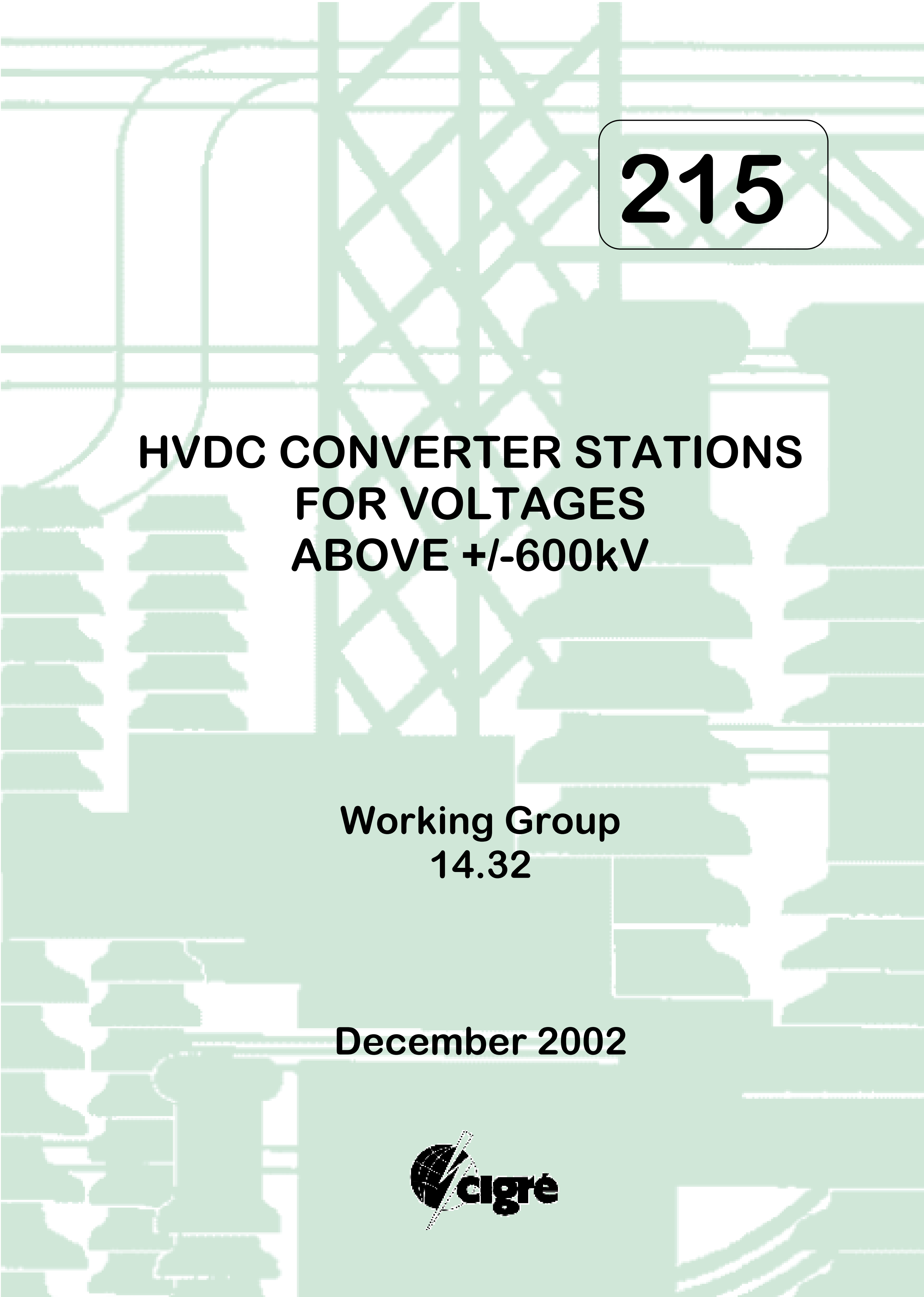

215

HVDC CONVERTER STATIONS FOR VOLTAGES ABOVE +/-600kV

Working Group
14.32

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HVDC CONVERTER STATIONS
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TABLE OF CONTENTS

HVDC CONVERTER STATIONS FOR VOLTAGES ABOVE +/- 600kV

1. SCOPE

In the previous studies the economic and technical aspects of building HVDC converter stations at voltages above 600kV dc were investigated. The scope of work of the WG14.32 is to review the current state of HVDC converter stations up to 600kV and the problems associated with it and to investigate in detail what needs to be done to expand the technology to voltages above 600kV and specifically to 800kV.

Parallel operation of converters is not considered in this document.

2. INTRODUCTION

At present only the Itaipu HVDC transmission system operates at +/- 600kV. There are 10 transmission systems now in operation at voltage levels between +/- 450 to 550kV and another three in various stages of engineering and/or construction.

Over the years the converter stations have gone through various transformations and adaptations as reported in the various papers presented at CIGRE and other international conferences. An important amount of development and research has been devoted to the optimization of converter station equipment and system design specially for the voltage levels of 500 to 600kV.

In order to meet the rapidly growing demand in some countries like Brazil and China, large hydro generating plants are being considered. These plants will be located at distances ranging from 1000 km to 3000 km from the load centers. Due to the amount of power to be transmitted and distances involved, many feasibility studies performed in recent years tend to conclude that Ultra High Voltage Direct Current systems are economically and environmentally preferred for the transmission of bulk power over long distances. Voltage levels of 800kV and above have been considered but no converter stations have been built at these voltage levels. This means that additional converter design and equipment prototype development and testing would be necessary in the coming years.

3. REVIEW OF THE MAJOR FAILURES IN THE CURRENT HVDC CONVERTER STATIONS

3.1 General

During the last two decades a number of HVDC systems up to +/-500kV and one at +/-600kV, were placed into operation in various parts of the world. Together they constitute over 50 years of operating experience at +/- 500kV and over 15 years experience at +/-600kV. In general, these HVDC systems have operated with very high availability levels. Each of these systems faced problems in different equipment on the ac and dc side. Most of these problems were minor in nature and related only to specific projects and were solved satisfactorily. However, some of the problems encountered on some pieces of equipment will require special attention in the design of converter stations at voltages above +/-600kV;

- Converter Transformers
- External insulation flashovers including wall bushings and transformer bushings
- Smoothing reactors

3.2 Converter Transformers

The converter transformers and the thyristor valves are the most critical components of a converter station. The failure of transformers has serious negative economic impact in a transmission system if no spare is available and the replacement facilities did not exist.

Information on the failure rate of the converter transformers can be found in data prepared by WG 14.04 and published by CIGRE every two years. Unfortunately not all converter transformer failures may have been reported to CIGRE. Converter transformer failure rate is about twice that of ac transformers, this is unacceptable for transmission systems. It can take 3 to 10 days depending on the setup, to replace the failed unit by the available spare.

Study committees 12 and 14 have joined their efforts and formed Task Force 12/14.10.01 to investigate converter transformer failures before 1991 and to suggest recommendations on how to improve the reliability. The findings of this task force were published in ELECTRA [155-1984]. One important conclusion of this report was that for valve winding failures there was no evidence of insulation failures either to ground or to the ac winding. The most common failures found within converter transformers lie in the following categories.

- Windings (dielectric failures)
- Tap changers
- Oil quality (reduced dielectric withstand)
- Cooling systems (pumps)
- Bushings

While the condition monitoring systems installed in a number of schemes, have allowed some potential failures to be avoided, the design of these monitoring systems has not matured to the stage where all potential catastrophic failures can be detected early enough to allow the corrective action to be taken.

3.3 HVDC wall bushings

HVDC wall bushings have for many converters been mounted on the valve building wall at a slight inclination to the horizontal plane. Many have experienced flashovers within the first year of operation or shortly there after, at service voltage and under a variety of wetting conditions and for some installations in the presence of light pollution. This was quickly recognized as a weakness of the HVDC technology and much effort has been devoted to the understanding of this phenomena. Important phenomena such as non-uniform rain or partial wetting of porcelains was clearly established as the cause of flashovers, especially for the wall bushings.

Many laboratory tests have demonstrated the poor performance of the porcelain bushings under pollution and non-uniform wetting.

Various means have been developed to improve the performance of the insulators, tested and successfully demonstrated in service, such as;

-Application of silicon grease over the whole surface of the bushing
-RTV (Room Temperature Vulcanized rubber) coating
-Booster sheds
-Composite bushings with silicone rubber sheds

These means have provided good results. However in the case of the silicone grease and RTV coating it does not protect the bushing against flashovers indefinitely. It requires replacement every 2 to 5 year. This is not a major issue if an outage of the converter can be arranged for a period of about one day per bushing in good weather conditions.

Composite bushings have been in operation for over 10 years in various projects around the world operating under different pollution conditions. These bushings have been free of flashovers and so far they have been maintenance free.

3.4 Smoothing reactors

3.4.1 Oil smoothing reactors

Oil immersed smoothing reactors have been commonly used for the first generation of the HVDC transmission systems. The experience with the oil smoothing reactors has been relatively good, except for some failures in some of the schemes. For some installations, the reactor bushings are arranged such that the horizontal bushing penetrate inside the valve hall connecting directly to the high voltage bus while the other bushing is mounted vertically on top of the reactor, thus eliminating the need for a separate high voltage wall bushing contributing to a reduction in the probability of a flashover.

Although oil smoothing reactors require high maintenance compared to an air cored air insulated smoothing reactors and there is the risk of oil leaks and fire hazard, they are still being used in some new HVDC systems as they represent a better technical solution under some environmental conditions (pollution).

3.4.2 Air cored air insulated smoothing reactors

Already in the early 1980's air cored air insulated smoothing reactors were introduced. First in conjunction with oil reactors and in stand alone operation at the 500kV level since1989. Among the most important advantages of the air cored air insulated reactor, the following should be mentioned:

- Lower capital cost in some applications
- Support insulators provide the insulation to ground
- Fire risk and environmental concerns are negligible due to the absence of oil
- During power reversal, stresses are only experienced across the support insulators
- No saturation under dc line fault (absence of iron core)
- Lighter weight and easier to handle
- Shorter installation time and replacement if necessary

Some problems were however experienced with the first units manufactured for installation at +/-500kV. All these problems were addressed and the recent experience with air cored air insulated smoothing reactors so far has been good. In the majority of applications of the air cored air insulated smoothing reactors at 500kV dc, more than one coil is required to achieve the inductance value depending on the dc current.

4. HVDC SYSTEMS AT VOLTAGES HIGHER THAN 600kV DC

4.1 VOLTAGE SELECTION

Although systems with voltages up to 1200kV are theoretically possible, it was decided by the WG to limit the scope of this document to +/- 800kV for following reasons

- The feasibility studies for the development of the Amazon River system concluded that the transmission system at 800kV can meet the transmission requirements even though systems with higher voltage up to 1200kV were considered. The study concluded that the transition from 600kV to 800kV can be achieved with very few technical challenges. Where as for voltages higher than 800kV more research will be required. A separate study on the R&D requirements for UHVDC voltages also concluded that 800kV transmission system can be developed.

- AC systems at 765kV have been in commercial operation for more than 25 years. In addition one AC system has been in commercial operation at 1200kV for a number of years. The technology for conventional AC equipment design (e.g. transformers, surge arresters, switchgear, etc.) at this voltage level is fully developed. The knowledge and experience gained from these systems although not directly applicable, can be used in the development of the 800kV DC equipment.

- The external environmental impacts such as corona, RI (Radio Interference) and AN (Acoustic Noise) at these AC voltage levels have been successfully mitigated and sufficient research information on the environmental impacts of 800kV DC is available.
- It would be beneficial to gain some operational experience at 800kV level before even higher voltage systems are contemplated.

4.2 BIPOLE POWER RATING

The power rating of the bipole is determined by the minimum size of the conductor required to keep the corona loss, radio interference and audible noise within the acceptable limits, the economic current density and the maximum current carrying capability of the thyristors. At 800kV the minimum conductor size required to meet the corona, RI and AN criteria limit is 3200mm^2 [4]. The economic current density for a certain power level to be transmitted by a transmission line depends on many factors such as environmental criteria, line investment costs, load curve, loss factor, cost of the losses interest rate, etc, and usually varies from 0.4 to 0.8A/mm^2. Using this range of current density the minimum pole current is between 1280A to 2560 A. At the current level of 1280A the minimum economic power rating for a +/- 800kV bipole is 2000MW. The thyristor current carrying capability determines the maximum rating of the bipole. Modern day thyristors can carry currents up to 3500 A. Assuming no parallel connection of thyristors, the maximum bipole power is then 5600MW. Using these criteria the range of the bipole power at +/- 800kV is between 2000MW and 5600MW, where 800kV is the dc voltage as measured at the rectifier line terminal with respect to ground and has a tolerance of $<\pm 2\%$.

For the purpose of this document the bipole rating is assumed to be 5000MW.

5. AC SYSTEM CONDITIONS

For a conventional DC system of 5000MW rating, the minimum short circuit requirements for power/voltage stability would be about 8200 MVA unless very special measures are taken. However, a short circuit level of about 10,000 MVA would be a more normal requirement for a conventional design.

If capacitive commutated converters are used then a system with a lower short circuit level is acceptable. However, this document is not considering such a topology.

Voltage source converters have not been considered in this document as, at the present time, the technology is not developed for such power and voltage levels.

5.1 SENDING END

For the case of an HVDC system from a single large power plant, two situations are considered. The first one is that the power plant is connected radially to the HVDC system without any connection to a local AC network. Under such a situation an AC system with moderate strength can be envisaged because both the rated power and transmitted power at any time will be matched by the capacity of the generators. The second case is that of an HVDC system is connected to a power plant, which is part of an AC network. Under such a situation, the AC system conditions will usually be worse than the first situation because some of the power transmitted by the HVDC system can come from generators far away in the AC network. Under some extreme conditions, the AC system may be weak. However it seems that the application of HVDC systems at voltages above 600kV are justified on the basis of transmitting bulk generated power from remote large generation sources, which means that the sending end AC system strength will be adequate.

5.2 RECEIVING END

The receiving network AC voltage where an HVDC system at voltages above 600kV is terminated has to be strong. AC networks with voltage levels of 765kV, 500kV, 400kV, 330kV and 230kV have been built. However, whether such levels are suitable for the dc system is a question we have to address.

If we assume that for a 5000MW HVDC system, the level of reactive compensation required is approximately 3000 MVARs, and assuming an effective short circuit ratio of 1.8 to 3, then the minimum AC system strength at the receiving bus would have to be in the range of 12000 to 18000 MVA.

230kV AC networks are widely used as the main transmission voltage in lots of AC systems around the world. However, at 230kV the system capacity is unlikely to be sufficient to support a dc power in feed of 5000MW.

The short circuit level of a bus in a 330kV network connected to an HVDC bipole is usually between 5000MVA to 15000MVA according to the location of the bus and type of generators in the network. For an HVDC bipole of 5000MW capacity, it becomes a weak or even very weak receiving AC system if connected to 330kV network. It may not be strong enough to support a 5000MW HVDC system without special measures, if the SCL capacity of the network is less than 12000MVA.

The short circuit level of a bus in a 400kV or 500kV network connected to an HVDC bipole is usually between 10000 MVA to 30000 MVA according to the location of the bus and the generators in the network. An ac system at 400 or 500kV ac network is likely to be a strong or moderate in relation to a 5000MW bipole.

It is evident that for such a level of dc power the ac system voltage would be 400kV to 765kV.

5.3 STRENGTH OF AC SYSTEM

As discussed in above sections, for HVDC bipole of high power rating both the sending and the receiving AC networks may be moderate or weak. All the technical problems and difficulties related to weak AC system are very likely to be encountered for 800kV system.

Technical problems related to weak AC systems can be divided into three main categories.

- reactive power compensation and voltage control, harmonics filtering and resonance and insulation coordination of the equipment connected to converter AC bus.

These problems are not special and can be solved with existing technology.

- control and protection of the HVDC system such as stability and transfer limitation, harmonic instability.

These problems can also be solved with existing technology.

- insulation coordination of converter equipment and dc side equipment. Weak AC system usually cause higher TOV and may in some cases require higher rated voltage arresters and higher insulation level of equipment.

Therefore the problems that may be encountered due to the application of an HVDC system of 5000MW capacity into a weak ac system are not any different from the current technology.

6. CONFIGURATION OF HVDC SYSTEM

6.1 DC CONFIGURATION

A long distance DC system with overhead transmission line can be a monopole with only one pole conductor, a monopole with a pole conductor and a return conductor, a bipole with two conductors and even a bipole with two pole conductors and a return conductor.

When monopolar operation is used, it can be either with ground return or with metallic return. The requirements for a ground electrode for an HVDC system at 800kV are basically the same as for the current HVDC systems. In case of 5000MW the higher rating of the ground electrode has to be carefully evaluated.

In the case of a bipole using metallic return the requirement for an MRTB and GRTS are the same as for existing HVDC systems. However for the higher current rating of 4000A these devices have to be carefully examined and evaluated.

6.2 FACTORS AFFECTING NUMBER OF SERIES CONVERTERS PER POLE

The choice of number of converters per pole is determined by the following

- The technical feasibility of building a single converter per pole.
- The size of the receiving end system and its ability to absorb the loss of a converter.
- The amount of power capability loss for major faults.
- The converter transformer rating, dimensions and weight
- The bypass equipment.

6.2.1 TECHNICAL FEASIBILITY

The largest single converter per pole currently in operation is rated at 1125MW and currently there are converters under construction at the rating of 1500MW.

From the technical aspect for HVDC system at +/-800kV, one converter per pole is still feasible.

6.2.2 SYSTEM SPINNIING RESERVE

The amount of spinning reserve required for any system is dependent upon the size of the largest single source of power (e.g. largest generator or the largest HVDC converter) and the size of the system itself. Typically the spinning reserve is in the range of 10 to 12% of the total generation in a power pool. At the same time it is desirable to keep the amount of spinning reserve as low as possible. For a bipole rating of 5000MW using a single converter per pole the spinning reserve would have to cater for the loss of a 2500MW converter. By using two converters per pole this value can be reduced to 1250MW. Therefore from a system operating point of view two converters per pole are preferred.

6.2.3 EQUIPMENT FAILURE

Although the HVDC systems operate at high availability level yet from time to time failure of major equipment do occur. It is expected that an HVDC system of this size will have on site spares for major components (e.g. converter transformers, smoothing reactors, etc.) that can be placed in service in a matter of days. During this outage, the loss of capacity must be made up from other sources. In today's open market system this could prove to be very costly. In order to keep these costs to a minimum two converters per pole would be more attractive.

6.2.4 TRANSFORMER SIZE

The size of the converter transformer is the single most important factor affecting the number of converters per pole. The ratings of the converter transformers for a single and two converters per pole are

No Converters Per Pole	3-phase transformers/bridge	1-phase three winding	1-phase two winding
1	1458MVA	972MVA	486MVA
2	729MVA	486MVA	243MVA

The only viable solution for a single converter per pole configuration appears to be the single-phase two winding transformers. Even at 486 MVA the transformer rating is too high and in all likelihood cannot be shipped due to transportation restrictions especially to a remote location (see section 9).

For two converters in series per pole, depending on the transformer weights there will be flexibility in the choice of the type of single phase transformer that can be used for the lower voltage converter. However using two different designs of transformers for the LV and the HV converters may not be practical. Thus such arrangement is not considered in this document.

6.2.5 BY-PASS EQUIPMENT

Single converter per pole does not require any bypass equipment. However multiple series converters per pole will require by-pass breakers, anode and cathode isolators and the by-pass isolator for each converter. The addition of the by-pass equipment adds to the cost of the system. The technology for operation of converters in series is very well developed already and is not considered to be a problem. The requirements for the by-pass breaker were investigated in the EPRI report EL-3892 [4] and it was concluded that no problems at higher voltages are anticipated.

6.2.6 PARALLEL CONVERTERS

Another alternative for reducing the size of the transformers is to use parallel converters. However the use of parallel converters adds to the complexity of the overall control and protection scheme. The parallel converters may offer an advantage over the series converters in the event the project is built in stages. In such cases this alternative has to be evaluated. The consideration for the insulation at 800kV in a parallel converter scheme is the same as in series converters.

6.2.7 CONVERTER CONFIGURATION

The factors affecting the number of converter per pole can be summarized as follows

	One converter per pole	Two converters per pole
Technical Feasibility	Yes	Yes
Generation reserve requirement	Higher	Lower
Cost of outage of major equipment	Higher	Lower
Transformer size	Transformer size is higher and may exceed transportation limits.	Transformers are easier to transport
By-Pass equipment	Not required	Required and adds to the cost and complexity of the system.

From the above table it is clear that a single converter per pole is technically feasible and related problems can be solved but in reality the weight restrictions and the size of transformers will most likely dictate the use of two converters per pole.

For the purpose of this document only two converters in series per pole are considered.

7. INSULATION LEVELS

7.1 INSULATION LEVELS AND AIR CLEARANCES

The expected insulation levels for an 800kV HVDC converter station are:

	LIWL kV	**SIWL kV**
DC-bus	2100	1675
Across smoothing reactor	2550	-
DC-bus between 6-pulse bridges	1550	1425

By use of the formulas
$d=(U_{50(SI)}/500*k)^{1.67}$ (Paris formula)
and
$d=U_{50(LI)}/540$

where
d is the required minimum air clearance
k is the gap factor characterizing the electrodes in the gap
The following values can be used [1]:
k=1 for point-plane
k=1.15 for conductor-plane
k=1.25 for conductor-structure
k=1.4 for conductor-conductor
For the lightning impulse this gives the following air clearances using correction factor 0.88:

LIWL kV	**U_{50} kV**	**Distance D m**
2100	2390	4.5
2550	2900	5.4
1550	1761	3.3

For the switching impulse the air clearances will be as below, using correction factor 0.82:

SIWL kV	**U_{50} kV**	**Air clearance, m**			
		K=1.0	**K=1.15**	**K=1.25**	**K=1.4**
1675	2042	10.5	8.3	7.3	6.0
1425	1737	8.0	6.3	5.5	4.6

The diameter of the conductor necessary for operation at 800kV without corona can be estimated by extrapolation of Peeks law, and this will give minimum diameter about 40 cm.

From above it is obvious that the air clearances will be given by switching withstand levels. However, for outdoor insulators the length of the insulators will be given by the requirements on specific creepage distance.

For indoor equipment, if 19mm/kV is used , the approximate length of the insulators will be 5 m for 800kV, and in this case the length of insulators is determined by the air clearance required by switching impulse.

7.2 Transformer Insulation Levels

Figure 1 shows the converter arrangement proposed including the location of surge arresters. In order to calculate the protective level of the valve surge arrester, which is the building block for the converter transformer valve side insulation levels, a Surge Arrester Protective Ratio (SAPR) of 1.65 has been assumed. Therefore the valve Switching Impulse Protective Level (SIPL) is:

$$175\text{kV} \times \sqrt{2} \times 1.65 = 408\text{kVpk} \qquad \ldots\ldots(1)$$

The bridge arrester will have a higher protective level than the valve arrester as a dc voltage is constantly imposed on its terminals. Therefore the 6-pulse bridge SIPL is:

408kVpk x 1.1 = 449kVpk …….(2)

It is common for a bipole HVDC scheme to have the neutral point between the two poles at each converter station connected to earth at an electrode site several km away from the converter station. The electrode line connecting the electrodes to the converter station will have an associated voltage. However, it has been assumed that the Maximum Continuous Applied Voltage (MCAV) at the converter station end of the electrode line will be sufficiently small so as not to effect the SIPL of the lower voltage converter to ground. It has also been assumed that arrangements can be made to always earth the inverter when operating with metallic return, hence the voltage drop of the return conductor at the rectifier will not increase the SIPL of the low voltage converter.

From equation (1) above the SIPL to ground between the two converters can be established as:

1.93 x 408kVpk = 787kVpk …….(3)

(Where 1.93 is the vector sum of the star winding and delta winding voltages)

The SIPL to ground of the mid-point of the higher voltage converter can be found from adding the results from (2) and (3) above giving:

449kVpk + 787kVpk = 1236kVpk …….(4)

The higher voltage transformer connections are connected to the insulation protective level defined in (4) via a valve surge arrester, as defined in (1) above giving a converter transformer valve winding SIPL of:

1236kVpk + 408kVpk = 1644kVpk …….(5)

For the transformer connected at the highest potential this gives the following insulation withstand levels:

Switching Impulse Withstand Level (SIWL) = 1644kVpk x 1.15
= 1891kVpk …….(6)

The Lightning Impulse Withstand Level (LIWL) can be found by applying the ratio 0.95 to the SIWL, giving:

Lightning Impulse Withstand Level (LIWL) = 1891kVpk / 0.95
= 1990 kV pk
= 1990 kV BIL …….(7)

8. THYRISTOR VALVES

8.1 PRINCIPAL DESIGN OF THYRISTOR VALVES

Modern thyristor valves are in most cases air insulated and use deionized water as cooling medium. They comprise of one or more identical modules, which are assembled to a valve tower. The modules contain the following components:

- a thyristor stack comprising series connected thyristors
- the snubber circuit components
- thyristor firing and/or monitoring electronics
- valve reactors
- grading capacitors
- miscellaneous equipment like cooling circuit components and optical fibers

The insulation coordination inside the modules is governed by the voltage capability of the installed thyristors. Thyristor level related components like the snubber capacitors or resistors are usually arranged along the voltage grading of the thyristor stack. The voltage capability of components like grading capacitors or valve reactors, which sometimes are related to more than one thyristor level, is designed for the chosen number of thyristor levels. From the insulation point of view thyristor modules may require only minor modifications for transmission systems with voltages up to +/- 800kV. The impact of EMI should be considered.

Thyristor modules are often arranged in quadrivalves, which comprise four valves of a twelve pulse group in one mechanical tower construction. A common design is also the arrangement of two valves in a double valve tower. The valve towers are either suspended from the valve hall ceiling, or base supported. In most designs the fiber optic cable and the water piping enter the valve structure at the low voltage end to reduce or avoid dc stresses on the insulation to ground potential.

The valve tower of 800kV systems should not differ in principle from this well proven design of systems in operation. But the valve tower height will increase due to the higher number of series connected thyristors/thyristor modules required. The height of actual valve towers for a 500kV transmission system varies between 11 and 16m. In a single converter design the height of a quadrivalve tower for a 800kV system will increase to approximately 17 to 24m. An additional clearance of approximately 10m at the high voltage end is required, which results in a height of the valve hall of 27m to 34m.

The quadrivalve towers of two series connected 12 pulse groups may have a height between 9 and 15m. The clearance for the low voltage converter will be around 4m, while the high voltage converter needs clearances at both ends. Assuming again 4m at the low end and 10m at the high end, the valve hall height for the higher voltage converter may be between 23 and 29 m.

This estimate indicates, that the valve hall height has to be one of the points of concern in a single converter design for a 800kV system, while for a two series connected converter design it is near the common valve hall dimensions.

In an 800kV valve design attention has to be given to the seismic requirements due to the increased dimensions and weight of the valves as well as the increased size of the valve hall.

8.2 THYRISTOR ASPECTS

Modern thyristors exhibit a practical withstand voltages of up to 9kV and have a current carrying capability of up to 3500 Amps depending on the silicon diameter. The diameters vary between 100 and 150mm. These thyristors are available in both electrically triggered and directly light triggered designs.

Based on actual thyristor numbers per valves in a 500kV system, the number of thyristors per valve necessary for a single converter design for a 800kV system can be estimated to be between 125 and 140. The valves of two 12 pulse series connected groups will comprise app. half of these numbers.

Parallel thyristor stacks are not economic and would need additional equipment and efforts to ensure uniformity in current carrying. If the transmission voltage is limited to 800kV, then the current capability of the thyristor gives the limit for the transmission power of the system.

8.3 THYRISTOR VALVE TESTING

Testing on thyristor valves is divided into two parts:

- Operational tests
- Dielectric tests

The operational tests are performed in a back to back or synthetic test circuits on a reduced number of thyristors as per IEC60700-1 and IEEE857 and therefore should not be any different from the current practice.

For the dielectric tests on the valve and Multiple Valve Unit (MVU) for 800kV the problems are:

- The test voltages have to be significantly higher than today. Problems may be to find test labs being able to produce the test voltages and to provide the necessary test equipment.

- The test lab has to provide a much larger hall to install the equipment. The most difficult dimension expected is the height of the test hall.

The surrounding of the valve towers will be different and research has to be done on this subject to verify how accurate the simulation of the surroundings can represent the real operating conditions should be.

9. CONVERTER TRANSFORMERS FOR 800kV HVDC

9.1 Main Design Parameters

The design consideration has assumed that each pole will comprise of two converters in series.
The following ratings are established:

Nominal Pole Power:	2500MW
Nominal Pole dc Voltage:	800kV
Nominal DC Current:	3125 Adc
Nominal Valve Winding Voltage Ell_{nom}:	165 kVrms
Maximum Valve Winding Voltage Ell_{max}:	175 kVrms
Transformer 6-pulse (3-phase) MVA:	730 MVA

9.2 Converter Transformer Design

From the conceptual design a specification has been produced for a transformer for the upper 6-pulse group. The outline specification can be found in Appendix 1. When preparing this specification it was assumed that the standard dc test determination method, as adopted for HVDC transmission schemes up to 600kVdc, could be applied to this design. (ELECTRA 46) and PC57.129/D10c March 1999.

9.3 Transformer Arrangement

The design of the converter transformer was mainly dictated by the large insulation clearance requirements. The most appropriate core construction for this transformer was considered to be a four limb design with two parallel wound legs and two flux return legs, having a winding arrangement of:

CORE – TAPS – LINE – VALVE

In order to achieve the required insulation on the upper-most valve connection it is preferable to connect this 6-pulse bridge in a delta configuration. This gives a greater number of valve winding turns than for a star connected winding and hence allows the designer a greater degree of impulse voltage distribution control for the winding.

9.4 Transformer Insulation

It is envisaged that the design methods applied to insulation structures for converter transformers for HVDC schemes operating at up to ±600kVdc will also be applicable to converter transformers for ±800kVdc schemes.

9.5 Transformer Impedance

It was felt that 12% impedance is the theoretical lower limit of impedance for such a transformer, as a lower impedance would require special and costly measures (e.g., half hard copper) to withstand the stresses and forces generated by a short circuit, also the short circuit current capability of the valve would be impacted by the lower impedance.

A practical upper limit of transformer impedance was considered to be 18%; increases beyond this would give rise to potentially high losses. A comparison between a 12% impedance transformer and an 18% impedance transformer was made and the results are shown in Table 1. It should be noted that no attempt was made when undertaking this comparison to equalize the capitalized losses between the two designs.

Transformer Impedance	12%	18%
Forces	May require special techniques to cope with the short circuit forces.	Easier to meet strength requirements.
Weight	-	Lower overall weight
Height	-	Lower for the same winding height
Losses : No-Load	-	Lower
: Load	-	Higher without additional copper being added to the windings
di/dt imposed on tapchanger	-	Lower

TABLE 1
Comparison of a 12% impedance and an 18% impedance transformer

9.6 Approximate Transformer Size and Shipping Weight

Based on the specification shown in Appendix 1 the following shipping dimensions were derived to give an indication of size and shipping weight:

Frequency (Hz)	50	50	60	60
Impedance (%)	12	18	12	18
Rating (MVA)	243	243	243	243
Arrangement	Single-phase/ 2-winding	Single-phase/ 2-winding	Single-phase/ 2-winding	Single-phase/ 2-winding
Weight (Tonnes)	306	261	268	230
Height (m)	5.5	5.3	5.6	5.1
Width (m)	5.5	5.4	5.4	5.3
Length (m)	10.7	10.4	10.3	10.0

It is not practical to expect the width and height of such units to be below 5m.

9.7 Testing

The test voltages for the converter transformer are given in the specification included in Appendix 1. These test levels are within the capability of present day test equipment.

9.9 Conclusion

The converter transformers for an 800kV HVDC scheme can be built and tested using technologies presently available. However, the size of the transformers may prove problematic for shipping to locations in the world where such high power schemes may be utilized.

One advantage of going to this higher DC voltage is that the insulation clearance between the valve winding and the line winding is proportionately larger than that between the tap winding and the line winding. Hence the variation in transformer impedance over the complete tapping range is only ±3.5% (allowing for manufacturer tolerance), where as for a converter scheme rated below 600kV a more typical value would be ±7%. This will of course only make a small difference to the overall rating of the HVDC scheme but never the less may impact on insulation levels and number of thyristor levels in a valve.

10. SMOOTHING REACTOR

The smoothing reactors can be oil immersed or air cored air insulated. For the system under consideration a 300mH reactor is envisaged.

10.1 OIL IMMERESED SMOOTHING REACTORS

For a 800kV, 3000A smoothing reactor the approximate insulation level is expected to be as following

LIWL/SIWL terminal-to-ground	2100/1675kV
LIWL/SIWL terminal-to-terminal	2550/1950kV
DC test voltage	1.5 U_{dN}
Polarity reversal test voltage	1.3 U_{dN}

With today's technology construction of 3000A, 800kV oil filled reactor should not be a problem. Impulse tests should be done with negative polarity as is the current practice, because it is the insulation under oil that is tested. BIWL/SIWL terminal-to-ground of 2100/1675kV inside the reactor is then no problem. Similar values are used for 750kV ac shunt reactors. The BIWL/SIWL terminal-to-terminal of 2550/1950kV is a problem because the test setups currently in use require that the terminal-to-ground insulation then be designed for this level also. It may be acceptable to demonstrate the terminal to terminal withstand voltage capability of 2550kV by calculations. At present the WG believes that test facilities are available in several independent labs.

10.2 AIR CORED AIR INSULATED SMOOTHING REACTOR

The air cored air insulated smoothing reactors offer some technical and economical advantages over the long proven oil smoothing reactor. Whether a dry type reactor can be built for HVDC system as high as 800kV remains to be demonstrated and proven by tests and field experience. As converter voltage and current increase, smoothing reactors will get bigger and series connected units will be required to meet the specified performance.

For 800kV dc proper shielding of top and bottom of the coils is important.

The WG has indication from a manufacturer that a 300mH reactor rated at 800kV and 3150A can be manufactured as three series units (See Appendix 2).

11. DC SWITCHYARD EQUIPMENT

The following apparatus may be connected to the 800kV pole bus, based on two series converters per pole:

- By-pass breaker
- Disconnects and grounding switches
- Arresters
- DC voltage dividers
- Current transducers (optical)
- PLC filter reactor
- PLC filter capacitors
- PLC coupling capacitor

- Harmonic filter capacitor
- Post and String Insulators

11.1 Current transducers

The present state of the art for current transducers for high voltage is optical current transducers. This means that the only difference between an 800kV current transducer and a 500kV current transducer is the length of the optical fibers. The optical fibers are enclosed in some kind of insulator, either a porcelain insulator that also serves as a support insulator or a composite insulator. The length of this insulator is determined as a conventional insulator.

11.2 Voltage divider

Since the voltage divider is mainly a pure resistive component, the voltage grading along the insulator is well controlled. For the insulators, the porcelains are glued together by segments, but composite insulators are preferably manufactured in one single piece. Most manufacturers of composite insulators has a limit of ~6 m in insulator length, but this limit is due to the existing tools, and can be solved.

There is no principal difference for the design of the voltage divider for 800kV compared to lower voltage levels. The internal design of the high voltage end must be done with care, since the corona inception is not only depending on the electric field strength, but also on the absolute voltage level. Also the cooling of the resistive element will be affected by the need for more radial paper insulation. Also this can be handled by a proper design.

Thus, voltage dividers will not encompass any difficulties, however a simple scaling of voltage dividers for lower voltages is not sufficient, but a thorough complete design is needed.

11.3 Arresters

The arresters for 800kV HVDC can be realized using the technique available today. Arresters are today manufactured in composite housings as a single string for each column, and the required energy capability is achieved by connecting two or more strings in parallel. Arresters usually cause no problem regarding external insulation, since the voltage grading along the arrester is well controlled by the leakage current through the arrester. Thus, no difficulties are foreseen at the design of arresters for 800kV DC.

11.4 Testing

For this type of equipment there should not be a problem in providing the test facilities.
The expected test voltages for the equipment connected to pole voltage are:

Lightning impulse test	2100kV

Switching impulse test	1700kV
Alternating voltage withstand	900kV
DC withstand test 60 min.	1200kV
DC polarity reversal test	1000kV

Several laboratories can provide the voltage levels required for the testing.

12. EXTERNAL INSULATION

12.1 General

If voltage levels far above what is in common use today are to be used, the design practice for HVDC stations should be reconsidered. However, some rules are valid, despite the voltage level:

- The converter stations shall be located in low pollution areas if possible
- The number of insulators on the DC-side shall be minimized, specifically large diameter insulators
- As far as possible the insulators shall be located in such a way to avoid uneven wetting.

12.2 Environment

Besides the voltage level, the pollution level is the most important factor for the insulator performance. Thus, for the proper choice of the insulators it is important to determine the expected pollution level.

Based on experience different degrees of pollution of insulators can be classified as:

Clean	ESDD	<0.01 mg/cm^2
Light	ESDD	0.01-0.03 mg/cm^2
Medium	ESDD	0.03-0.1 mg/cm^2
Heavy	ESDD	0.1-0.25 mg/cm^2
Very heavy	ESDD	>0.25 mg/cm^2

In coastal areas the free salt particles from the sea are transported by the wind on to the insulators. The deposit depends on the wind, direction and velocity, the nature of the shore and the distance and topography between the shore and the insulator. There are no reports of any difference between the pollution level on AC and DC insulators in this case, since the wind and not electric forces distribute the pollutant on the insulator. Thus for a given location for a future HVDC station the pollution level can be quite well predicted by studying existing AC insulators.

Industrial pollution is a more complicated case compared to coastal pollution. The composition of industrial pollution is not as well defined as sea generated pollution, but can vary considerably in composition at different locations in parameters like dissolving ability in water and ratio between NSDD and ESDD. Also the pollution level on the insulators can change with time depending on changes in industrial activities and that can be difficult to predict. In the western world general trend is that the pollution level is decreasing due to restrictions, but in other parts of the world the pollution level is increasing due to industrialization. The deposition of the contaminant on the insulator is different compared to NaCl deposition, since the pollutant is in the form of an aerosol and is affected by the electrostatic field around the insulators. In some cases the opinion is that the pollution level for DC is up to five times the pollution level for AC insulators in equivalent environment, but a common value is 1.5 to 2, [14].

All these factors together make it more complicated to predict the performance of DC insulators in heavy polluted industrial areas. Also industrial pollution contains a considerable amount of unsoluable (neutral) contaminants, whose influence on the withstand voltage is not fully mapped yet.

12.3 Type of Insulators

The most common material used in HVDC insulators is a porcelain. A common design target for HVDC-stations is 40 years lifetime. Porcelain insulators fulfill this requirement even in severe environment conditions. During the years porcelain insulators have been developed regarding new shed profiles and insulator strength.

The only types of composite insulators to be considered here are silicone rubber insulators. Composite insulators have come to wide use in AC transmissions in recent years, particularly as line insulators. The advantages compared to glass and porcelain insulators are:

- Lower weight
- Lower price
- Good surface properties: The surface has high water repellant properties, at least for new insulators
- Personal safety: In case of exploding insulators, the composite insulators do not launch heavy solid pieces like porcelain insulators do

Some reasons why composite insulators have not come into more use for HVDC are:

- Reluctance among the users regarding the long term properties for the material
- Composite insulators are not as well suited for axial compressive load as porcelain insulators
- Lower resistance against arcing
- Limitations in the shed profiles that can be manufactured

The personal safety advantage is unquestionable and enough reason to implement composite insulators for apparatus in HVDC-stations.

12.4 Corrective Actions

Due to the problems associated with pollution flashover on HVDC insulators different countermeasures have been developed during the years. A survey of the flashover rate and countermeasures for most of the existing HVDC stations is found in [16]. On 10% of the existing converter stations no maintenance at all is done. On the remaining 90 % some kind of actions is done, and in most cases only a few critical insulators are treated. The different actions taken to reduce the flashover rate have been effective. The most common countermeasures applied after the design of the converter station are:

- Washing
- RTV-coating
- Silicone-grease coating
- Booster sheds
- Live washing

12.5 Alternative Design

To avoid the problems with outdoor insulation, the DC-yard has been enclosed in a separate building in two converter stations, Sellindge in the 2000MW Cross Channel transmission and in the Korea/Cheju Island connection. The reason was the extreme salt contamination expected because of the proximity to the sea. In Sellindge the specific creepage is only 20mm/kV and no flashovers have been reported. For the Zhangping bipole 1 end of the Three Gorges transmission scheme where heavy pollution is expected, indoor DC-yard is designed.

The requirements on the DC-yard enclosure will depend on the type of pollution expected. A quite simple building will be enough to give good protection for salt storms. However, aerosols will contaminate the insulators unless the enclosure is sophisticated. Also the contamination might be wetted by condensation or absorption [12]. Thus an enclosure for protection from industrial pollution must be more sophisticated with controlled tightness and controlled humidity and temperature variations. For a well designed indoor DC-yard the specific creepage distance can be as low as 14mm/kV, and thus the switching impulse withstand level will determine the length of the insulators.

SF_6 encapsulation of the DC-equipment is a possible way to reduce the outdoor insulators, although this has come to limited use. In the Gotland transmission, 150kV DC, the connections between the converter transformers and the thyristor valves were done by SF_6 insulated conductors. The station has been in operation for 16 years with good results and the SF_6-buses have been performing well. Japanese manufacturers have produced prototypes of SF_6 enclosed DC-filters and thyristor valves [19], although there is no report on commercial operation. The main reason why SF_6 is not used more in HVDC is the cost and lack of operating experience.

12.6 Dimension of Porcelain Insulators

By curve fitting of experimental results it is easy to find formula for dimensioning of porcelain insulators:

k = $140 \times SDD^{0.33}$ where
SDD = pollution level in mg/cm^2 in laboratory testing
k = specific creepage in mm/kV

In figure 2 the insulator height is given as a function of specific creepage distance given for insulators with 250mm average diameter at different DC-voltages using the relation above. Discussions with insulator manufacturers the impression is that it is possible to manufacture support insulators that are 10m tall. 10m for an insulator with diameter 250mm (support insulator) corresponds to a length of 13m for an insulator with diameter 600mm for the same withstand voltage. However, already above 5-6m the diameter of the support insulators should be bigger than 250mm due to mechanical reasons, or alternatively parallel insulators could be used. If the upper limit of 10m is accepted as maximum insulator length this means that without special arrangements outdoor converter stations for voltage levels above 500kV is only possible to realize in areas which give rise to pollution levels on insulator, equivalent to clean or light according to the classification above.

12.7 Dimensions of Composite Insulators

There are no generally accepted dimensioning rules for composite insulators for HVDC. In some installations composite insulators with very short creepage distances have worked very well, like one 500kV wall bushing in Dorsey converter station, Manitoba Hydro, 22mm/kV as a replacement of a porcelain bushing, and one 400kV wall bushing in Sylmar converter station, LADWP, 23mm/kV. In both these cases, there had been several flashovers on the porcelain bushings, but no single one on the composite bushings following several years of operation.

Proper operation of composite insulators in DC applications for at least 10 years have been demonstrated in Anneberg test station, although at low pollution level [20].

Still there are no generally accepted rules for dimensioning of composite insulators for DC. In the specification for the Three Gorges project in China the requirement on SIR insulators is that the creepage distance can be 75% of the corresponding creepage distance for the equivalent porcelain insulator. This is also supported by the laboratory tests [21].

Most manufacturers of composite insulators have an upper limit of ≈ 6 m in length for the insulators, thus restricting the possible creepage length. However, this limitation can be overcome by investments in tools.

12.8 Conclusions

It is obvious that outdoor insulation is a major issue for converter stations for DC voltages above 600kV. The most effective way around the problem is to use an indoor DC-yard, and thus there will be only one single outdoor insulator per pole for line termination. For cable transmissions (when cables for voltages higher than +/-500kV are available) the cable termination can be indoors as well. An outdoor yard can be used in clean and light polluted areas, however it is desirable to reduce the number of insulators in the DC-yard as far as possible. In heavier polluted areas frequent maintenance is needed.

13. CONVERTER STATION LAYOUT

When designing the converter station for 800kV designers will be faced with large space requirement especially for the valve halls, converter transformers and other system equipment such as filters.

While the actual station layout will vary slightly from one system to another, however the general layout of the 800kV station will be similar to the present day systems with two converters in series per pole. Figure 3 shows the single line diagram of one pole in the converter station.

The final station layout will have to strike a good balance between the following;

- equipment insulation and air clearances
- creepage distances
- ease of equipment replacement
- costs of the converter station

13.1 EQUIPMENT INSULATION AND AIR CLEARANCES

The equipment insulation levels and the air clearances given in Section 7 are the approximate values only and must not be considered to be a guide. The actual insulation level and the air clearances will vary from one project to another and must be determined by a detailed insulation coordination study specific to that project. The environment (heavy pollution, seaside or low pollution, etc.) in which the station will be located will also have an influence on the layout.

For details on creepage and outdoor insulation refer to section 12.

13.2 EASE OF EQUIPMENT REPLACEMENT

The service experience of converter transformers shows that in addition to providing site spare transformer, it is very critical that the transformers and the associated bus work should be arranged in such a way that the spare transformer can be placed into service in maximum of 3 days (in any location) without having to remove any other equipment or structures. The bus must be designed so as to allow enough clearance for the rigging equipment to operate without affecting the operation of the healthy converters. This requirement will naturally result in larger station area and higher cost.

13.3 VALVE HALL DIMENSIONS

Over the years, the converter station space requirement has been reduced and optimized. When comparing with mercury arc valve, it has probably been reduced by half. This space has been further reduced by having converter transformers installed adjacent to the valve hall wall with the secondary bushings penetrating inside the valve hall. In the case of a bipolar system it is common to find a building space connecting the valve halls of the positive and negative poles. The space usually houses the mechanical systems, control room ventilation room, air conditioning system, spare parts, maintenance areas and service rooms. Over all layout of the converter station is envisaged as shown in fig 4.

As discussed in section 9, the converter transformers for both the low voltage and the high voltage converters will be of the single phase two winding type with the valve side bushing penetrating through the wall.

The valve hall size for the lower voltage (400kV) converter is expected to be slightly smaller than the present day 500kV converter valve hall and is not expected to present any technical challenge.

The plan area of the valve hall is dictated by the connection between the transformer and the valves.

Theoretically there are a number of ways to connect the transformers to the valves. However the following two arrangements are most likely to be used.

ALTERNATIVE 1

- **The thyristor valves are quadrivalves.**
- **The transformers are arranged as shown in fig 5**.

This design is similar to the present day designs for single converter per pole at 500kV level. The star and delta connections on the valve side are formed inside the valve hall.

This alternative results in a valve hall of slightly smaller width than the alternative 2.

The design can be used for both the low voltage and the high voltage converters although the connections for upper bridge in the high voltage converter may present a problem.

ALTERNATIVE 2

- **The thyristor valves are built as double valves.**
- **The transformers are arranged as shown in fig 6**.

In this arrangement the transformers and the double valves belonging to the star bridge are located on one side of the valve hall and those belonging to delta bridge are located on the other side of the valve hall. The star and delta connections on the valve side are formed inside the valve hall.

This alternative results in a wider valve hall than the alternative 1.

This design is more likely to be used for the higher voltage converters.

13.5 DC SWITCHYARD

The basic layout of the dc switchyard will be similar to the existing schemes with two series converters per pole (fig 4). The dc switchyard will contains

- four by-pass breakers,
- twelve disconnect switches,
- two neutral bus switches,
- four ground switches,
- two smoothing reactors,
- the DC filter with respective switches,
- two low voltages high speed breakers
- one neutral bus ground switch
- two high voltage high speed breakers or disconnects, depending on the application .

13.6 TOTAL DIMENSIONS

The dimensions of the complete station considering the clearances and the layouts presented above are as shown in figure 7 [4].

14. SUMMARY

HVDC systems above 600kV are most likely to be considered where large amounts of power is required to be transmitted over distances in the range of 1000 km to 3000 km. Based on the research available and experience gained from AC systems above 765 kV, an HVDC system at voltage level of 800 kV is technically feasible. For voltage levels above 800 kV more research will be required. Although the economic bipole rating at this voltage level may vary from 2000 MW to 5600 MW, a more practical range is between 4500 MW and 5600 MW. At these power levels, the limitations on the weight and size of the transformer due to transport restrictions will likely dictate the use of two series converters per pole.

The ac system connected to an HVDC system of this power level can be at 400kV to 765kV. At these power level the system strength may be moderate to weak however the technical problems related to weak ac system are not any different from the current HVDC systems.

No problems are anticipated in building thyristor valves however finding a test lab being able to produce higher test voltages may be a problem.

The converter transformers can be built and tested using present technologies. However based on the failure rate of the converter transformers in the existing schemes special attention must be paid to the design of the converter transformers.

The smoothing reactor (oil immersed or air cored air insulated) can be built and tested at this voltage level.

In the existing HVDC systems, the flashovers on the outdoor insulation are a major problem. The insulation level of the external equipment at 800 kV level, in areas with pollution level of higher than the medium, would require special design practices and deviation from standard design. The converter stations should be located in low pollution area if possible.

Other DC equipment such as by-pass breakers, voltage dividers, current transducers etc. are not expected to present any major problem.

The main driving force behind applying HVDC voltages above 600 kV will be strictly dictated by economics and cost of losses.

15. CONCLUSIONS

It is possible to build converter stations at 800kV dc, provided the design is done specifically for 800kV without extrapolation from the current dc voltage levels of 600kV.

The following areas are of concern for the 800kV level

- External insulation in medium to heavy pollution areas.
- Converter transformers
- Smoothing reactors

With the current state of the art, the thyristor valves can be built for the 800kV dc converter station.

Limited test facilities are available to accommodate the test voltages specified and the physical size of the equipment.

More stringent quality control will be required if the 800kV converter stations are to succeed.

Converter stations at voltages higher than 800kV are not envisaged.

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APPENDIX 1

Upper Bridge Converter Transformer Specification

1 GENERAL

This specification provides outline information on the transformers required for a 5000MW, ±800 kVdc, bipole transmission scheme. Each pole is to consist of two series connected converter.

2 ARRANGEMENT

Single phase two winding.

3 TRANSFORMER DATA

3.1 General Data

3.1.1	Vector group (in final 3 phase configuration)	YN/d11/y0
3.1.2	Nominal system frequency	50 Hz
3.1.3	Maximum ac system SCL	15,000 MVA

3.2 Power Rating

3.2.1	Nominal rated power / nameplate rating	243MVA

3.3 Line Winding Voltages

3.3.1	Nominal ac system voltage	500 kV rms.

3.4 Valve winding Voltages for the higher voltage 6 pulse bridge

3.4.1	Nominal rated valve winding ac voltage (Line to line value of)	165.0 kV rms.
3.4.2	Maximum rated valve winding dc voltage with respect to ground	± 800 kV dc

3.5 Valve Winding Current

3.5.1	Nominal direct current	3125 A dc
3.5.2	Maximum normal repetitive di/dt of valve winding current	3.7 A/µs
3.5.3	Converter induced fault current	60-kA peak

3.6 Impedance

3.6.1	Nominal impedance	0.12 pu
3.6.2	Base power (3-phase valve winding)	730 MVA
3.6.3	Base voltage	165 kV rms.

3.7 On-Load Tapchanger

3.7.1	Range of tapchanger expressed as a percentage of Nominal line winding turns	-7 to +15%
3.7.2	Maximum tap step expressed as percentage ratio change (e.g. $(R_2-R_1)/R_1$)	<1.5 %

Insulation Levels at the Bushing Terminals

The bushing manufacturer shall add atmospheric correction to the insulation withstand capability at bushings for both indoor and outdoor application.

3.8.1 Line winding and Neutral Insulation

3.8.1.1	Line winding lightning impulse (chopped)	1425 kV pk
3.8.1.2	Line winding lightning impulse (full)	1425 kV pk
3.8.1.3	Line winding switching impulse	1175 kV pk
3.8.1.4	Line winding bushing lightning impulse (chopped)	1550 kV pk
3.8.1.5	Line winding bushing lightning impulse (full)	1550 kV pk
3.8.1.6	Line winding bushing switching impulse	1175 kV pk

3.8.2 Valve Winding Insulation Levels

3.8.2.1	Valve winding lightning impulse (chopped) to ground	1990 kV pk
3.8.2.2	Valve winding lightning impulse (full) to ground	1990 kV pk
3.8.2.3	Valve winding switching impulse to ground	1891 kV pk
3.8.2.4	Valve winding lightning impulse across winding	1050 kV pk
3.8.2.5	Valve winding switching impulse across winding	803 kV pk
3.8.2.6	Valve winding 60 minute dc withstand	1223 kV dc
3.8.2.7	Valve winding polarity reversal withstand	834 kV dc
3.8.2.8	Valve winding bushing lightning impulse (full) to ground	2290 kV pk

APPENDIX 2

AIR CORED AIR INSULATED REACTOR

1. Performance specification

DC system voltage	+/- 800 kV
DC system current	3150 A
Nominal inductance	300 mH
Ambient temperature	-45°C to +45°C
Atmospheric pollution	medium

2. Manufacturer technical data

Number of units in series	3
Dimensions of each unit:	
External diameter	4267 mm
Height	3972 mm
Weight:	
Transport weight	62, 500 Kgs
Installed weight	60, 500 Kgs
Number of parallel elements per unit	25
External withstand capabilities	
Basic impulse level per coil	
Terminal to ground:	
Upper terminal	1300 kV crest
Lower terminal	2000 kV crest (insulator)
Terminal to terminal	1300 kV crest

Recommended factory tests

Type tests as per standard: IEC or ANSI

- Temperature rise
- Wet switching impulse on insulators
- Wet dc withstand on insulators
- DC RIV
- Sound Level

Routine tests, as per standard

- R.D.C.
- Load loss

-Impulse test

Support insulators	
Number of supports	8 Assuming no seismic
Support height	9150 mm
Support creepage distance	33 mm/kV Based on 800 kV
Mounting arrangement	8 vertical support legs
Recommended surface treatment	nil
Temperature rise @ 3150 A	
Average	60°C
Hot spot	90°C
Short time temporary overload	
1 sec	3 p.u.
1 min	1.2 p.u.
1 hour	1.05 p.u.
Long time overload	
at 20°C	1.1 p.u.
at 0°C	1.2 p.u.
Audible noise at rated power	
10 meters from reactor	73 dBA pressure
50 meters form reactor	60 dBA pressure
Reactor construction description	Air core Air insulated Aluminum winding Fiberglass Encapsulated

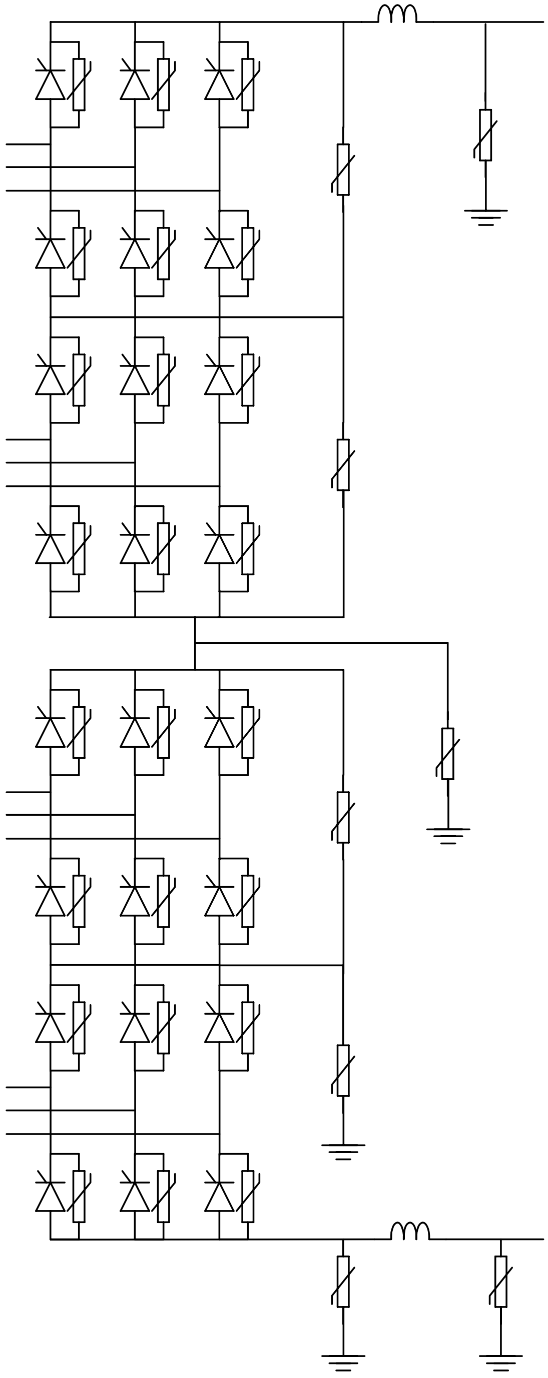

FIGURE 1   SURGE ARRESTER ARRANGEMENT

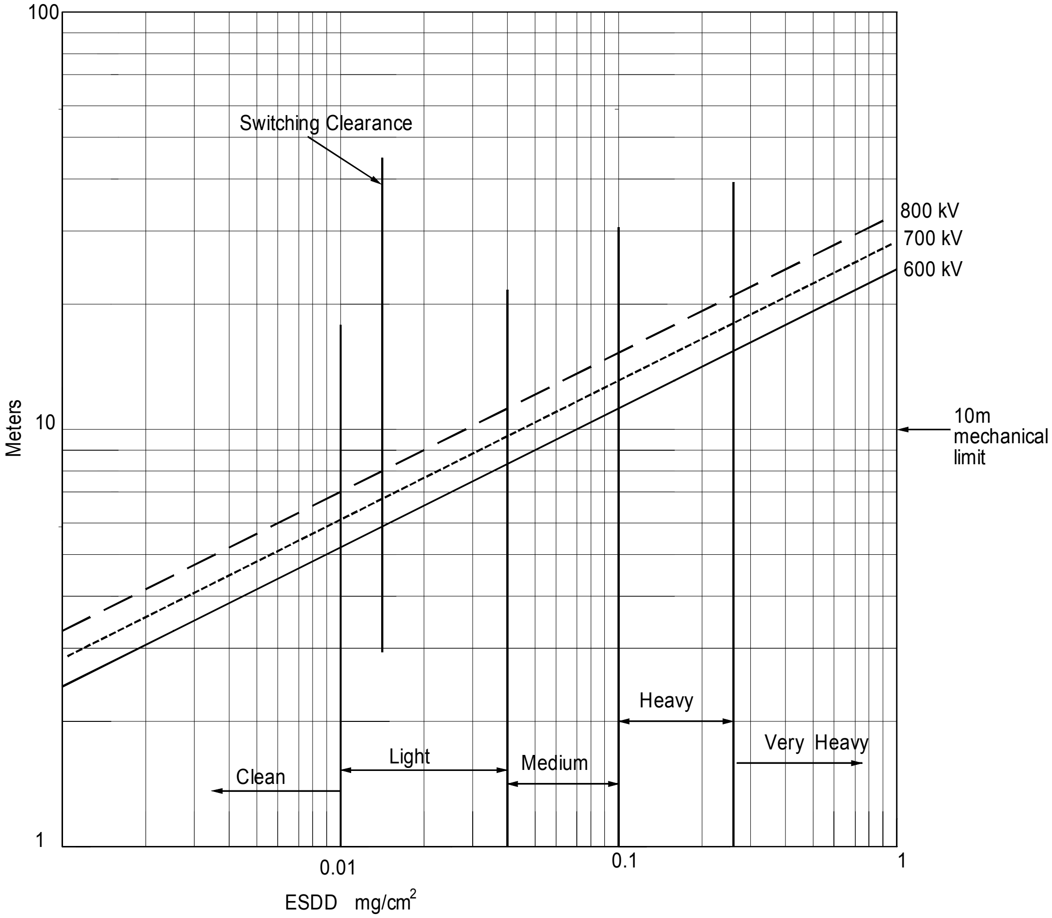

FIGURE 2 REQUIRED INSULATOR LENGTH AS A FUNCTION OF POLLUTION LEVEL

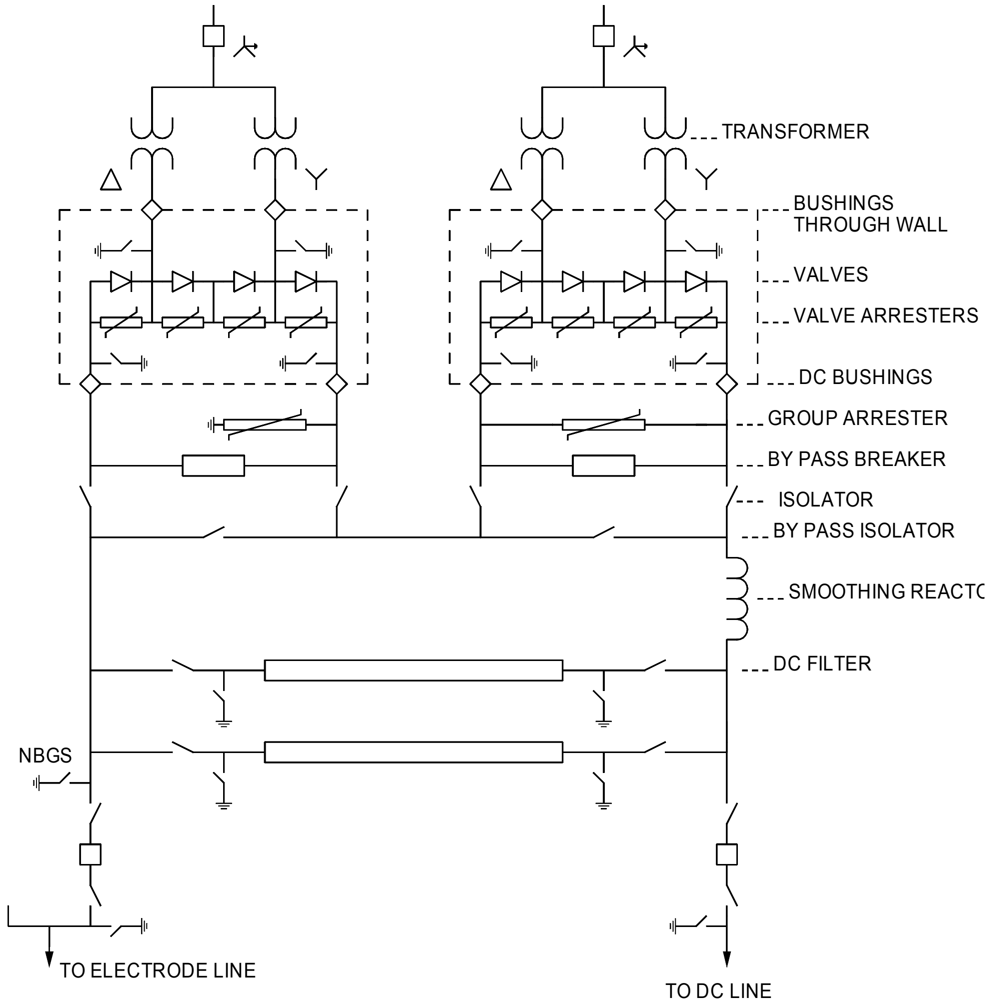

FIGURE 3 SINGLE LINE DIAGRAM OF ONE POLE IN A CONVERTER STATION

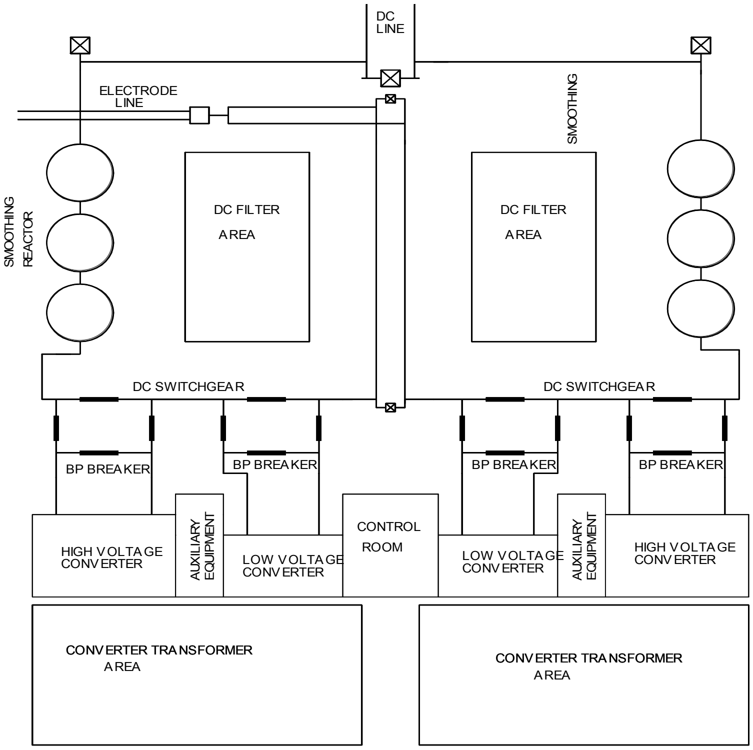

FIGURE 4 CONVERTER STATION LAYOUT

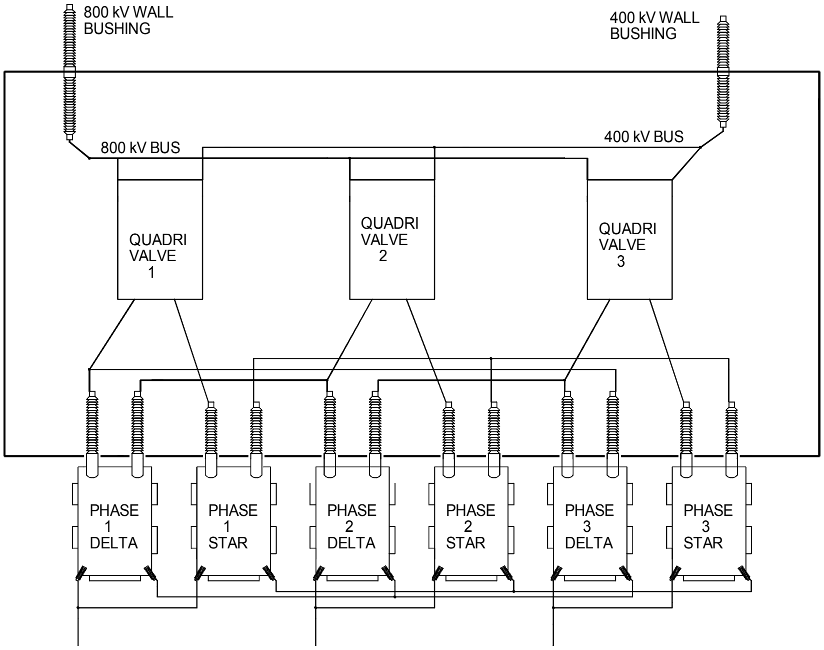

FIGURE 5 VALVE HALL WITH QUADRI VALVES AND SINGLE PHASE TWO WINDING TRANSFORMERS

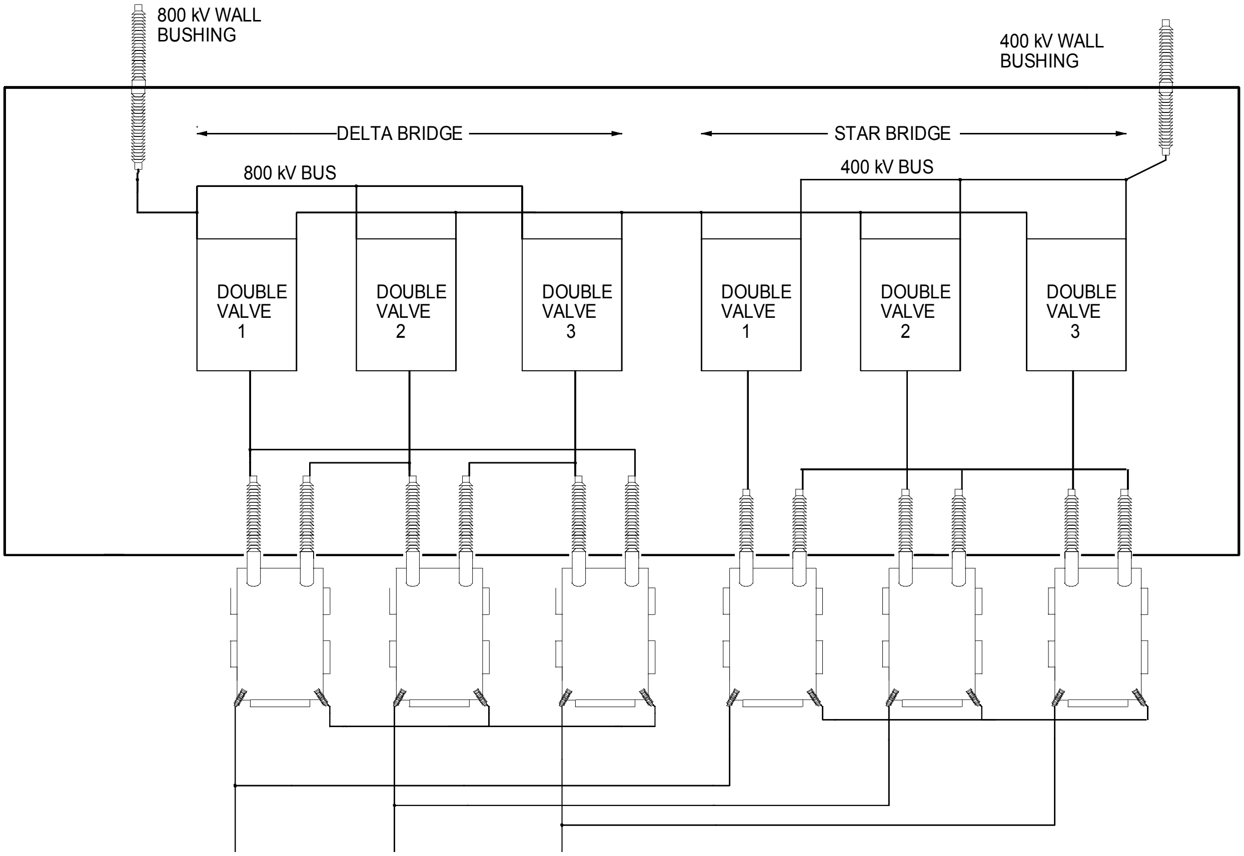

FIGURE 6 VALVE HALL WITH DOUBLE VALVES AND SINGLE PHASE TWO WINDING TRANSFORMERS

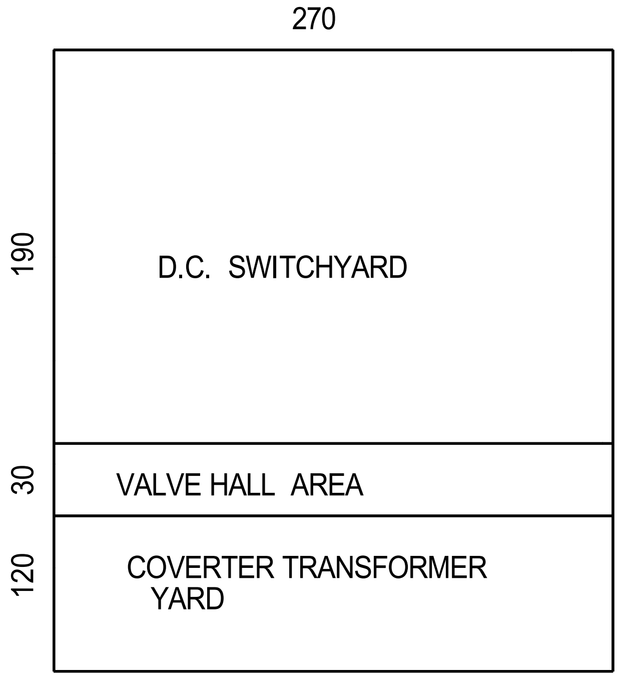

FIGURE 7 OVER ALL STATION DIMENSIONS