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Powering The Way – A Paper on AC Link™ Technology for 21st Century HVDC Transmission

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Abstract The new AC-Link™ HVDC transmission converter employs a new technical approach that bypasses the problems affecting currently available products. This new approach is based on the AC-Link™ topology which was originally validated in the military. The AC-Link™ technology, patented globally, is a resonant converter topology which is naturally "soft switching", which is characterized by negligible switch turn-on and no turn-off losses. With no switching losses, the AC-Link™ system can use high voltage solid state power devices (i.e. IGBTs or IGCTs) and run at high converter frequencies (up to 20kHz using IGBTs). Power electronics systems that rely on PWM topologies are limited by the PWM characteristic of "hard switching", which produces undesirable switching losses and high dv/dt (voltage rate of change). With switching losses as a limiting factor, PWM systems must use lower voltage switches, and more of them. The result is higher cost, higher complexity, higher component count, and thereby higher risk factors.

1.0. Introduction to HVDC transmission

The benefits of DC voltage transmission have been well documented in numerous scientific papers and have been successfully operated for over 60 years. The original, now 'Classical,' line commutated converter (LCC) based HVDC transmission system is now almost used exclusively for the bulk transfer of large power and at very high DC transmission voltage levels. These large LCC systems currently utilize light triggered (fiber optic) thyristor valve assemblies and have DC transmission voltages of up to plus and minus (+/-) 600 kV DC. For overland transmission the rule of thumb is the transmission system must be operated with a minimum voltage of 500kVDC, a minimum power level of 500MW and over a minimum transmission length of over 500km. Below these minimum values of MW, voltage and distance DC transmission is more expensive than AC transmission due to the additional cost of the electronic AC-DC and DC-AC converters (including harmonic filters, VAR controllers and other equipment).

It is widely acknowledged that DC transmission is more efficient than AC transmission. In addition, the cost of construction for AC transmission lines is more costly than a HVDC. This is illustrated by the Siemens diagram reproduced as Fig 1 below. As can be seen, the 'break-even distance' is that distance prior to which AC transmission is less expensive. Beyond the 'break-even distance' AC transmission is more expensive than DC transmission. The crucial component in the DC transmission costs are that of the electronic converters and other equipment, including the facility.

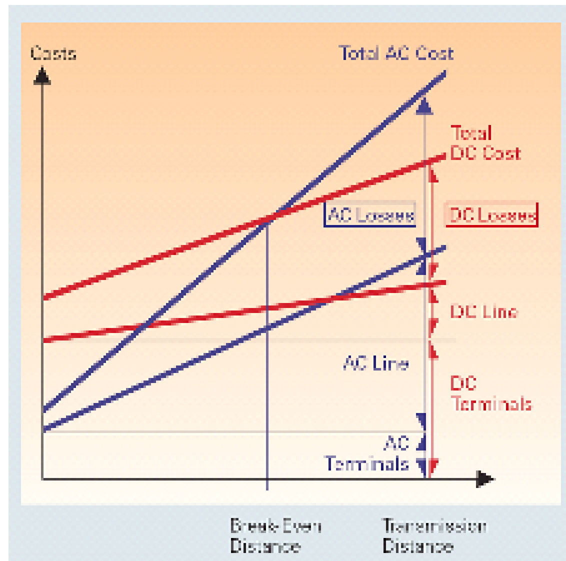

Figure 1 - AC and DC transmission costs as a function of the transmission distance

(Courtesy of Siemens)

Power transmission cost however is not the only reason for DC transmission. A large number of DC transmission systems are via subsea cables where DC is the only option since the AC cable charging current for cable length of over ~50km precludes the use of AC cables.

Back-to-back AC to DC and DC to AC converter stations are also used to transfer power between unsynchronized AC systems. Such systems are usually lower in power than the 500MW to 2000MW overland converter stations.

At present, there are two main types of HVDC converters; the Classical, current source, line commutate converter (LCC) and more modern PWM voltage source converter (VSC).

1.0.1. The 'Classical' line commutated converter (LCC)

The line commutated converter is essentially a current source converter which uses thyristor valves and large DC link reactors to provide the current source. Fig 2 below illustrates a simple mono-polar system.

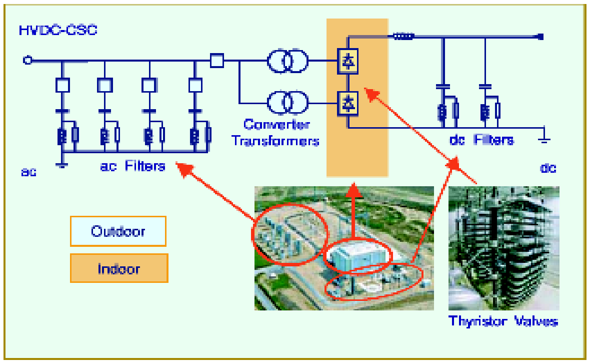

Fig 2 – Representation of Classical mono-polar LCC HVDC system

Classical HVDC converter systems can transmit very large amounts of power and at high voltages but require ‘line commutation’, or in other words, a substantial 60Hz (or 50Hz) AC power source to convert the DC power back to AC (i.e. to ‘naturally’ commutate the thyristors). Therefore, an AC power source is required at the receiving for these Classical HVDC transmission systems.

In addition, due to the phase controlled operation of ‘Classical’ line commutated converters substantial reactive power correction via capacitors is required at the stations in order to maintain a satisfactory displacement power factor. In addition, a number of switched tuned harmonic filters are also required to attenuate the subsequent voltage distortion.

There is a variant, termed a ‘Capacitor Commutated Converter’ (CCC) now available which improves the commutation failure performance when the converters are connected to weak networks. The commutation capacitors are connected between the converter transformers and the thyristor valves.

A typical layout for a bipolar Classical LCC system station is depicted in Fig 3 below.

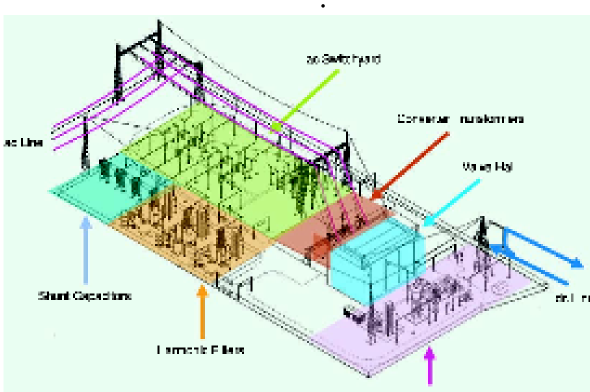

Fig 3 - Space requirements for a Classical HVDC 2 pole station with all the associated components

1.0.2. PWM Voltage Source Converters (VSC)

The problems associated with line commutation are eliminated with more modern Pulse Width Modulated (PWM) converters which are self commutating. Such systems are typically lower in power levels compared to the Classical LCC system and utilize power devices such as GTOs, IGBTs, or IGCTs. The companies which dominate this market are undoubtedly ABB with the ‘HVDC Light’ and Siemens with HVDC PLUS technology. Since PWM has both turn-on losses and turn-off losses, low switching frequencies are used to minimize the switching losses. Fig 4 illustrates a simplified VSC HVDC system.

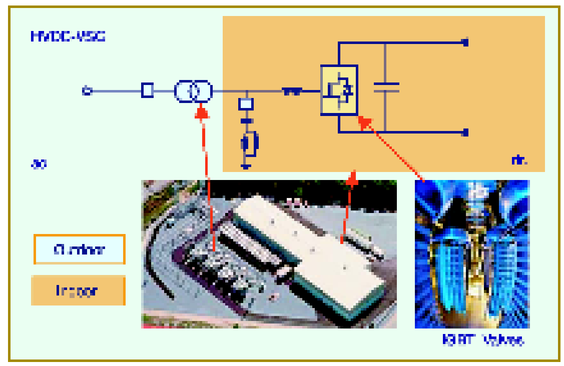

Fig 4 – Representation of 500MW PWM VSC HVDC system (ABB HVDC Light)

This technology, currently one of the two most advanced on the market, also requires a large foot-print area for large passive components (i.e. transformers, reactors) requires a number of large harmonic filters on the AC end, and large DC filters on the DC side. The net result is still a large (but not as large as for the Classical LCC installation) and costly converter installation. Please refer to Fig 5 for a typical layout of 500MW VCS system.

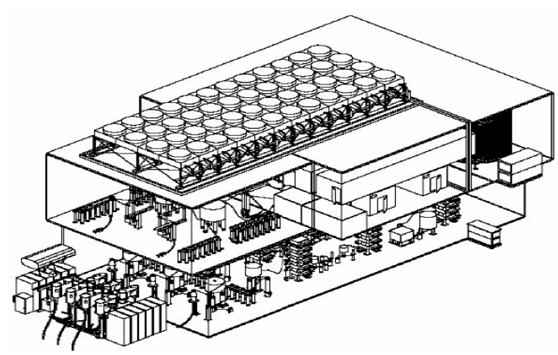

Figure 5 - Possible layout of compact VSC station for 500 MW. Dimensions in this configuration are 48 x 25 x 27 metres (L x W x H) = 32400 cu. metres. Ground floor: Transformer and AC-side filters. First floor: Phase reactors, converter valves, control and cooling equipment, DC-side filters and cable terminations. Second floor: Cooling fans may be omitted if a nearby river or other water is available for cooling (ABB).

Fig 6 below illustrates the 75MW ABB Murray-Link HVDC Light circuit installed in a 130m x 40m meter facility. This installation required a +/- 150 kV DC connection and significant harmonic filter requirements (75MVAr) for higher order harmonics.

1.0.3. HVDC significantly increasing in popularity

For many applications including subsea and now also overland, power transmission DC transmission is very attractive. The original HVDC subsea cables were pressurized, oil filled, paper insulated cables. Such were expensive and for the majority of cases not very economical. However, in the last 20 years much lower cost, extruded cables are available for DC operating voltages of up to 500kV with the required shielding and armor, for both subsea operation and for directly buried solid dielectric for overland.

The Murray-Link project (Fig 6) is an overland installation with a transmission distance of 167km. With a plus and minus installation (i.e. two poles of the DC voltage) no significant magnetic field is produced beyond a certain distance from the DC cables, the cables are out of sight, and no significant right of way is required. Cables can be installed parallel, even under the road or rail road and are protected from most adverse affects of the weather.

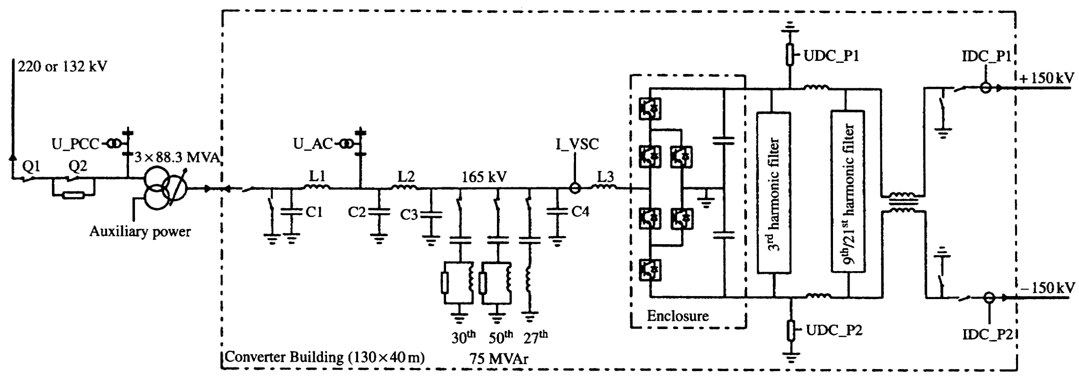

Figure 6 - HVDC Light (75 MW/+/-15-kVDC) converter station with power density of 0.014 MW/m^2

1.0.3. HVDC significantly increasing in popularity

Figure 7 illustrates complete AC to DC and DC to AC VSC system with the two converter stations and dual plus and minus cable configuration with 12 pulse input supplies.

The major problem with the DC transmission is not necessarily the cable cost but the cost of the AC to DC and DC to AC converter stations (this can also be appreciated by considering the physical size of the required stations).

In addition, a problem wilh all the converters, LCC, CCC and VSC discussed so far is that they are "hard switched", the converter station losses and the transformer windings are exposed to high dv/dt (voltage rate of change). In addition, the connecting transformers operate at the line frequency (50 or 60 Hz) and are therefore very large and expensive.

2.0. Introduction to AC Link™ HVDC transmission

The proposed AC Link™ HVDC transmission converter is based on the AC Link™ topology which was developed under the auspices of the so called US 'StarWars' program; it has been further refined and patented under the US patent …678. AC Link™ has also been patented in most industrial countries. Since the year 2000 AC Link™ based products have been developed for a number of US military applications (US Navy, USAF and US Army) by the defense contractor, SAIC, under the guidance of the inventor, Dr. Rudy Limpaecher. Since 2001, however, AC Link™ products have been developed and manufactured in parallel by the co-inventor, Erik Limpaecher, through his company, Princeton Power Systems Inc.

Varentec LLC, where Dr. Limpaecher is a senior board member, has secured all of the transmission and distribution rights for AC Link™ applications. It has commenced the required developments for HVDC (and distribution via DC ring mains) applications.

The AC Link™ technology is a resonant converter topology which is naturally "soft switching". (i.e. it uses a solid state, soft switching operation with neglible switch turn-on and no turn-off losses; unlike most conventional technologies). This permits the AC Link™ system to use high voltage solid state power devices and run at high converter frequencies (up to 20kHz using IGBTs).

It should be noted that the operational limits of a solid state switch (e.g. IGBT) is limited by the maximum heat ($P_{th\,max}$) that can be removed from the device in order to maintain the junction temperature at or below a defined maximum temperature.

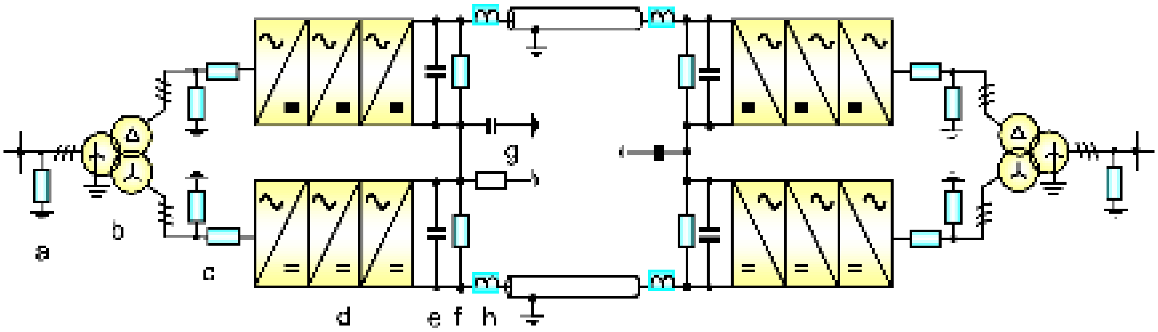

Fig 7 - Dual DC cable configuration with large 12-pulse HVDC Light converter stations.

Key : a) AC filter; b) phase shift transformer; c) HF blocking filter; d) two level VSC converter; e) DC capacitor; f) DC filter; g) grounding circuit; h) DC reactor

The equation has the form of:

$$P_{th\max} = A * I + (B_{ton} + C_{toff}) * V_s * I * f_s \quad (1)$$

Note that the first term in equation (1) is the conduction loss and the second term consisting of the switch turn-on and switch turn-off losses. The constants, including the maximum switch dissipation are defined by the device characteristics. As can be seen, both terms are proportional to the switch current which are in turn proportional to the switch power being controlled. As the second term increases, proportional to the switching frequency, the current and the subsequent throughput power needs to be reduced to retain (for most switches) the junction temperature below a value of, for example, as 125 deg C.

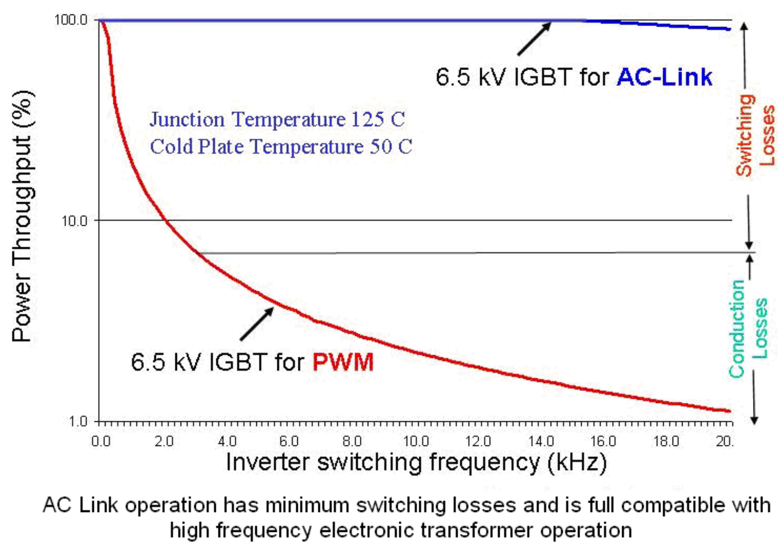

Figure 8 - IGBT throughput power with AC Link^{TM} operation and with PWM operation

A typical electronic power switch throughput is illustrated in Fig. 8 for 6.5 kV IGBTs and compares an AC-Link converter and a PWM converter. At low switching frequencies for both convertors it can be seen that the device has a similar throughput since all of the losses are conduction losses. If the switching frequency is increased however, the current has to be reduced for PWM operation. For example, if the switching frequency for the PWM converter is increased to 400Hz (0.4kHz), the switching losses and conduction losses are about equal and the power throughput has to be reduced by about 50% in order to maintain the junction temperature below a maximum 125 deg C. This reduces the IGBT throughput power (kW rating) for the PWM converter to about 50%.

Looking at higher switching frequency, it follows that a medium voltage, PWM inverter rated 6.5 kV IGBTs cannot be used for most applications as the required switching frequency is significantly higher than 400Hz. To reconstruct a 60 Hz AC waveform usually requires a minimum of 18 pulses per AC waveform or about 650Hz-800Hz. It therefore follows that in practice, a MV voltage source PWM converter requires five or six series connected 1200 V IGBT; since lower voltage devices have lower switching losses, and the total switching losses have to be distributed over the five or six junctions.

In comparison, since the AC Link™ switching losses are almost zero, due to the “soft switching” characteristic, the AC Link™ medium voltage converter can be operated, unlike the PWM converter, with 6.5 kV IGBTs at any switching frequency, up to about 25kHz. In other words, the second term in equation (1) above is zero. This not only reduces the overall component count (in this instance by a factor of five to six) and resultant system physical size and complexity but also significantly reduces losses. It also permits the use of ‘high frequency transformers’ (i.e. the transformer core size is inversely proportional to the applied frequency {i.e. inverter switching frequency}). This feature is a key to the AC Link™ DC transmission converter design.

AC Link™ is a unique and relatively new power conversion technology which provides both ‘clean’ (i.e. virtually harmonic free and dv/dt free {voltages only}) input and output voltage and current waveforms. AC Link™ utilizes proven and reliable components, control circuit design, control techniques and software.

Fig 9 depicts a complete AC-AC AC Link™ converter, typically used for induction motor speed control (i.e. as a variable frequency drive) or as a static frequency changer.

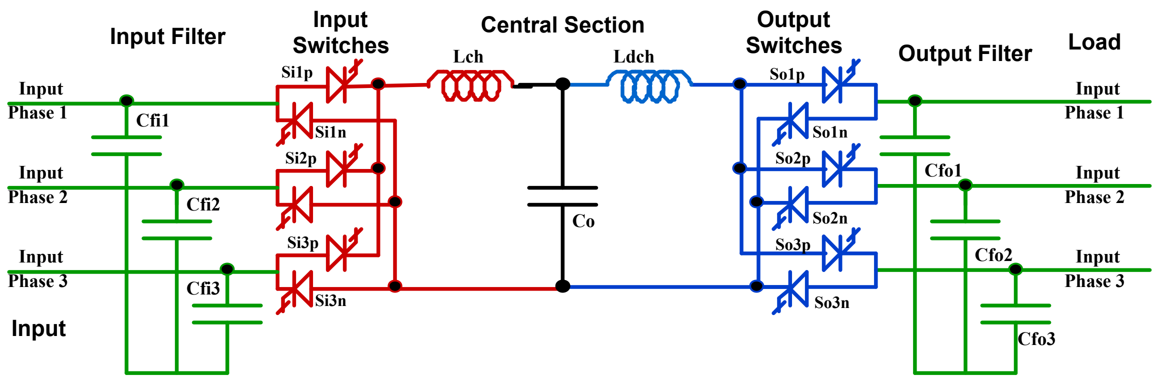

Figure 9 - AC Link™ converter for AC-AC conversion

(for VFD control or static frequency changer application)

As can be seen, the AC Link™ converter has on the left side an AC input section called ‘input filter’ which resonantly charges the central capacitor “Co” in the ,central section, through the input charging inductor “Lch” at a frequency of between 2kHz to 20 kHz. For the lower frequency operation, typically inverter grade SCRs are utilized, while for the higher frequencies and higher operating voltages, IGBTs or IGCTs are used. For HVDC operation, with the inbuilt voltage transformation, it is proposed to use higher frequency operation in order to reduce weight, physical size and cost of the single phase transformer magnetic components.

Once “Co” is charged, it is subsequently discharged through the discharge inductor “Ldch” through the ‘output switches’, reconstructing an AC waveform with the desired voltage, frequency, and phase.

Figure 9 can be used as AC to DC AC Link™ converter with a regulated DC voltage reconstruction for the output. Only two output terminals are used for DC This type of converter system has an input current of 1-2% THD (total harmonic current distortion) and does not have the usual 360Hz DC output ripple associated with other 6 pulse AC converters. This configuration is also symmetrical so power can flow and can be bi-directional with an output voltage level that can be boosted to over 150% of the input.

If high voltage step-up or step-down ratio is required, the discharge inductor “Ldch” is replaced with the leakage inductance of a single phase transformer. Any ratio of rms AC input to DC output can be achieved by adjustment of the transformer ratio. It should be noted that the transformer is operated up to 20kHz and is a fraction of the physical size and weight of a conventional (50Hz or 60Hz) transformer of a similar kVA rating.

This implementation permits the configuration with an AC input and high voltage DC output. Fig. 10 illustrates a configuration where the leakage inductance of the single phase output replaces the discharging inductors “Ldch” of Fig 9. This generated a positive current pulse on the secondary that is rectified by the bridge rectification circuit.

In Fig. 10 a second AC Link™ module is connected in parallel. Note that both modules share the same transformer. While the first module charges, the second module discharges and produces a negative output pulse on the secondary winding of the transformer. With this configuration the transformer sees a nearly sinusoidal high frequency current output that is rectified and utilizes the core of the transformer effectively.

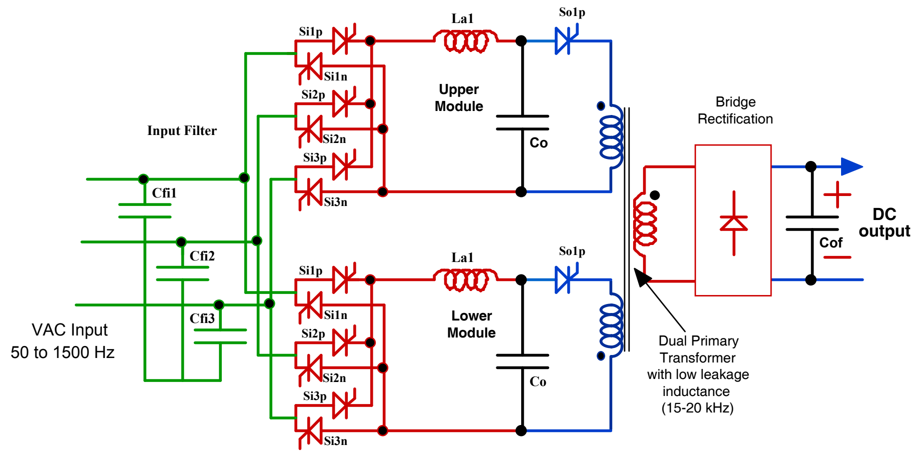

Figure 10 - AC Link^{TM} HVDC converter configuration

For HVDC operation the HV transformer will have multiple windings. The transformer winding voltage is carefully selected to match the diode or active switch (e.g. IGBT) voltage to ensure that no series connected HV devices are required to be switched simultaneously with sub-microsecond timing. A filter capacitor is typically used as shown in Fig. 9 such that it yields a single winding stage voltage. These capacitors represent voltage sources which are connected in series to form a HV DC voltage string.

Recently a regulated HV power supply was constructed for the US military to yield 50kVDC output, using a 2.5kV winding section. This transformer operates with an inverter frequency of 20 kHz, resulted in a transformer of 11kg weight for a power output of 250kW and thus a weight density of 44 kg/MW. The total core weight was 5 kg yielding 20 kg/MW. With such a low weight AC Link^{TM} can afford to use low weight nanocrystaline core material, yielding minimum core losses.

For HVDC to AC operation, a similar architecture can be utilized, however, the passive diode would be replaced by active switches (e.g. IGBTs or IGCTs). These switches would be controlled (i.e. triggered) via fiber optics. Using the segmented configuration, the switch triggering synchronization is much less critical than for the IGBTs connected and triggering directly in series as for the ABB HVDC Light system.

In summary, the HVDC AC Link^{TM} AC-HVDC converter and the HVDC-AC inverter can be operated at high inverter frequency with readily available 6.5 kV IGBTs and IGCTs since the soft switching topology does not have any significant switching losses. In addition, by using the leakage inductance of a single phase transformer as part of the AC Link^{TM} circuit topology, a low weight and efficient transformer can be used to eliminate the large 50 or 60Hz three-phase transformer that is required for both HVDC classic and ABB HVDC Light operation.

Furthermore, the AC Link^{TM} transformer winding can be segmented to completely eliminate the sub-microsecond trigger synchronization on the high voltage DC receiver end, a problems often suffered by conventional HVDC converters.

It should be noted that AC Link^{TM} converters (AC-DC) and inverters (DC-AC) are virtually harmonic free (<1-2% THD). Both the present Classical and VSC converters required multiple harmonic filters, especially the former; these only add to the significant harmonic problems apparent on modern electrical networks. Harmonic filters are very expensive at these higher power levels and also require significant floor space and cooling.

2.0.1. Architecture of HVDC AC Link^{TM} transmission system

For high power, medium (MV) and high voltage (HV) transmission the multi-module AC Link^{TM} configuration shown in Fig. 11 would be applicable. The configuration on the left is the AC to HVDC conversion section which yields the voltage step up and AC-DC rectification. Conventional low frequency transformers (i.e. 50Hz or 60Hz) are not required since the high frequency single phase transformer, part of the AC-Link circuit topology introduced in Fig. 10, is utilized for the voltage transformation as can be seen. The system is configured with the standard a ‘plus’ (+ HVDC) and ‘minus’ (-HVDC) DC transmission configuration where the ground return can be utilized if one of the DC transmission lines fails.

As can be seen in Fig 11, the system has multiple AC Link^{TM} converter inputs. The input voltage is usually assumed to originate from an 11kV or 13.8kV power generator but higher voltages may be accommodated. Multiple AC input sections are required, since a single, high current 6.5kV section has a limited power rating. In addition, and importantly, the multiple converter inputs provide redundancy.

The AC Link^{TM} converter inputs are paralleled up and time interleaved with respect to individual operation; the interleaved operation yields an input ripple given by the inverter of one AC Link^{TM} module time 2 x N times modules used. Input filter inductors (as for PWM systems) are therefore not required. A harmonic free current (<1-2% THDi) and voltage is drawn from the power source at a unity or at a selected displacement power factor.

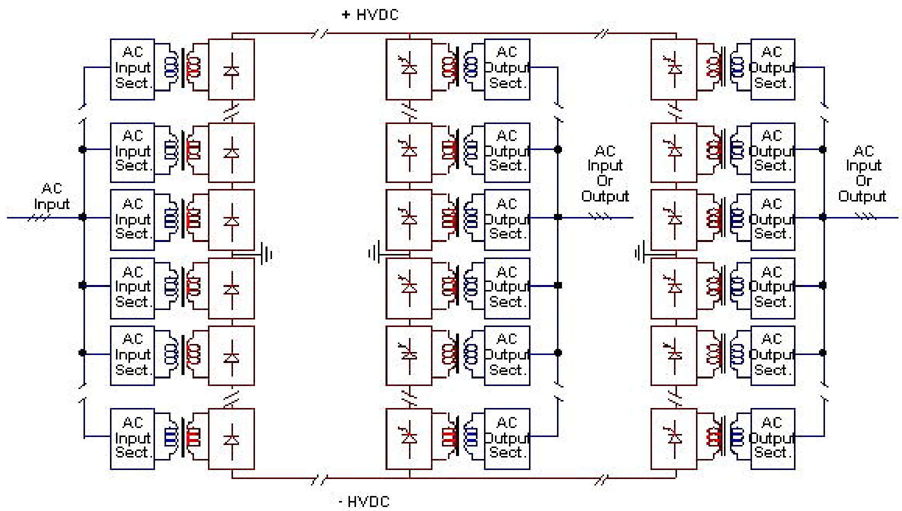

Figure 11 - Multi MW, multi-module AC-Link^{TM} DC transmission and conversion configuration

Once the total number of modules are defined, based on peak power requirements, the nominal DC output voltage can be selected by dividing the total DC voltage requirement by the number of defined input (and respective output) modules. Once connected in series, each AC Link^{TM} module, can provide a defined proportion of the required DC voltage.

For the unidirectional AC-HVDC operation the HVDC section consists of a number of bridge rectifiers connected in series, as intimated above. Each of these bridge rectifiers are supplied by a set of high voltage, high frequency transformer windings. The module's output voltage is then the sum of the series connected high voltage filter capacitors. The same approach of adding the voltage of each series connected module is then used to obtain the total HV transmission voltage.

The isolation between the lower AC voltage and HVDC occurs between the primary and secondary windings of single phase, high frequency transformer. The high frequency transformer, including the high voltage rectification section, would be placed in oil for high voltage hold-off and heat dissipation for the Litz wire and core. The voltage hold-off requirement is mainly DC, since the AC winding voltage is typically less than 3V rms. Such a DC hold-off design procedure for a coaxial AC to DC windings is well established and low risk.

The AC Link^{TM} modular design has a number of advantages. Firstly, the development cost of a single module is much lower in cost. In addition, single lower power modules can be extensively tested, prior to a full, higher system being assembled. Secondly, as a module is essentially a 'building block', a single spare module can be kept on hand on site for replacement if a failure occurs and does not have to wait 9-12 months as usually required for a transformer in for a classical DC system. Since each module has the capability to produce an output of up to 150 % of the nominal voltage, a defective module can be shut down in the event of a failure with the remaining modules retain the capability of still being able to produce the required output voltage. The high voltage DC section does not have to be disconnected, since the bridge diode section normally conducts. The same is the case if one of the bridge diodes is shorted, no disconnection is required. The system can still function up to rated voltage and power.

Similarly, on the input side, should one of the AC section components fail or be damaged, turning off its power device triggering providing isolation. The operation of the remaining modules may continue without a disconnect or loss of power. However, usually a disconnect switch would be used to open under no input fault current. Since the AC Link^{TM} fault detection can turn off within one cycle if a fault occurs, the converter will shut immediately off all solid state switches and subsequently then open disconnect switches safely.

If further redundancy is required, additional AC Link^{TM} modules can be inserted into the DC voltage chain for standby in event of failure. This permits the system to operate at full throughput power at all times, since that standby module can be switched instantaneously, while a faulty one is turned off. It is often the case that the operation of duty/standby units are cycled regularly to ensure even use of the converters.

The DC transmission lines required for the Classical, HVDC-Light or HVDC-PLUS systems can also be used for the HVDC AC-Link converter system. The HVDC-AC shown in Fig. 11 is nearly identical to the AC-HVDC and converts the HVDC back to AC. The only difference between the AC-HVDC and HVDC-AC modules is that the former (AC-HVDC section) has a passive HVDC section while the latter (HVDC-AC) has an active section.

The active HVDC-AC section controls the power flow from HVDC to AC and requires four active switches per transformer winding. Since these switches are 'floating', both control power and fiber optic signals are required for each HVDC section with one transformer winding.

The three phase AC is reconstructed on the lower voltage AC side using normal AC Link^{TM} reconstruction techniques to provide the voltage, frequency, and phase with virtually no harmonic current distortion (<1-2% THDi), very low rate of rise of voltage (dv/dt) and full control of displacement (i.e. fundamental power factor). The AC reconstruction is controlled both by the real and reactive within the MVA rating of the AC Link^{TM} AC module. No AC line commutation is required on the AC reconstruction end, as is the case for the Classical HVDC DC transmission system, nor any harmonic or high frequency filters.

The HVDC AC system with the active HVDC section is configured such that the controlled power can flow to the HVDC or is drawn from the HVDC line. The reversal can be almost instantaneously and the DC voltage level maintained at the same level, since the AC-Link converter can boost the voltage by as much as 50%.

The DC branching with multiple points to tap off power is problematic for a Classical HVDC system. For the AC Link^{TM} system, any number of DC sources can be accommodated with both consuming power and injecting additional power. Since no reactive power is required for DC transmission, a complete DC grid can be established with the AC Link^{TM} system. A DC fault on any of the DC branches can be instantaneously interrupted by simply turning off that inverter connected to the HVDC grid system. Once the fault is cleared the voltage can be slowly turned on, testing if the fault has cleared.

2.0.2. DC Transmission and distribution using AC Link^{TM} technology

The AC Link^{TM} AC to HVDC and HVDC to AC power conversion is illustrated in Fig.11. Unlike the HVDC Classical, ABB HVDC Light or Siemens HVDC Plus systems, low frequency (50Hz or 60Hz) transformers are eliminated with the HVDC AC Link^{TM} system. With AC Link^{TM} the AC is converted directly to HVDC and stepped down to AC in one integrated operation. This is totally revolutionary, as is the integration between the high frequency transformer and the AC Link^{TM} inverter.

Most of the power is generated by rotating machinery as AC in the voltage range of 11kV to 13.8kV. In this voltage range, the AC Link^{TM} technology is ideal for HVDC DC transmission. However, at the transmission end it is not necessary to invert (i.e. convert DC to AC) the power to AC since AC Link^{TM} can convert (and distribute) with similar ease the HVDC to a medium voltage DC (MVDC) via HVDC to MVDC operation. The simplified illustration is shown in Fig. 12.

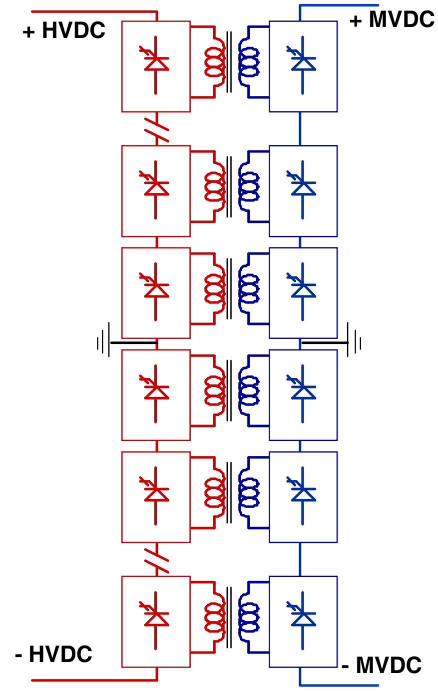

Fig. 12 - Direct HVDC to MVDC transformation

As can be seen on the left side, the active HVDC side is identical to the HVDC-AC converter shown previously in Fig. 11, whilst on the right side (i.e. the AC reconstruction side) has been replaced by a second active DC section, which can be either 'active' if bi-directional operation is required or simply 'passive' for uni-directional power flow. The system is again reconstructed to with 'N' number of HVDC section to yield the desired power and HVDC input voltage. Each output section may be constructed for a voltage step-down, such as 200 kV DC to 60 kV DC for additional power distribution. In this case the secondary module voltage is 60 kV/N (where N is the number of modules), with all of these modules connected again in series. It is also possible to have two MV modules designed for a 60 kV x 2/N voltage with two modules operating in parallel. Or, if the step-down is to a low voltage DC level, then all of the right hand modules can be paralleled.

The system may be required to undertake additional DC step-down transformation and bring down the DC power to the user in low voltage DC (LVDC). The DC power may be used directly as a DC bus for variable speed motor drives (VSD) or other multiple inverter systems which require DC ring main or common DC bus type supplies, to a voltage that can be directly used by the user with DC appliances or converter to standard 50 or60 Hz AC voltage with loads that are used today in factories and residential areas including to remote areas of the world. This would bypass the AC transmission and distribution directly, eliminating the need for VAR control requirement and the typical stabilisation issues with weak supply lines.

In addition, the power flow in each of the DC transmission and distribution lines would be controllable in order to maintain individual contractual power delivery requirements, short circuit current can be electronically controlled and instantaneously interrupted. Essentially, much simpler, stable, and cheaper power grids could be configured. With such a DC system controlled directly by a regional controller and any line or inverter fault be immediately bypassed and no critical load can be shut down.

The AC Link™ converters for a DC transmission and distribution system can be designed for the same redundancy as was described above for the AC-HVDC and HVDC-AC modules since any of these modules can be load-idled (i.e. sit quiescent until energized instantaneously when the load requires more power). In other words the individual configuration can idle some of its series section, while a complete module in a HV configuration can be switched out, while the system is such that other modules take over the power flow. This redundancy will significantly increase the system availability and provide a reliable DC power transmission and distribution system.

2.0.3. AC Link™ HVDC cost scaling and break-even cost

The operating features of the AC Link™ HVDC transmission is one important factor in the selection for this type of application. However, it is often the installation cost and total operating cost for a defined period, such as 20-25 years, which is often the salient determining factor as to which technology is finally selected for a given project. For this purpose therefore the semi quantitative Siemens comparison between HV AC and the Classical DC transmission of Fig. 1 has been modified with the AC Link™ comparison added. The result is illustrated as Fig. 13.

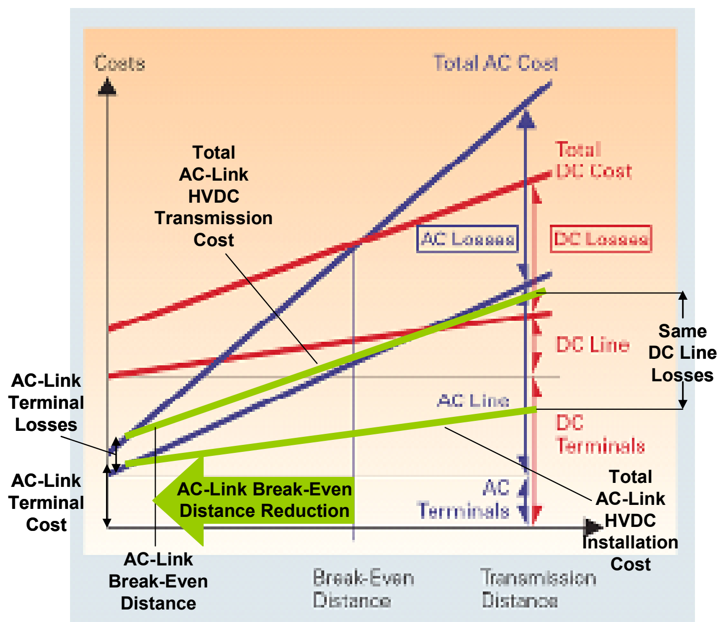

Figure 13 – Modified Fig 1 (Siemens)

HVAC, HVDC Classic, and HVDC AC Link™ costs as a function of the transmission length

It is estimated that the "AC Terminal Cost" as shown in Fig. 13 (left hand side) consisting of the switchgear, high voltage transformer, and VAR correction equipment is comparable to the AC Link™ AC-HVDC plus AC Link™ HVDC-AC converter (terminal) cost. Adding the same DC power line cost, intimated by Siemens in Fig. 1, the AC Link™ HVDC plus DC Line cost of Fig. 1 is shifted downwards. In order to obtain the total transmission cost, the cost of the AC Link™ HVDC converters and HVDC transmission line costs and losses require to be added to the equation.

The HVDC AC Link™ converter losses are similar or actually lower, on average, than the conventional (i.e. 50Hz or 60Hz) transformer losses (estimated to be between 98.5% and 98.8%). This is lower than for a transformer operating at maximum (optimised) power level. However, the efficiency of an AC Link™ high frequency transformer configuration is nearly constant over the complete power range, since the repetition frequency can be reduced. The transformer efficiency increases at reduced load levels due to the absolute core losses remaining constant. Since a typical conventional distribution transformer 'sees' a daily average load factor of about 30%, the transformer average daily losses are comparable, if not higher than the HVDC AC Link™ converter losses. Therefore, we have used similar losses as shown for the AC-terminals losses. This is shown on the lower left of Fig 13.

With reference to Fig. 13 above; the total AC Link™ system cost comprises the combined costs of the two AC Link™ terminals (i.e. transmitting and receiving converter and ancillary equipment), the DC transmission cables, and, in addition, the complete operating costs over a perceived minimum lifetime of 20 years. (Note that the AC Link™ DC cable costs are very similar to that for the alternative systems).

As can be seen above in Fig. 13 (where the green line intersects the right hand Y axis), the costs of an AC Link™ system are considerable lower than for either Classical LCC or HVDC Light.

The result is the upper "Total HVDC AC Link™ Transmission Cost" as shown in Fig. 13. Essentially, the "Total DC Cost" for the Classical HVDC is shifted downwards, by the reduced AC Link™ terminal cost and AC Link™ losses.

The key result is that with the AC Link™ HVDC technology a shift of the break-even distance for typical 500km to practically a zero distance is obtained. In addition, the break-even distance for a Classical HVDC is only economical, if the power level is of the order of 500 MW and the voltage level 500kV DC. This practically eliminated most applications unless the DC system was for long distance transmission, such as the Pacific HVDC Inertia, the interconnection between the Hydro Quebec and the USA National Grid system, and the number of European sub-see interconnections such as the first HVDC cable system from the island of Gotland to the Swedish mainland.

For such HVDC cable transmissions, high quality, pressurized oil-impregnated paper dielectric cables have to be used. These cables made DC transmission subsea and on overland expensive. However, in about the last 25 years Cross-Linked polyethylene (i.e. XLPE) cables have been developed up to about 500kV. These types of cables are much less expensive nowadays and therefore can make overland transmission attractive. Such cables can be installed in most right-of-ways or next to roads, railroad, or gas lines. There is no magnetic fields our ground currents, with bi-polar operation and the system is completely weather immune. Since HVDC AC-Link converters are cost effective at any DC transmission and distribution voltage and power level, HVDC cable transmission can solve many existent transmission problems or can be used for completely new installations.

3.0. Summary

It is well established that the HVDC transmission cost is a fraction of that of the HVAC transmission line cost. The major impediment for both the MV and HV DC transmission cost is the higher AC-HVDC and HVDC-AC converter cost and the additional cost of the terminal power losses. This is true for both the Classical HVDC as well as for the voltage source converters (VSC) on the market from ABB and Siemens. The result is a break even distance remains in terms of hundreds of kilometers for conventional HVDC transmission.

The AC Link™ AC-HVDC and HVDC-AC converter designed reduces both the terminal cost and terminal losses, such that the break even distance is significantly reduced to the point where it is practically zero. This results in AC Link™ HVDC and MVDC being cost effective and very attractive for any distance. Indeed, it is not outwith the realms of possibility that AC Link™ technology may eventually replace conventional AC power for transmission and distribution applications.

In addition, the AC Link™ converter topology replaces the large, low frequency isolating transformers (50Hz or 60Hz) with very much smaller, more efficient and internal high frequency transformers, which continues to provides full galvanic isolation between the input and output terminals.

The key operational features of the resonant AC Link™ system is a natural "soft switching" converter topology, with insignificant switching turn-on or turn-off losses. This yields a higher efficiency but most importantly, permits the utilization of a significant reduction in the required number of the higher voltage rated IGBT and IGCT compared to conventional HVDC converters currently on the market. This reduces the component count, the cost and increases the system reliability. The "soft switching" permits a higher switching frequency that reduces the component size and thereby yields a 'cleaner' AC deconstruction and reconstruction, resulting in low THD (total harmonic distortion – voltage and current) with the elimination of all harmonic filters for the AC power and 360Hz DC ripple.

The high frequency, resonating AC Link™ converter has a low di/dt which minimizes EMI (i.e. electromagnetic interference) and improves EMC (i.e. electromagnetic compatibility). AC Link™ is the only converter that fully complies with the US Navy power quality, EMI, and EMC specification. The subsequent component and equipment reduction for HVDC applications result in the AC Link™ terminals being relatively small, reducing the facility cost, and permitting the installation of a DC transmission system into urban environments which usually have limited space availability.

The AC Link™ converter can be configured as a direct DC to DC converter with voltage step-up and step-down, providing full galvanic isolation between its input and output terminals. This configuration permits the transmission and distribution with multiple nodes as are currently used with the AC grid system. This is obtained by converting the generated AC power to HVDC utilizing multiple interconnections with power tapping, stepping further down to MVDC for distribution. The DC voltage level can be further reduced down to provide a DC ring bus as a DC power source for variable speed motor drives (i.e. common DC bus systems), or converters to 50/60 Hz AC for medium or low voltage standard loads. This eliminates the present day grid stability issues and its control complexity, VAR compensation, and uncontrolled AC power flow.

Unlike the Classical or the HV-PWM based converters, AC Link™ HV converters are modular in design. In addition, a single HV AC Link™ module has redundancy and a single component failure or an HVDC module failure can be instantaneously isolated by the removal of the switch triggering of the failed module or its isolated section. This is a key DC grid requirement for high system reliability.

Most importantly, no technical breakthrough is required, and advances into components, such as Silicon Carbide switches, can further enhance the HVDC AC Link™ converter capability.

This white paper has outlined important weaknesses in present power conversion technologies for Classical LCC and HVDC Light VCC converter systems for HVDC transmission technologies with respect to first cost, physical size, and space requirements, efficiency and operating costs, harmonic distortion and dv/dt filters. AC-Link™ HVDC technology addresses ALL these issues and is ready to take low cost, high performance HVDC into the 21st Century.

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4.0. References

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