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Measuring Solution for (U)HV DC and AC

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SUMMARY

Measuring currents and voltages on high voltage potential in harsh high voltage environment poses many challenges resulting in high cost for insulation, limited performance or special-purpose solutions requiring costly development.
A new aspect in this respect is the emerging combination of AC and DC grid components and their mutual interaction, especially if e.g. mounted on one common tower.
Most state of the art solutions are designed for AC use, only. They are usually optimized for AC protection purposes, delivering limited measuring accuracy and limited dynamic performance, which is by far not sufficient e.g. for HVDC closed loop control.
Standard interfaces increasingly used by these solutions even add to this optimization, because sample- and transmission rates used by these interfaces are far from being useful for any type of real time application.
Other solutions deliver reasonable accuracy and dynamic performance but are e.g. bulky or require very high effort for installation and insulation, especially for voltages exceeding some 300kV. In many cases these solutions are highly specialized for sometimes even one single type of application. This leads to a very limited number of devices in operation with consequential limited operating experience. Excessive cost of application is common for many of these systems.
The cost of system development – therewith part of the product cost – is not only determined by the initial system design itself but is quite often even dominated by costly testing and qualification processes required by variant design for each individual voltage level that has to be considered. If system parameters are sensitive to climatic influences, variants for different climatic conditions may again significantly increase the cost.
A large number of different systems and variants is not only inefficient from a cost point of view, but poses significant risks for the reliability of the systems. If there is only a very limited number of devices in the field it is basically impossible to gain proper operating and lifetime experience.
Measuring at remote or distributed locations again requires additional effort for most of these systems, which is especially high in a (U)HV substation environment with all related electromagnetic disturbances and sometimes harsh climatic conditions.

KEYWORDS

(U)HVDC, HVDC, (U)HVAC Measuring Solution, Hybrid Optical Measurement, HOM7

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1 Introduction

Measuring of currents and voltages in high voltage substations mainly uses conventional technologies which evolved and improved over the last decades.
Main drivers for change for these technologies in the long run were increasing voltages of the transmission networks and cost reduction by better adaption to the field of application.
Main application is control and protection of the transmission network, mainly reliable and selective fault clearing.

1.1 Conventional Current Transformers

For current measurement mainly inductive current transformers are used. These are usually optimized for 50/60 Hz fundamental frequency application.
Their major advantage is that they are usually very robust, reliable and perfectly suit their main application. Some drawbacks result from the principle of these devices, though.

- Transient conditions – e.g. network fault currents – cause distortions to the measured value (secondary output value) due to saturation of the core. This effect may result in inaccurate secondary readings.
- DC overlay currents – even at low magnitude – cause distortions of the measured value. The measured value may still be good enough for protective functions using the fundamental frequency. It may not be useful any more for other applications, e.g. harmonic evaluation.

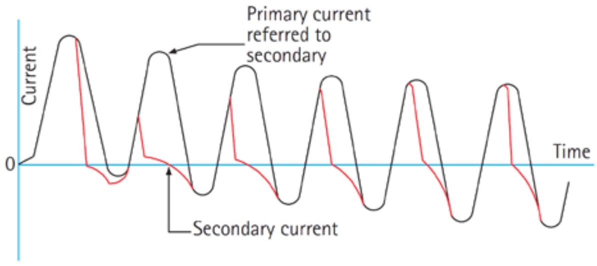

Figure 1: Transient condition at conventional CT [1]

- Measuring accuracy is only granted at the rated (fundamental) frequency. High frequencies as well as very low frequencies will be increasingly cut off by inductive current transformers. DC currents cannot be measured at all by conventional CTs

1.2 Non-Conventional Current Measuring Devices

Direct optical current sensors, e.g. Faraday-Effect based systems, are not very common, yet. Complex electronics and lack of field experience due to limited number of systems in service may raise concerns about reliability and often results in still high cost for these systems.
Concerning their technical performance, they are usually designed to compete with the above mentioned, conventional CTs. Combined with the requirement of a digital interface this results in many cases in providing an IEC61850 interface with 80 samples per power grid cycle (equals 4/4.8kHz sampling rate), which significantly limits the usable bandwidth of the measuring device.
Many of these devices are not showing distortion effects as mentioned for conventional CTs. But that does not necessarily mean that the device is able to correctly measure mixed DC-/AC signals such as DC components of AC currents or AC ripple in DC currents.

Fast current measuring devices delivering high accuracy do exist, e.g. flux compensated or Hall Effect based systems. They often deliver sampling rates in the upper kHz range and are able to correctly and precisely measure DC currents and mixed DC-/AC signals. They usually use specific interfaces and mostly specific and complex ground based electronics. The "primary" measuring unit of these systems itself is basically always on ground potential by principle. This requires extra effort for insulation which may become excessive for UHV application.

Figure 2: Non-conventional CT with insulation (180kV)

1.3 Voltage Measurement Devices

For voltage measurement there is again a variety of systems with different capabilities, advantages and drawbacks.

The two main types used today are inductive/magnetic and capacitive voltage transformers (MVT and CVT).

Both are widely used and proven for fundamental frequency, i.e. 50/60Hz application.

For measuring of harmonics, other frequencies or DC voltages / DC components they do not deliver reasonable performance. Even considering frequencies of only about 1 kHz the measuring error may not be expressed in per cent any more but rather by factors (⬀Figure 3 [2]).

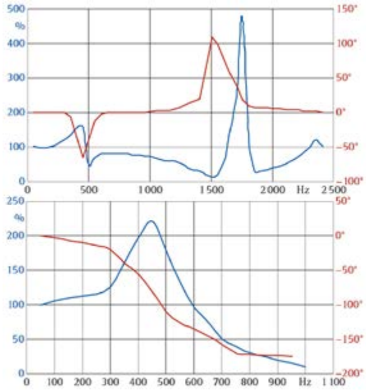

Figure 3: Relative output value and phase error of a MVT (top) and CVT (bottom) over signal frequency [2]

Newer systems are sometimes built as RCVT (resistive-capacitive voltage transformer). They usually deliver constant accuracy from DC to high frequency values.

RCVTs are difficult in application, though. They are very sensitive to the burden that is connected. Even variations in cable length and type used to connect the secondary equipment may result in inaccuracies of >>1% due to the capacitance of the cable.

2 The World of HVDC

"The world of High Voltage Direct Current transmission systems" (HVDC) nowadays mainly consists of two technologies:

- Thyristor based converters which are also called "line commutated converters" (LCC) or "Classic HVDC".
- IGBT based converters which are also called "voltage sourced converters" (VSC) or "modular multilevel converter" (MMC).

Common for both of these technologies is that the primary equipment of the converter stations basically consists of:

- An AC yard which consists of the connection to the AC grid, filters and other equipment.
- The converter itself which is usually located in a converter hall.
- A DC yard comprising the connection to the DC line or cable, in some cases with other equipment such as switches or filters.

Typical voltage levels for these installations are 400/500kV$_{AC}$ at the AC grid connections points. For HVDC overhead lines typical voltages are 500-800kV$_{DC}$. 1100kV$_{DC}$ are under construction in China. These installations are usually realized with thyristor based converters.

MMC technology based installations are currently mainly used in combination with DC cables at voltages of about 320kV$_{DC}$.

Voltage and current measurement equipment for the AC parts of an (U)HVDC usually consists of standard AC instrument transformers, since it is used together with standard AC protection equipment for busbar-, transformer- and AC-line-protection.

In case of extended requirements RCVTs may be used. As discussed above they are difficult in application, though. This is especially true in large installations such as an (U)HVDC (⬀Figure 8).

For the DC parts of the plant usually specific systems are used. As discussed above conventional systems are either not capable of measuring DC at all or they do not provide the required dynamic performance.

For decades shunt based current measurement systems were developed and used for the DC measurement points. These systems were specifically designed for LCC HVDC application and do still perfectly suit this application.

Figure 4: 800kV VT [4]

⇗Figure 5 illustrates the basic principle of a MMC architecture based HVDC to achieve an AC voltage at the AC terminals of the converter which is as close to a perfect sinus as possible. In contrast to the figure the “steps” of a real converter are very small and would actually be invisible in a figure with real, i.e. scaled values.
This is achieved by the closed loop control of the plant by controlling the AC voltage and actively compensating for unwanted voltage components such as harmonic- or DC components.

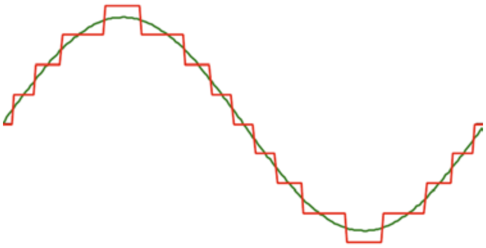

Figure 5: Illustration of principle of sinus approximation by MMC HVDC [3]

Therefore the closed loop control requires adequately high precision and high speed measured values over a wide frequency range from DC to high harmonics, of course. This is true for the AC- as well as the DC-side of the converter.

Currently flux compensated, Hall Effect based or similar non-conventional systems are used for this purpose.
As discussed above one characteristic of these systems is that the measuring head itself is always on ground potential thereby requiring adequate insulation. Up to now VSC based converters are mainly used in combination with cable transmission at voltage levels of ~320kV$_{DC}$. At this level the insulation is large and expensive but somehow still “reasonable”. Please refer to ⇗Figure 2 for an example of a non-conventional CT for 180kV$_{AC}$.

Considering overhead-line-application (500-1100/1200kV$_{DC}$) and increasing AC grid voltages (e.g. 765kV$_{AC}$ which is quickly gaining importance e.g. in India) the insulation effort will be remarkably higher as can be derived e.g. from comparing above mentioned ⇗Figure 2 (180kV) with ⇗Figure 4 (800kV).

3. HOM7 – A New Measuring Solution for HVDC and HVAC

A new measuring solution to be presented in this paper is a consistent refinement of proven shunt based measuring solutions and addresses the needs of state-of-the-art LCC and VSC (U)HVDC application, as well as (U)HVAC applications.
Nevertheless it is much more than just a “face lift” because for the first time it considers the requirements of different HVDC technologies, as well as application in the field of high performance HVDC and HVAC measurement, thereby largely widening the field of application of this system.

3.1 System Overview

Core of this solution is an optical signal transmission system that works independently of external power supplies such as batteries, solar cells, line current transducers or similar.
It uses remote units, e.g. sensors, with low voltage input to acquire the secondary signal of the primary measuring equipment.
There is basically no limitation concerning the choice of the primary equipment.
A voltage divider may directly deliver a suitable secondary voltage signal. In case of a conventional CT this can easily be achieved by an appropriate measuring burden.
For measuring points with a shunt as primary part the primary shunt voltage on (U)HV potential can even be directly used as sensor input.
The sensor can be installed on high voltage potential, the only connection required between sensor and ground is a pair of fibers per sensor. This allows for a very easy, straightforward and relatively cheap insulation and installation (compared to conventional insulation). ⇗Figure 6 shows an 800kV$_{DC}$ shunt based current measuring point, equipped with multiple redundant sensors on HV (busbar) potential and fiber optic insulated power- and data transmission.

Figure 6: Shunt for 800kV$_{DC}$

The system consists of one or more remote units which can be sensors or other components.
The sensors are converting their analog input voltage(s) to digital values. Signal processing in the sensor unit includes e.g. EMI-filtering and anti-alias low pass filters
The preprocessed digital value is then sent to the ground based control unit via data fiber.
Status and power supply of the remote units is continuously monitored to allow for early detection of malfunction and to minimize the risk of false trips or other false action of connected systems, e.g. open- or closed loop controls.
Other remote units may be specific function elements e.g. for MOV operation cycle counting or triggered spark gap control.

Power is transmitted via laser and is converted to electric power for the remote units using a miniature photovoltaic receptacle. Power is continuously controlled to allow for changing power requirements, e.g. fiber damping changes resulting from aging, or simply environmental effects, e.g. temperature change. This minimizes the stress for the power laser which easily allows for operating times of several decades without replacement.

Besides the system management, the ground based control takes care of the communication with all of the own-system components as well as communication with connected control and/or protection systems. Of course communication monitoring is also included.
System management functions are mainly startup control, own-system status supervision of all system components, firmware management, service functions and laser power control.
In addition to that it supports a wide range of digital value processing capabilities suiting all needs of a control and protection system, such as digital filtering, spectrum analysis and many more, depending on the requirements of the connected C&P systems. An appropriate engineering interface for configuration and programming of the system functions is provided.
The measured values – raw data and/or preprocessed – are usually sent to the connected C&P system via system backplane bus or dedicated fiber optic interface designed to provide the required performance.
Of course all-purpose analog interfaces or standardized interfaces like IEC61850 are also possible if considered to be advantageous.

The main advantages of the system are:
- Laser power supply of remote units making them independent of any line load, solar cells, batteries or comparable technologies which are either not reliable or require intensive maintenance.
- Simple, proven and reliable insulation by fiber optics. No bushings, heavy-duty supports or other large and expensive equipment required – even in case of UHV voltage levels
- Very flexible concerning application with a variety of different primary components.

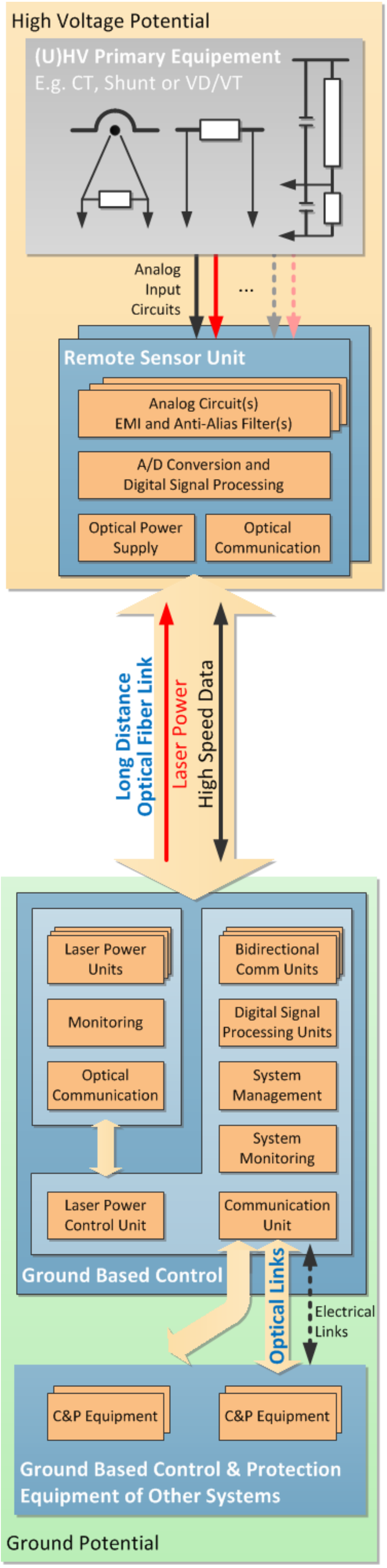

Figure 7: Illustration of the hybrid optical measuring solution HOM7 and system integration of other components

Compared to conventional systems (e.g. conventional CT/VT with 1A/5A interfaces) it may seem to be costly to use fiber optic based laser power supply in combination with optical data transmission. Considering UHV applications with associated insulation requirements this is not true, any more.

Even an application as ground based signal transmission system e.g. for use with RCVTs in remote locations in large high voltage substations may be advantageous to overcome the burden-issue due to long cabling. Due to the system design with laser power supply no electrical power supply (usually redundant), heating and similar effort is required at the measuring location.

3.2 Application Example – (U)HVDC

As mentioned above the hybrid optical measuring system as well as shunt based current measurement emerged from the shunt based DC current measuring used in many HVDC installations.
This is of course still one application of this system.
Recently the hybrid optical signal transmission has been used for RCVT based DC voltage measurement as well, for easy and reliable signal transmission in the yard.
The new system easily delivers the required performance to be used in the AC yard as well.
This can be as signal transmission system for RCVT – as in the DC yard – or in combination with AC current measurement.
Other applications are e.g. measuring applications for filters in the AC or DC yard or even other components.

- Easy and straightforward insulation with only minimal additional effort for higher voltages (e.g. 765/800/1100kV).
- Easy and reliable signal transmission through the yard basically without concern about disturbances, or non-constant burden and potential problems linked to the distance (e.g. burden for RCVT).
- AC current measurement without accuracy limitations due to DC- or high frequency current components.
- One common system for the installation instead of a variety of different systems, which allows e.g. for easier operation, maintenance, spare part handling, etc.

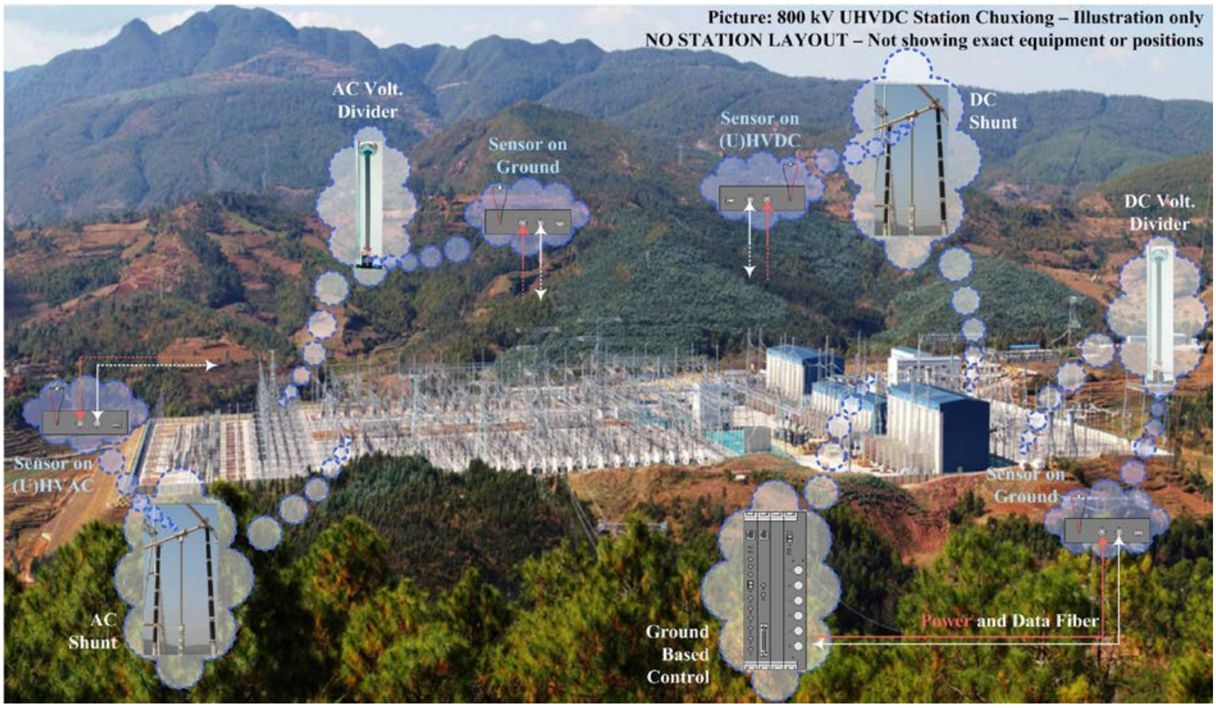

Figure 8: Schematic illustration of HOM7 for (U)HVDC application

3.3 Application Example – (U)HVAC Series Compensation

Very common for this application is the use of standard CTs for current measurement for control and protection purposes.
For series compensation (SC) applications usually multiple current measurement devices are installed on high voltage potential without the possibility to use regular copper wiring to the ground based control and protection systems. ⬀Figure 9 shows a typical single line layout of a series compensation installation.

Thus SC application basically requires the use of line current powered transducers or other non-conventional measuring devices. Light powered sensors supplied by ground based laser are one advantageous possibility.
They are by principle independent of any line load condition, while line powered devices would require either a minimum line load or any kind of high-maintenance energy storage devices on the platform.

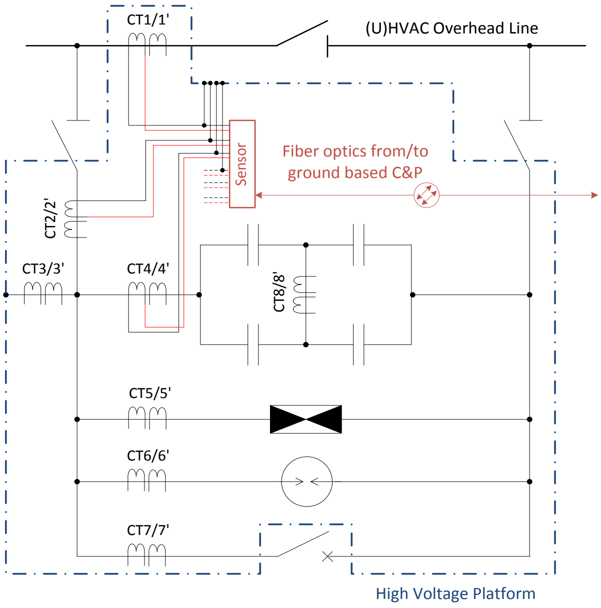

Figure 9: Typical single line diagram of SC installation

The HOM7 measuring sensors provide optical interfaces for standard fiber optics which allow for both, data transfer and power supply. They offer reliable operation at all load conditions including e.g. low or even zero line load and zero line voltage operating modes. The main advantage though is an easy to install, maintenance free and long term stable isolation between (U)HV potential and ground.
An ultra-low power consumption design ensures long lifetime of the power lasers and the capability of use within an extended temperature range usually resulting in relatively high fiber damping. ⬀Figure 10 shows an illustration and a picture for a 500kV installation. No major effort – especially no development or qualification effort – would be required in case of e.g. 765kV or even higher voltages.

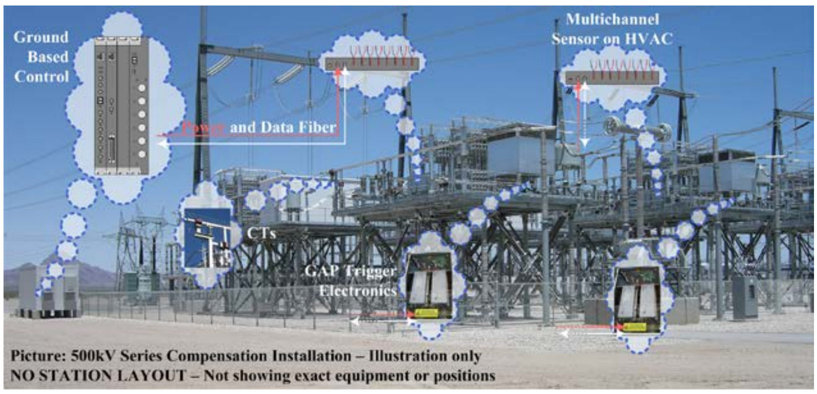

Figure 10: Schematic illustration of HOM7 for (U)HVAC SC application

For this application the sensors are typically wired to conventional current transformers as shown in ⬀Figure 9. The sensor input signal is measured via simple shunt used as a burden for the CT.
Due to the poor frequency response of conventional CTs, this installation is quite limited regarding dynamic performance and accuracy. Replacing the current transformers by e.g. shunt based or other primary components might improve the dynamic performance significantly.

Most series compensation installations are equipped with forced triggered spark gaps. They are an economical solution to handle high fault currents for the time the bypass circuit breaker needs to close. This of course requires the possibility to actively, quickly and reliably trigger this gap especially in case of extreme electromagnetic disturbances during fault conditions and in the vicinity of the resulting double-digit kA arc.
This is another obvious application for robust optical power supply and communication. Remote units for triggered spark gap control are available and seamlessly integrated in the measuring system for immediate and reliable protection action.

4 Conclusions

Two major trends for the next decades will be an increasing number of power electronic based (U)HV applications and a quickly increasing number of HVDC transmission systems within the (U)HV grids. Above that it is most likely, that higher voltage levels will gain importance, at least in some countries. For measuring solutions within the (U)HV grid this will result in increasing requirements, especially concerning high frequency- and DC-components within AC currents.
This may pave the way for high performance shunt based measurement solutions to make their way from a DC niche into a widely used and flexible high performance application.
This on the other hand will challenge the signal transmission systems, especially considering not only the insulation requirements but electromagnetic influences, climatic environment and long transmission distances required in large high voltage installations.

One obvious solution easily meeting these requirements is an optical signal transmission solution sparing any power supply issues by using fiber optic based laser power supply, which allows for easy application basically independent of location and voltage level.

BIBLIOGRAPHY

[1] http://www.cigre.nl/media/40320/06_current-___voltage_transformers.pdf

[2] etz issue 06/2012."Übertragungsverhalten von Messwandlern im kHz-Bereich" by Kerstin Kunde, Holger Däumling, Ralf Huth, Hans-Werner Schlierf, Joachim Schmid

[3] Siemens publication „HVDC PLUS – Basics and Principle of Operation" by M. Davies, M. Dommaschk, J. Dorn,J. Lang, D. Retzmann, D. Soerangr

[4] „Technik in Bayern", Issue 6/2009. "Hochspannungs-Gleichstromübertragung Energie-Autobahn und „Firewall" für das Netz" by Prof. Dr.-Ing. Dietmar Retzmann