed and our approach to each will be explained in more detail below.

III. FUNCTIONAL REQUIREMENTS

There are many reasons for installing reactive power compensation such as increasing power transfer capability, reducing upstream losses, connection agreement requirements for power factor and voltage support in steady state or for short periods. All of these are possibly in conjunction with a requirement for reducing or at least not increasing harmonic distortion in the network.

A. Enclosed, outdoor

Reactive power solutions can be designed for indoor or outdoor use, inside enclosures or open type. At medium voltage levels, there are often functional features that force solutions to be designed for enclosed, outdoor application. Examples of such features are:

- 1) Lack of space inside existing or planned switch-rooms,
- 2) Physical environment that makes open type equipment non-viable, for example corrosive or conductive dust, or vermin that cannot practically be kept from open type equipment,
- 3) Need for multiple switched steps in a compact footprint,
- 4) Possible relocation of equipment during the project lifetime,
- 5) Civil construction complications apart from limited footprint, such as poor soil conditions, sloping land, or buried rock, and
- 6) Other environmental factors such as visual appeal or permitted noise levels.

These are common and valid reasons for choosing outdoor enclosed capacitor banks. It must be clearly understood: outdoor enclosed capacitor banks are in general more expensive than open type or indoor enclosed solutions. End users should carefully consider in the light of the above features whether there really is a need for outdoor enclosed banks and what the key requirements are.

B. Basic ratings

Reactive power compensation and harmonic filters have a basic function: delivery of a certain amount of reactive power to the network. The total amount of compensation and number of steps have a direct impact on cost and functionality. Correct selection is quite straightforward and worth considering carefully. Typically, a recording of existing load, projections of future load, knowledge of actual loads, or a combination of all these are used to determine the time-varying loads (active, reactive and apparent power).

An example is shown in figure 3 where only the apparent power and reactive power (in MVA and Mvar respectively) for more than a week of operation is shown. The graph also shows the result of applying power factor correction: reactive power is managed and the apparent power is reduced.

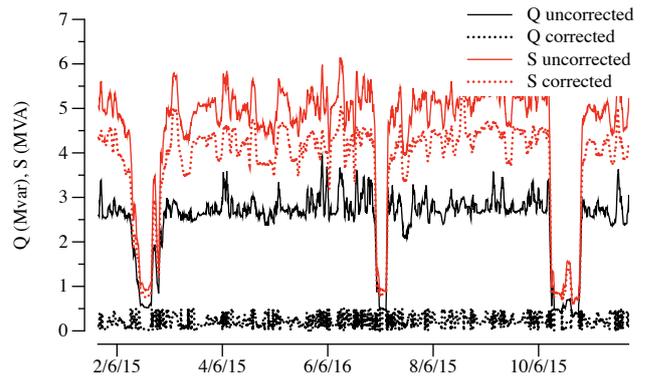


Fig. 3. Corrected and uncorrected reactive and apparent power

This preliminary simulation of how the capacitor bank will react to actual load variations is vital in determining the overall amount of reactive power and the number and size of steps. Careful selection of step sizes and control algorithm make it possible in almost all cases to use three steps or less, while minimising the number of switching operations. Knowing how many switching operations can be expected during the planning stage is very useful in reviewing performance once the equipment is installed.

A compact and powerful presentation of the impact of power factor correction is shown in figure 4. The relationship between apparent power and power factor for the uncompensated and compensated cases are shown, with a clear indication of the resulting reduction in demand.

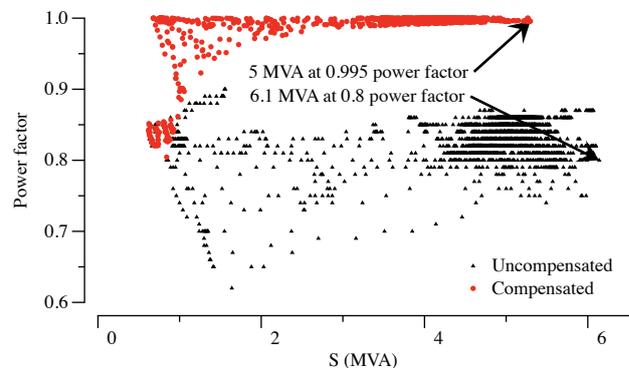


Fig. 4. Compensated and uncompensated apparent power and power factor

Note that in this case, even with apparent power varying between 0.6 MVA and 6.1 MVA, only three steps of power factor correction

of 3.5 Mvar in total is required to limit reactive power to less than 0.5 Mvar.

C. Avoiding harmonic concerns

Once the basic ratings and configuration of the compensating equipment are known, attention can turn to another crucial design requirement: avoiding or managing the impact of harmonic distortion. Capacitors are unique among electrical equipment as deploying them in the network changes the network behaviour fundamentally by causing parallel or series resonance between the capacitance and a typical inductive network impedance.

The effects of harmonic distortion cannot be discussed in sufficient detail here and the reader is referred to some additional information in section IX. The topic can be summarised as follows:

Capacitor banks (and especially where there is more than one step connected in parallel) are often supplied with series reactors. These reactors have the effect of reducing the peak amplitude and frequency of switching transient to ensure that capacitors and associated switchgear can cope with switching events. Such reactors are referred to as damping reactors. These reactors are typically air core, light, are relatively compact and have low losses. Damping reactors are therefore somewhat easier to incorporate into an enclosed capacitor bank design.

Damping reactors, however, do not address the potentially destructive impact of harmonic amplification, and specifying banks with such reactors is a false economy. Unless detailed harmonic impact studies have been done and it is clear that there will be no significant non-linear load in the network and that network conditions will never change, it is highly recommend to specify so-called detuning reactors with each step.

Detuning reactors ensure that no harmonic resonance can occur when the steps are connected. Use of the reactors normally results in somewhat reduced harmonic distortion levels in the network, and they also limit the impact of switching transients. In enclosed applications the reactors are normally dry type, iron core devices and are therefore relatively heavy, with greater losses than damping reactors. These drawbacks are compensated by good design and product selection, and will almost always result in a more robust, safer and reliable solution.

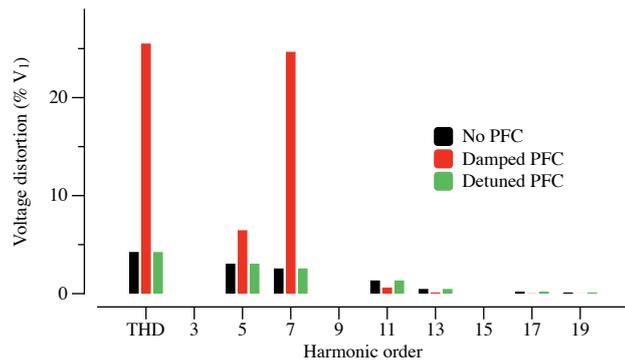


Fig. 5. Harmonic spectra with no, damped and detuned PFC

Figure 5 illustrates the high and potentially destructive voltage distortion that may occur when capacitor banks are used with no reactors or damping reactors. In this case, amplification of the seventh harmonic occurs to the extent that any equipment connected to that busbar is likely to fail or malfunction. A detuned bank with the same reactive power output, however, results in a slight reduction of harmonic distortion.

This simple example amply illustrates the merits of a design approach that includes detuning reactors in all applications.

At this stage, the size and number of steps are known, and the detuning reactor has been selected. It is now possible to calculate the electrical ratings of the equipment in the context of applicable standards and the electrical environment. This topic is covered in detail in the further reading. In summary:

- The capacitor bank is to be rated to withstand the continuous voltage stress resulting from fundamental frequency over voltage, harmonic distortion and the voltage rise effect of the series reactor.
- The reactor must be rated to withstand the current spectrum that it will be subjected to, including all harmonic currents. Notably the losses, including those arising from harmonic current, must be accounted for.

From an electrical design perspective, these two parameters (voltage rating of capacitor units and current rating of reactor) are the most important and most commonly incorrect ratings in the entire application.

IV. SAFETY

Safe operation of equipment entails a number of topics such as the protection of the individual steps against failures in the equipment itself, protecting the capacitor bank as a whole against internal or external failure, protection of operators against exposure to potentially lethal voltages, and interfacing with site-specific safety requirements.

A. Protection of each step

Each step of the capacitor bank needs to be protected. The extent and type of protection will depend on what is practical and the risk of any failure to detect faults.

It is best practice to implement sensitive unbalance protection at all times to detect failed elements and prevent case rupture. In most applications it is preferable to arrange the step in an ungrounded double star configuration. This allows cost-effective sensitive unbalance current protection, and blocks zero sequence currents through the step.

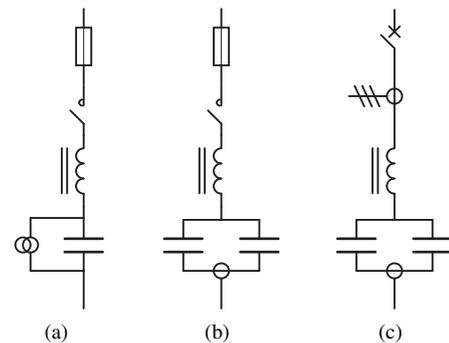


Fig. 6. Three options for protection of capacitor steps

There is a lower limit on the reactive power rating of capacitor units that will provide reliable internal fuse operation. In such cases, a scheme as shown in figure 6(a) is used. Voltage transformers are connected across each phase and the resulting unbalance voltage is used in a special relay that can detect individual fuse operation. This scheme provides the additional benefit that capacitor units can be discharged very rapidly after de-energisation. The voltage transformers must be designed to cope with the relatively high energy dissipation that occurs when the bank is discharging.

The common current unbalance scheme is shown in figure 6(b). In this scheme, a special relay is used for detecting small changes in the neutral point current.

Short circuit protection is normally provided by suitably rated fuses on the line side of each step. These fuses protect the contactor and remainder of the step against internal faults, and make it possible to use contactors that are not able to withstand system fault currents to switch the capacitor steps.

Where banks are too large to be switched by means of contactors, a circuit breaker can be used control the step. In such cases it is necessary to include line side current transformers to detect faults, as shown in figure 6(c). There are advantages to such line side current transformers: more sophisticated protection can be provided in the form of thermal protection of the detuning reactor, voltage protection of the step capacitors, line side unbalance, over- and under current, as well as the required sensitive star point unbalance protection.

B. Protection of the complete system

The primary interface to the external network takes place in the high voltage section of the enclosed bank. Here access is provided to terminate the incoming cable from the upstream network and functional integration with the necessary protection functions and safety interlocks are provided.

As shown in figure 7 this section can contain a number of components determined by the end user requirements and existing equipment. For example, the upstream feeder may contain a circuit breaker and then it may not be necessary to incorporate a breaker in this section.

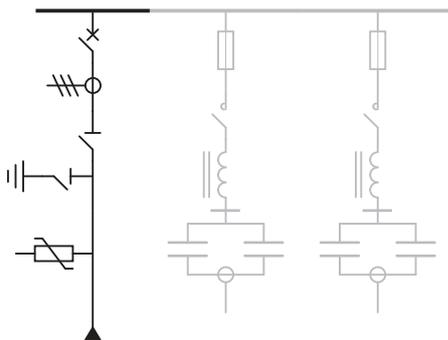


Fig. 7. Incoming section of a bank with two steps

It is recommended to provide at least an earthing facility and the ability to isolate the equipment (and provide visual confirmation of this isolation). This fundamental safety feature should be provided with mechanical interlocks to allow access to equipment only when it is safe to do so. End user preferences for interlocking range widely and it is important to take a sensible approach that will guarantee operator safety.

The section is also likely to contain a surge arrester near the incoming cable termination. Such surge arresters are part of the substation insulation coordination and should be rated accordingly. These components are often applied in capacitor banks but should not be used as a means to reduce voltage withstand levels below what is required by the substation insulation coordination or to mitigate over voltages from switchgear restriking. The design of the equipment and component selection should be such that restriking does not occur, clearances match the overall requirements of the substation, and any switching transients caused by operation of the bank do not result in over stressed equipment or detrimental effects on the substation. At medium voltages restrike is uncommon, however it is important

in all cases to ensure that switchgear is used that has a proven track record of not restriking.

C. Safety of the operator

The first step to operator safety is to make human interaction with the equipment inherently safe. This is done in several ways: mechanical timed interlocks that ensure access to live parts is not possible, smart control that prevent user actions that can cause damage to equipment and smart system supervision that ensure that minimal human interaction is necessary to operate the equipment.

Each customer, and each site, has specific safety requirements and policies. This important interface point needs to be described and clearly documented: it is not sufficient for a supplier to provide what is considered good practice or for the customer to make a vague statement about operator safety.

The interlocking diagram in figure 8 provides a useful framework and also demonstrates clearly which part of the safety system is in which party's hands. In this scheme using captive key interlocks, an upstream breaker is tripped which releases key A. This key is inserted and turned in a timed release mechanism, ensuring that no operation can be made on the capacitor bank before a certain discharge time. After this time, key B is released.

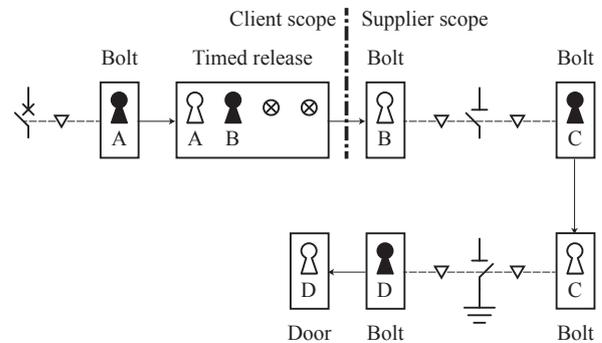


Fig. 8. Typical safety interlock system

Key B is inserted and turned on a bolt interlock, allowing an isolator to be opened. This isolator also provides visual confirmation that the bank is now isolated from the supply. Once opened, key C is released, allowing the earth switch to be put in the earthed location. This finally releases key D which is used to open the door to the high voltage equipment.

This fairly elaborate interlock scheme can be simplified however the most important aspect of operator safety and careful integration with site-wide safety requirements must be clearly understood by supplier and end user to ensure safe and smooth operation.

V. ENVIRONMENTAL REQUIREMENTS

Enclosed bank design must consider at least three different environments, each with onerous challenges.

A. Transport

Getting the equipment to site and moving the equipment between sites can be a very costly affair and it is between the factory and site that damage is most likely to occur. Solutions that can be shipped and transported using normal sea and land freight without undue external protection and preferably using standard freight handling facilities offer significant savings compared to oversized enclosures, or enclosures with external components that need to be specifically protected during transport.

Internally mounted equipment must be secured for transport. The typical enclosed capacitor bank contains a number of heavy iron core reactors and several capacitor units and other fragile and/or high inertia components. Adequate internal bracing for transport is essential and where such bracing is for transport purposes only it should be easy to remove it once the equipment is located on site.

B. Storage

Enclosed capacitor banks may need to be put in storage if delivered earlier than required or when removed temporarily from service or in the process of relocation. Storage is normally relatively benign, however important aspects need to be considered:

If the equipment is to be transported to a storage location, even on the same site, due consideration should be given to transport preparation and bracing. Standard container dimensions for handling once again greatly facilitates collection from site and delivery to the storage location.

Long term storage may result in ingress of dust and vermin that will make it difficult to place the equipment in service again without a major overhaul. A fully sealed enclosure will avoid this problem.

In some climates moisture may accumulate in the enclosure and result in degradation of insulation, especially of the dry type iron core reactors that are used in the steps. With the exception of the high voltage capacitor units inside the enclosure, none of the components are intended to be exposed to moisture. The most common solutions to this problem are the use of desiccant or space heaters inside the enclosures. Both of these have complications: desiccant requires replacement, implying some level of maintenance during storage, while space heaters require a power source which may be problematic in typical storage situations.

The capital cost of the equipment, sensitivity of components to moisture and the potential cost to re-enter service warrant care during storage. It is recommended to monitor humidity inside the enclosure so the extent of condensation is known, that the enclosure is sealed during storage, limiting the amount of moist air exchanges, and if necessary, the internal moisture is managed by means of space heaters or moisture extraction.

C. Site environment

Conditions on site can vary considerably, from arid desert environments with large temperature variations during the day, to highly humid, warm tropical environments and to sub-zero environments. Altitude can range from near sea level to high altitude, and seismic and wind loading may be important considerations. Rainfall and the likelihood of lightning strikes need to be taken into account. It is important to give a detailed description of site location and conditions, as well as any specific requirements for design that may exist in local regulations. In many cases, air-borne dust can be conductive so it is vital that it should be kept out of the enclosure.

Suppliers of enclosed capacitor banks must take all these conditions into account and should be able to prove that their design can withstand the conditions. Designs are generally standardised as much as possible in order to reduce design and manufacturing costs and to improve quality management, however good designers will be able to demonstrate that appropriate measures have been taken to ensure correct operation under the specific conditions on site.

There are two related, important aspects to the design of enclosed capacitor banks that often cause problems for end users:

- 1) The equipment is not kept cool enough. Service life of capacitor units, reactors, switchgear, in fact all equipment used in the enclosed capacitor bank requires operation under a specific ambient temperature. High temperatures result in rapid failure,

derated capacity, or equipment failure. Temperature is also important in cold climates – much of the equipment cannot operate below a certain temperature.

As mentioned above, detuning reactors are highly recommended for purposes of avoiding harmonic resonance, however these reactors can be substantial sources of heat. The enclosed bank is mounted outside and subject to heating from sunlight and potentially high ambient temperature air for extended periods. These internal and external heat sources can cause high temperatures inside the enclosure to rise significantly, to levels beyond the rated capability of the components.

A common solution is to ensure cooling of the internal components by forced ventilation, with vents for air to enter and exit the enclosure. At high ambient temperatures a very large volume of air has to pass through the enclosure to ensure sufficient cooling. This results in a paradox: vents must be large and allow efficient air flow, but must also keep rain, vermin and dust out of the enclosure.

- 2) The equipment is dusty, dirty, or vermin-infested. Dusty, dirty equipment results in insulation breakdown, local hot spots and flashovers. To avoid dust ingress, air filters can be placed over air inlets. In a dusty, hot environment, these filters may require frequent maintenance. Such maintenance is essential if the designed air flow is to be maintained.

As the filters are often mounted under cowls that prevent water ingress, it is difficult to notice the condition of the filters, and these can easily be neglected. This can result in underperformance and even failure of the bank. Cowls also inherently restrict air flow.

An alternative approach is to seal the enclosure completely on all sides, to provide a real dust-free and moisture free internal environment, and to manage to the temperature by means of heat exchangers. The sun and ambient temperature loading of the enclosure is reduced by means of thermal cladding applied to the inside of the enclosure, ensuring the components can be operated at a constant, comfortable temperature in a clean environment — ideal for a long operating life.

The completely sealed approach is inherently vermin proof and the thermal cladding provides the additional benefit of noise mitigation.

VI. OPERATIONAL REQUIREMENTS

Once equipment is installed and in service, the real need is to provide the operator with full control of the equipment in a simple and clear manner. The enclosed capacitor bank must be easy to use whether it is in automatic mode, manually operated or controlled remotely either by a remote control system common in energy distribution utilities or by the plant-wide control system in an industrial application.

Figure 9 indicates an approach that gathers all the necessary information regarding the status of the enclosed bank and presents that information to operators through a single interface.

Accepting delivery of the equipment on site, placing it in the correct location and making it ready for operation is a very important aspect of handing the enclosed capacitor bank over to the end user. Proper coordination in the form of mechanical and civil drawings, supported by instructions and training of the relevant personnel are essential at this stage. From a design perspective, making the equipment easy to transport, off-load on site and place it in position will make the lives of operators, and hence the use of and caring for the equipment much easier.

VII. MAINTENANCE REQUIREMENTS

Enclosed bank specifications often state the requirement that equipment can be accessed via doors or lift-off panels. This is a

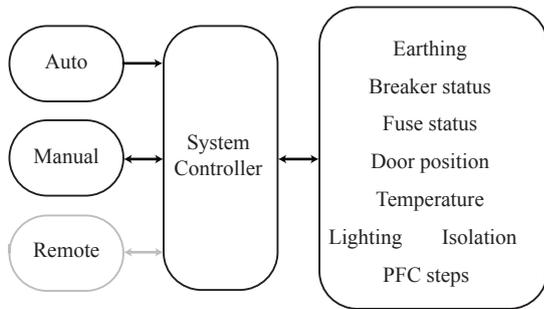


Fig. 9. Control hierarchy and layers

sensible requirement, as for maintenance or repair requirements it is of course essential to have easy access to all the equipment. This access introduces two complications:

- Multiple openings inherently makes ingress protection more difficult, weakens the structure of the enclosure and adds to the cost by requiring access protection on more than one physical entry point.
- A door or lift-off panel does make it possible to reach equipment, but to actually remove and replace any component is in fact very difficult when only a part of the side wall is removed. In most cases, replacing or exchanging a major component like a capacitor unit or detuning reactors requires substantial work on site, including possible removal of the roof of the enclosure.

A fully enclosed, sealed enclosure may seem to make it especially difficult to access equipment however the converse is true. The main, heavy equipment is mounted on frames as shown in figure 10 that are connected electrically by means of three bolts, and mechanically by means of two locking bolts. The complete assembly is removable, and work only needs to be done on steps that require work. Thus it is simple to access the equipment without any work on the enclosure other than opening a single door.

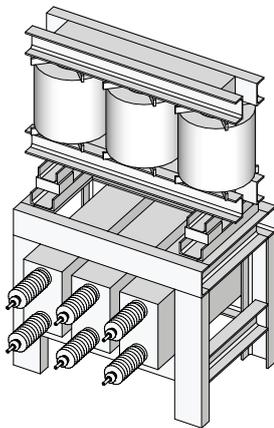


Fig. 10. The step module contains all major components

Easy access to a complete module is one thing, but it is very important to remember that maintenance intervals can be considerably extended: no work is required on the inside of the enclosure as the environment is clean and closed off. Work can be performed on the exterior of the enclosure, including on the external parts of the heat exchangers, without removing the equipment from service. Heat exchangers can be serviced by personnel with no special training on high voltage equipment.

Reduced service visits and simple external mechanical maintenance contribute to lower lifetime costs for the enclosed capacitor bank.

VIII. CONCLUSION

Specifying, procuring, and owning an outdoor enclosed bank is similar in some respects to other medium voltage equipment like outdoor switchgear or transformers. Unlike such equipment, there are few standards to guide the end user in the process of procuring or owning it and therefore special care and thought should be given to this process to avoid pitfalls.

This note provides designers and specifiers of such equipment with key aspects of functionality, safety, operability, maintainability and longevity to consider.

IX. FURTHER READING

Reactive power compensation and harmonic filtering is a niche of electrical engineering and it can be difficult to find unbiased, purely technical documentation on the subject. The following literature is recommended to the interested reader:

Topic	Document / Location
General notes on power factor correction	http://www.onegrid.com.au/wp-content/uploads/2012/03/BR-EN-TH01-11_2004-Power_Factor_Correction.pdf
Benefits of detuning	http://www.onegrid.com.au/wp-content/uploads/2012/03/BR-EN-TH08-11_2004-Reactors_and_Shunt_Capacitor_Banks.pdf
Harmonic resonance	http://www.onegrid.com.au/wp-content/uploads/2014/10/0MPRIH-2-Harmonic-mitigation-in-modern-networks.pdf
Component ratings	http://www.onegrid.com.au/wp-content/uploads/2015/02/0MPCR-5ComponentRatings.pdf
Units of measurement	http://www.onegrid.com.au/wp-content/uploads/2015/09/0MAUOM-1UnitsOfMeasure.pdf