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765 kV Series Capacitors for Increasing Power Transmission Capacity to the Cape Region

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***Abstract* – A total of six series capacitors are coming on line in 2012 in the 765 kV national grid in South Africa, to strengthen the power transmission network in the Western Cape region. The installations, which form part of an initiative to increase power transmission capacity to the Cape region, will allow the utility more flexibility and reduce its reliance on existing local power generation. The ratings of the series capacitors range from 450 Mvar up to approximately 1300 Mvar.**

With series capacitors, the capability of already existing power lines can be increased considerably, thereby decreasing the need for new lines in cases where the need for power transmission capacity has grown. Likewise, in green-field projects, the amount of transmission lines to take care of a certain amount of power transmission can be kept to a minimum.

Series capacitors have undergone strong development in recent years, as well. A hardware platform named Fast Protective Device (FPD) has been developed, and successfully introduced into the commercial series capacitor market.

The paper presents the ESKOM 765 kV series capacitor project, offers some background regarding grid performance requirements, highlights a few vital steps in project execution, as well as gives some salient design features of the series capacitors.

I. INTRODUCTION

With power demand on the rise, power transmission needs to be developed at a corresponding pace. In long power transmission systems, care must be taken to maintain synchronism as well as voltage stability at all times, particularly in conjunction with system faults. For 765 kV, this is particularly true, since at this voltage level, large amounts of power are typically transmitted, and lines tend to be very long, with power transmission corridors reaching and even exceeding 1.000 km of length, thereby putting particular demands on voltage as well as angular stability.

A traditional approach to transmission network development would simply be building more as well as more powerful lines. This, however, may not at all be the best way, as power transmission lines over long distances and of large power transmission capability cost a lot of money, take considerable time to build, and may be perceived as unattractive in the landscape. In fact, for environmental and esthetical reasons alone, it may very well turn out impossible to obtain the necessary permits to build new transmission lines. A more intelligent way may be to take a fresh look at facilities already in place in the system, and find ways for increased utilization of the said facilities. This is where series compensation is coming in.

Many years of successful use of series compensation in long and very long power transmission systems at voltages including 765 kV has proved the viability of this option for bulk power transfer [1]. With series compensation, by means of angular as well as voltage stability improvement, the power transmission capability of existing, long lines can be increased considerably [2]. Likewise, in green-field projects, the number of parallel lines can be kept to a minimum by using series compensation from the outset. This can be utilized to benefit when large amounts of power need to be transmitted over long distances to consumer areas.

In summary, series compensation of power transmission circuits enables several useful benefits as follows:

- An increase of active power transmission over the circuit without violating angular or voltage stability;
- An increase of angular and voltage stability without derating power transmission capacity;
- A decrease of transmission losses in many cases;
- A reduction of the number of required EHV transmission lines.

II. THE CASE

The electricity supply in South Africa is dominated by a large generation pool in the Mpumalanga province. Although the other provinces have some local generation, in order to satisfy the demand in all the other provinces a high voltage transmission network is required. The Western Cape, Eastern Cape, Northern Cape, Free State and North West provinces are supplied from a central backbone of the transmission grid known as the Cape Corridor. The Cape Corridor is a portion of the transmission network that stretches from Mpumalanga down to the Western Cape, approximately 1400km. The large distance and loading requires very high voltages and hence the corridor has 765kV and 400kV transmission lines. However the current 765kV network only extends half way along the corridor.

Two key factors are driving the strengthening of the Cape Corridor. The first is the requirement for network security and the second is the high forecasted demand in the greater Cape area. Eskom identified and initiated a number of transmission projects to address these issues. The projects identified included additional 400kV substations, 400kV series compensation and additional 765kV infrastructure. The 765kV projects included extending the 765kV lines further south down the corridor.

The transmission network was designed for an N-1 probabilistic network. However, after the Cape outages in 2006, NERSA (National Energy Regulator of South Africa) reviewed and changed the security planning criteria from N-1 probabilistic to a deterministic N-1 transmission network design. In light of these changes the Cape Corridor was reviewed and it was identified that additional strengthening was required. The most vulnerable part of the network was the northern half of the corridor. Four options were considered namely, i) Business as usual (no capital expenditure); (ii) Install 765kV series compensation and establish the Hydra – Gamma 765kV line; (iii) Build a new Zeus-Perseus 765kV line and establish a Hydra-Gamma 765kV line and (iv) Build a third Alpha-Beta 765kV line and establish a Hydra-Gamma 765kV line.

The preferred option was to implement the 765kV series compensation and establish a Hydra- Gamma 765kV line. The solution provided the overall best improvement in transfer limits, was the lowest cost option, had the least environmental impact, resulted in a significant reduction in system losses and provided the best project timelines to achieve the required increased capacity.

A. Series capacitor solution

A total of six series capacitors are coming on line in 2012 in the 765 kV national grid in South Africa, to strengthen the power transmission network in the Western Cape region (Fig. 1). The installations will allow the utility more flexibility and reduce its reliance on existing local power generation. The series capacitors are located at four sites along the Cape Corridor, with ratings of the series capacitors ranging from close to 450 Mvar up to more than 1300 Mvar:

- Alpha 1 & 2, 2x 446 Mvar
- Beta 1 & 2, 2x 1340 Mvar
- Perseus, 893 Mvar
- Mercury, 1119 Mvar

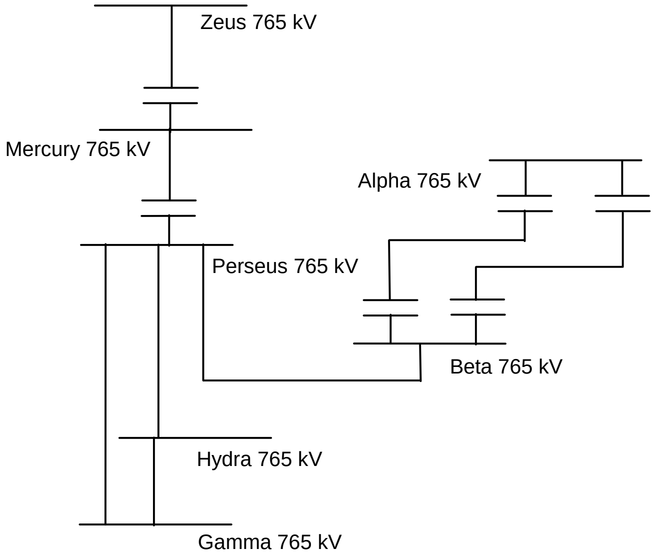

Fig. 1. 765 kV series compensated transmission corridor.

III. BASIC MECHANISMS

Series compensation of AC transmission systems has been utilized for many years with excellent results in a number of countries all over the world. The usefulness of the concept can be illustrated by means of well-known expressions relating to angular and voltage stability of power transmission systems (Fig. 2).

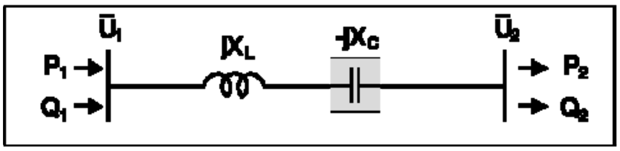

Fig. 2. Series compensated power transmission corridor.

A. Angular stability improvement

With regard to angular stability improvement, series compensation is highly efficient. By means of series compensation, the overall reactance between the line ends is reduced. The power transfer across a line can be approximated by the following expression:

$$P = \frac{U_1 \times U_2}{X_L - X_C} \times \sin\delta \qquad (1)$$

where
P = active power transfer
U_1 and U_2 = end voltages of the transmission circuit
X_L = line reactance
X_C = reactance of the series capacitor
δ = angular separation between the line ends

From (1) it is evident that the flow of active power can be increased by decreasing the effective series reactance of the line. In other words, if a reactance of opposite sign (i.e. a capacitive reactance) is introduced in the denominator, a corresponding increase in power transmission is enabled without having to increase the angular separation of the end voltages, i.e. with the angular stability of the link unimpeded.

Similarly it is demonstrated that by introducing a capacitive reactance in the denominator of (1), it is possible to achieve a decrease of the angular separation with power transmission capability unaffected, i.e. an increase of the angular stability of the link.

An alternative way of expressing the impact of series compensation is by means of an increase of synchronizing torque, equal to the slope of the power vs angle separation relationship given by (1).

The influencing of transmission reactance by means of series compensation also opens up for optimizing of load sharing between parallel circuits, thereby bringing about an increase in overall power transmission capacity again.

B. Voltage stability improvement

The voltage of a transmission circuit depends of the flow of active power (P) as well as of reactive power (Q):

$$U = f(P,Q) \tag{2}$$

The explicit relationships between the quantities are not simple. Closer analysis reveals, however, that the reactive power contribution from a capacitive element in series with the line acts to improve the reactive power balance of the circuit, and thereby to bring about a stabilization of the transmission voltage. It can further be shown that this reactive power contribution is instantaneous and of a self-regulatory nature, i.e. it increases when the line load increases, and vice versa. It consequently contributes to voltage stability in a truly dynamic fashion. This makes series compensation a highly effective means for maintaining or even increasing voltage stability in a heavily loaded transmission circuit. And likewise, it allows additional power transmission over the circuit without upsetting voltage stability.

C. Degree of compensation

With the reactance of the capacitive element, i.e. the series capacitor equal to X_C and the inductive reactance of the line equal to X_L, we can introduce a measure of the degree of series compensation, k:

$$k = X_C / X_L \tag{3}$$

In power transmission applications, the degree of compensation is usually chosen within the range $0{,}3 \le k \le 0{,}7$.

Substituting k for X_C, we get

$$P = \frac{U_1 \times U_2}{X_L (1-k)} \times \sin\delta \tag{4}$$

which links power transmission capacity improvement of the intertie directly to the degree of compensation of the series capacitor(s).

D. Summary, usefulness of series compensation

The overall impact of series compensation of a transmission circuit can be summarized as in Fig. 3.

To summarize, series compensation of power transmission circuits enables several benefits:

- An increase of active power transmission over the circuit without violating angular or voltage stability;
- An increase of angular and voltage stability without derating power transmission capacity;
- A reduction of the number of required EHV transmission lines.

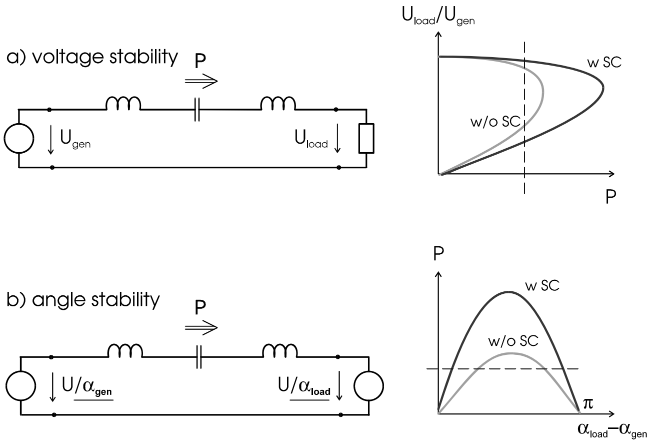

Fig. 3. The impact of series compensation on a) voltage and b) angular stability.

IV. MAIN ISSUES OF PROJECT EXECUTION

The project was awarded in late 2008. The locations of the four (4) stations Alpha, Beta, Mercury and Perseus can be seen in Fig. 1. The Alpha and Beta series capacitors compensate the existing Alpha-Beta 765 kV Lines 1 and 2, while the Mercury series capacitor compensates the new 765 kV line Zeus-Mercury, and the Perseus series capacitor compensates the new 765 kV line Mercury-Perseus. At Alpha and Beta the areas allocated for the series capacitors were inside the boundaries of the existing substations in order to avoid increasing the existing substation area. It shall be pointed out that both Alpha and Beta comprise two series capacitors, one for each AC line. With this in mind, several iterations of the layouts were necessary in order to fit the series capacitors within the existing areas. For the stations Mercury and Perseus, the areas for the series capacitors were allocated outside of the boundaries of the existing substations.

The design of the series capacitors is discussed in section V “Some Salient Design Features”. During the design phase, all the design and study reports and drawings were reviewed, discussed and finally approved before manufacturing started.

Before the site work could start at any station the health plan, environmental plan, method statements, etc had to be carefully reviewed.

At Alpha excessive amounts of “cut and spoil” soil needed to be removed from the site area (Fig. 4). Even though thorough soil investigation had been performed during the tender and design stages a solid rock was found during the excavation. Late changes of the layout were necessary, resulting in design changes to allow for the solid rock.

At Beta there were special concerns regarding water supply as there was a draught in the area when the civil works were planned to start. Water had to be withdrawn from a licensed water hole. The start of the civil works was postponed until the existing water hole in the area had been registered and approval had been given to draw water for the civil work. This issue postponed the start of the civil works by approximately one month.

At Mercury there was a lot of water in the ground as the site was built on wetland. A special solution was applied by using pile to support the foundations.

At Perseus the access to site was postponed by a lengthy process to acquire the land for the site.

Fig. 4. Alpha: excavation of excessive soil.

The equipment was delivered and stored at site until the installation work could be commenced. One of the important stages of the installation work is the lifting of the platform. In Fig. 5, the lifting of the double-segment platform at Beta is shown. The total length of the platform is 32 m.

Fig. 5. Lifting the double-segment platform at Beta.

The physical connection of the series capacitors to the 765 kV overhead lines is made via droppers. Before the droppers can be installed the line needs to be cut and flying insulators installed. In Fig. 6, both the flying insulator and the droppers are shown for one of the platforms at Beta. The series capacitor banks were installed between two towers. The droppers are required to be flexible for any movement of the overhead line. Therefore careful consideration must be applied during the design phase of the movement of the line and the corresponding forces applied on the dropper and busbar. For all operating conditions, the droppers need to be flexible enough to follow the overhead line. Furthermore, sufficient current carrying capability needs to be considered, using a large aluminum area, without any steel core. This makes the conductor soft. On the other hand, the conductor needs to have a certain stiffness not to take wind and create a bird cage of the conductor. A lot of iteration was performed both at the design stage and during the installation stage to find the optimal solution.

At Alpha, to fit busbars and disconnectors below the existing 765 kV overhead line, the clearance up to the existing line had to be increased. This was performed by installing additional, new towers. This work, at Alpha and Beta, required several outages of each of the 765 kV lines. Applications for outages were made, but with the 2010 World Soccer Cup and, at the time, bulk power transmission capability constraints in the network, outages were not granted until February-March, 2011. This greatly affected the time schedule and the finalization of the installation work. The completion of the installation work had to be postponed.

Fig. 6. Flying insulator and droppers for one Beta platform.

The commissioning of Alpha and Beta was successfully completed shortly after the permission was given for energization. For Mercury and Perseus, all the commissioning without live voltage (cold commissioning) has been completed. The 765 kV overhead lines at both Mercury and Perseus were not ready for energization and the hot commissioning (with live voltage) has been postponed until the AC line is fully available.

V. SOME SALIENT DESIGN FEATURES

The main circuit design is based on single segment schemes in four of the series capacitors (Alpha 1&2, Perseus and Mercury) (Fig. 7).

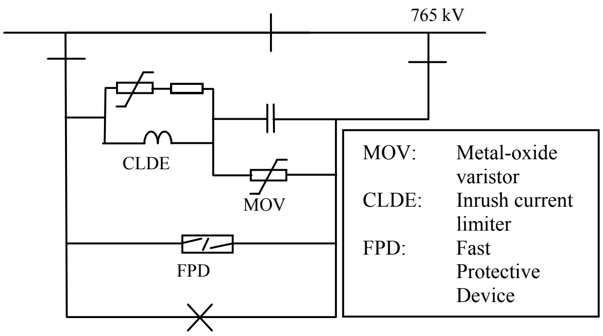

Fig. 7. Single segment series capacitor scheme.

In the remaining two (Beta 1&2), due to their sizes (each 1340 Mvar), sub-division into dual segments schemes has been applied (Fig. 8).

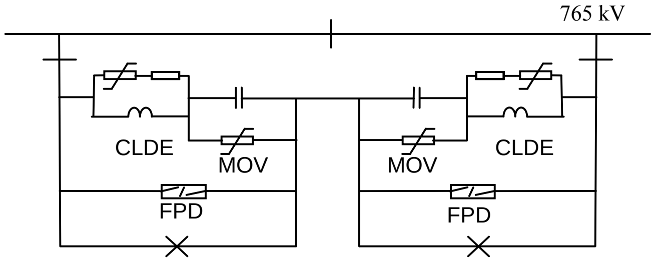

Fig. 8. Dual segment series capacitor scheme.

The main technical data of the series capacitors are listed in Table I:

Table I. Main technical data of the series capacitors (1).

Parameter	Alpha (per SC)	Beta (per SC)
System voltage (kV)	765	765
Rated reactive power (Mvar)	446	1340
Rated capacitor current (A)	3150	3150
Rated capacitor reactance (Ω)	15.0	2 x 22.5
Overload current for 30 minutes (A)	4253	4253
Rated cap bank voltage (kV)	48.0	2 x 71.8
Installed MOV, including 10% redundancy (MJ/phase)	20.9	2 x 25.4

Table I. Main technical data of the series capacitors (2).

Parameter	Mercury	Perseus
System voltage (kV)	765	765
Rated reactive power (Mvar)	1119	893
Rated capacitor current (A)	3150	3150
Rated capacitor reactance (Ω)	37.6	30.0
Overload current for 30 minutes (A)	4253	4253
Rated cap bank voltage (kV)	119.6	95.7
Installed MOV, including 10% redundancy (MJ/phase)	62.1	98.1

A. Protective scheme

The series capacitor protective scheme consists of a Metal Oxide Varistor (MOV), Current Limiting Damping Equipment (CLDE), the Fast Protective Device (FPD), and a

Bypass Switch (B). The Bypass Switch is of SF_6 type, with a spring operating mechanism. The CLDE consists of a current limiting reactor, plus a resistor and a varistor in parallel with the reactor. The purpose of the resistor is to add damping to the capacitor discharge current, and thus quickly reduce the voltage across the capacitor after a bypass operation. The purpose of the varistor is to avoid fundamental frequency losses in the damping resistor during steady state operation.

The damping circuit is connected in series with the capacitor in order to limit the stress on the bypass disconnector as well as allowing fast "nullification" of the voltage across the series capacitor following a bypass operation in order to mitigate high TRV on the line circuit breakers.

Upon fault initiation in the surrounding network, an increased current through the series capacitor generates a high voltage across the capacitor and the MOV. The increase in voltage causes the MOV to conduct the excess current past the capacitor, thus limiting the voltage across both the MOV and the capacitor to a defined protective level. During the conducting periods, the MOV absorbs energy. The design criterion for the MOV is to withstand the maximum energy accumulated during defined fault cycles.

The MOV has been designed to withstand the energy from external faults, i.e. faults appearing outside the series compensated transmission circuit, without bypassing the series capacitor. The series capacitor may be bypassed for any internal fault, i.e. faults located within the compensated transmission circuit and which is limited by the line circuit breakers for that circuit.

Each series capacitor is connected and disconnected from the line by means of two isolating disconnectors and one bypass disconnector.

B. Fast Protective Device

The FPD scheme is based on a hermetically sealed and very fast high power switch, CapThor™, which replaces conventional spark gaps. The FPD works in combination with the MOV, and allows bypassing in a very controlled way in order to reduce the energy dissipation in the MOV. The FPD scheme has advantages over previous, conventional schemes with spark gaps such as:

- More compact
- Unaffected by the environment
- Capacitor by-passing possible for a wide range of voltages over the series capacitor, including such voltages as appear over the series capacitor for smaller load flows than would be possible with conventional spark gaps.
- Adds flexibility for future series capacitor upgrading.

The encapsulated design is made possible by a combination of a mechanical switch called Fast Contact (FC) and a forced triggered spark gap called Arc Plasma Injector (API), both shown in Fig. 9.

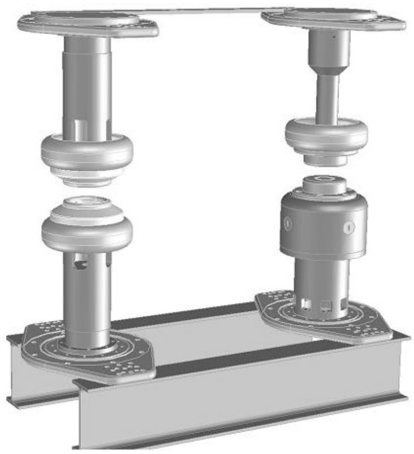

Fig. 9. CapThor: Arc Plasma Injector (API) to the left and mechanical Fast Contact (FC) switch to the right.

The API is made up of two high power electrodes arranged in such a way that an electric arc or plasma can be injected in the gap formed between the two electrodes. This will effectively create an electrical short circuit between the two electrodes. The electrodes are connected across the series capacitor and the short circuit between them will be a short circuit of the series capacitor [3]. The controlled environment in the encapsulated design also makes it possible to bypass the SC with the API at very low line currents, current levels that are significantly lower compared with the traditional open air spark gap. The bypass times are also way below the times possible if the series capacitor is bypassed by means of only the bypass switch. As stated, this makes the FPD concept a very effective counter measure to common series capacitor related problems such as TRV. This functionality is further described later in the paper.

The design of the arc plasma injector is based on a fundamental law of physics, according to which the breakdown voltage of a plasma gap is a unique function of the product of pressure and the electrode separation for a particular gas and electrode material[1] [4]. By keeping the gas pressure high, this together with an efficient triggering procedure allows a plasma gap of small physical dimensions and hence, a compact FPD.

Additionally, with high pressure in the plasma gap, the relative content of combustion products after a discharge can be kept low, and does not to any significant degree derate the voltage withstand capability of the gap.

The FC is based on a Thomson coil actuator [3]. This makes it possible to create a switch that can operate in times below 5 msec. To ensure that the contact is not stuck in a mid position a robust solution with linkage arms with springs is used. This allows for reliable and fast operation.

In case an operation is ordered a triggering pulse will be sent to the API that will bypass the series capacitor bank. At

[1] Paschen's Law

the same time an operation pulse will be sent to the FC that will start to close. Within 5 msec the Fast Contact has closed and the current will commute over to the switch branch.

A picture of CapThor from a field installation is shown in Fig. 10.

Fig. 10. CapThor, field installation.

C. Control & protection

The control system is based on the MACH 2 concept, which is a system of both hardware and software, specifically developed for power applications. MACH 2 is built around an industrial PC with add-in boards and I/O racks connected through standard type field buses like CAN and TDM (Fig. 11).

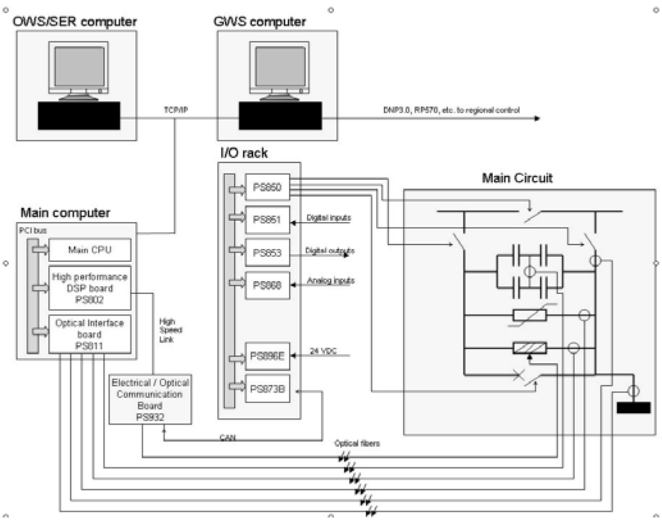

Fig. 11. MACH 2 control and protection system overview.

The series capacitors can be controlled from two different locations. Locally in the series capacitor control room there is an Operator Work Station (OWS) based on an industrial PC. The series capacitors can also be controlled from by a remote terminal unit (RTU) from a remote control centre. As an option, control can also be obtained via a Gateway Station (GWS), which is a protocol converter that enables communication with the series capacitor by means of a standard protocol.

The operator's interface (HMI) in the series capacitor control room is an InTouch application running on the OWS/SER computer (Operator Work Station/Sequence Event Recorder). This computer uses an SQL (Standard Query Language) database for the event handling. Event, alarm and fault lists are displayed on the OWS.

Current measurements for control and protective functions are attained by use of OCTs (Optical Current Transformers). The OCT consists of a current transducer in the high voltage busbar and an optical interface module in the control room. Signal transmission between the transducer and the interface is performed by an optical fibre system including platform links, high voltage signal columns and fibre optic cables.

This system offers benefits such as:

- No relay protection equipment needed on the EHV platforms;
- The optical current transducers are powered solely by means of light generated at ground level.

The following are the main part of the protective functions of the series capacitors:

- Capacitor unbalance protection
- Capacitor overload protection
- Capacitor discharge function
- Line current supervision
- Line voltage supervision
- Flashover to platform protection
- MOV overload protection
- MOV failure protection
- CapThor protection
- Pole disagreement protection
- Bypass switch failure protection

D. Mechanical design

As the series capacitors are operated at the same voltage level as the power transmission system into which they are integrated, they are located on fully insulated steel platforms, one platform per phase. The by-pass switch alone is located directly on the ground.

A lay-out of one phase out of three for a series capacitor of single segment type is shown in Fig. 12 (Mercury). The capacitor banks are located on either side of the platform, protective devices (MOV, CLDE and CapThor) in the middle. A site photo is shown in Fig. 13 (Mercury s/s).

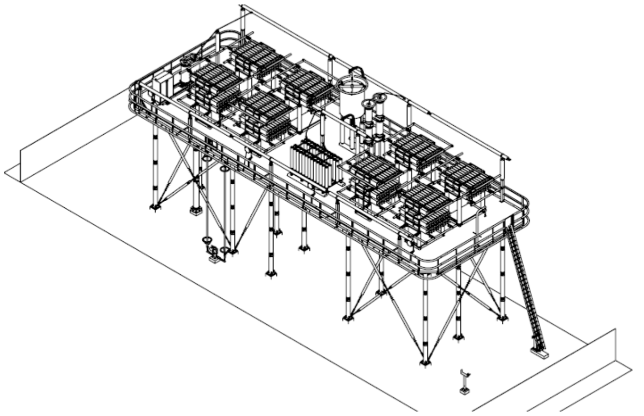

Fig. 12. 765 kV single segment series capacitor lay-out, one phase out of three.

Fig. 13. Site photo at Mercury s/s.

A dual segment lay-out is shown in Fig. 14, and a site photo in Fig. 15 (Beta s/s).

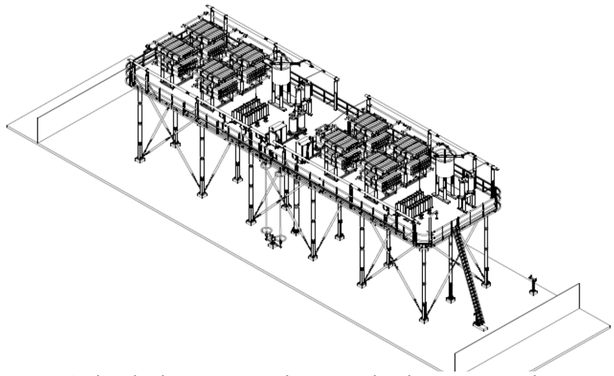

Fig. 14. 765 kV dual segment series capacitor lay-out, one phase out of three.

Fig. 15. Site photo at Beta s/s, one phase out of three.

VI. TRANSIENT RECOVERY VOLTAGE

The installation of a series capacitor in a transmission line can have a significant effect on the amplitude of the transient voltage which appears when a line circuit breaker opens to clear a fault [5]. The voltage, which affects the breaking performance of the line circuit breaker, is referred to as the Transient Recovery Voltage (TRV). Increased TRV is caused by the trapped voltage over the series capacitors when the line breaker is opened. Detailed studies of TRV were performed for the line circuit breakers in Alpha, Beta, Perseus and Mercury. The studies showed that increased TRV could be mitigated by feeding an external bypass order to the series capacitors from the line protections. Due to the speed of the FPD, this allows very fast bypassing of the series capacitor before the line circuit breakers break the fault current. This means the impact of trapped charges in the series capacitors is eliminated, and does not add to the TRV stressing of the circuit breakers.

In cases where series capacitors are installed in existing lines with existing line circuit breakers (Alpha-Beta 765 kV Lines 1 and 2), this is a highly beneficial feature which becomes available when utilizing an FPD.

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