High Voltage Technologies

Powering the Future: Renaissance of High Voltage Technologies

By Prof. Peter Vaessen

This article is based on the guest lecture "Essential high voltage and high-current knowledge", given for the Sustainable Energy Supply (EE2E210) course. It highlights the importance of understanding high-power technologies as being one of the key enablers of the energy transition towards a sustainable, affordable, and reliable electric power supply.

Introduction

High voltage is often associated with danger and life threatening. In a lot of common everyday equipment like traditional cars with internal combustion engines and microwave ovens high voltage technology is present. It is also used in medical diagnostics, industrial disinfection, and the chip industry. High voltages and associated high electric fields are also very common in nature, think e.g., of lightning but also inside semiconductor devices. High voltage is essential to allow for long distance electricity transmission and grid connection of large-scale renewable generation and batteries.

The source of electric fields and voltage is charge. Charge is a fundamental property of nature and is measured in Coulombs [C]. A 1.5V penlight battery contains around 10,000C and a typical lightning bolt of 1MV annihilates 2C. Charge creates an electric field [V/m] and when this is measured along a path a voltage is created. Moving charge [C/s] or current creates a magnetic field. The energy density of the magnetic field is about 100,000 times bigger than that of the electrical field, this explains why all energy conversion machines like motors, generators and transformers are magnetically based.

A safe voltage for humans to touch is 50V and a safe current flowing through the body is 30mA. Voltages to ground of more than 1000V AC_{rms} or 1500V DC are considered high voltage. For current there is no such sharp definition, in general currents more than 100A are considered as high current.

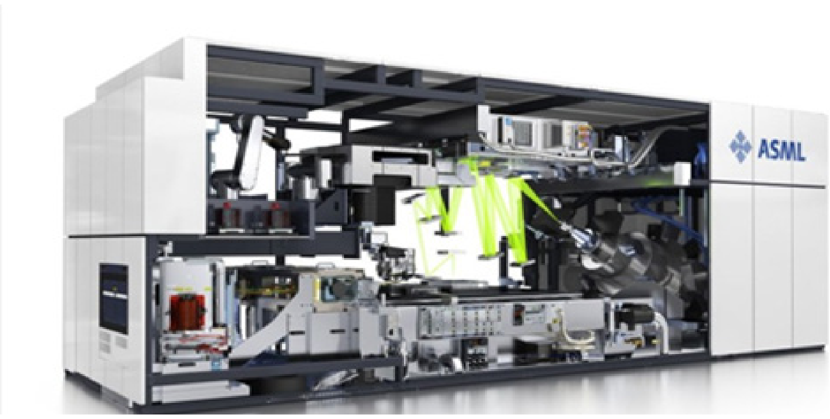

Figure 1. ASML Wafer stepper, typical beam DC voltage 10kV to 100kV.

When the electric field strength becomes too high, the gaseous, liquid, or solid insulation breaks down with a spark and a conducting channel is created to ground. If the spark is fed from a strong power source a short circuit current starts to flow and creates an arc. A power arc is a plasma with a temperature of more than 6000K, hotter than the surface of the sun, is very destructive and must be switched off as fast as possible to prevent further damage. If the arc current is above 1000A the arc starts moving and becomes even more dangerous.

The power grid and variable renewables

In the early days of electricity, some 150 years ago, customers and factories were supplied with power by a local generator or from a nearby power station. The advantages of sharing generation capacity and connection high voltage transmission systems became apparent. The synchronized electric grid frequency of 50Hz was established. As high voltage is not suitable to be directly used, transformers step down the high voltages to the 230V for domestic use. The familiar power grid architecture of high voltage pylons and substations, as

Figure 2. Sustained power arc (South America) because a cable short circuit current could not be interrupted.

well as the medium and low voltage distribution transformer substations began to appear.

Today, electricity makes up 20% of the world's energy consumption. In 2050 the electric power grid becomes the backbone of the entire energy system as the share of electricity increases to some 40%, therefore a factor 2 to 3 times as much transmission capacity is needed.

Variable renewables like wind and solar become abundant. At the end of 2022 about 950GW wind and 1210GW solar capacity was installed globally, this amounts to $270W_{peak}$ for every person on earth. In the coming period renewable capacity will double every 3 to 4 years. Some 50% to 60% of grid connected renewables are multi-MW, even GW-scale, e.g., off-shore wind farms in the North Sea and solar plants in China, India, and the Middle East.

The technologies to meet the challenges for the power system are available. Advanced solid-state power electronics, combined with HVDC (High Voltage Direct Current) is easing the connection of large-scale renewables to the grid. Interconnection of grids, congestion reduction and keeping the grid stable is also supported with these technologies.

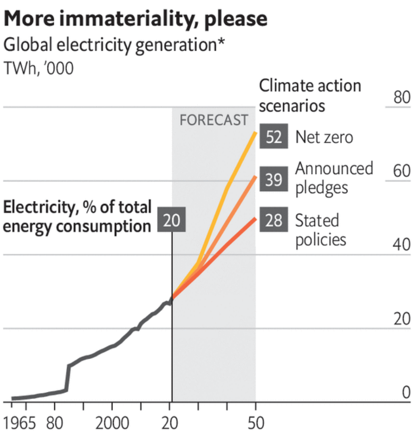

Figure 3. Global electricity generation and 2050 projections based on climate action scenarios. (Sources: Our World in Data; IEA)

The need for high voltage

Why high voltage is needed for power transmission and connection of large-scale renewables? The transmitted power in watts equals voltage times current, as expressed by the formula $P = V.I$

If a large amount of power must be transmitted or connected, a principal choice for high voltage or high current has to be made. In Table 1 the challenges when using high voltage or high current are summarized.

If High Voltage is chosen, electrical insulation material is needed to prevent breakdown of the high electrical field. The insulation material can be seen at high voltage overhead transmission lines, where air is used as an insulation gas, combined with insulator strings connected to the grounded pylons. In underground high voltage cables cross-linked polyethene, XLPE, is used as solid insulation material. Ballpark estimates for allowable field strengths in air and XLPE are 20kV/cm and 100kV/cm respectively. The higher the voltage, the more the details become crucial to prevent local field enhancement and initiation of breakdown phenomena that occur on a micro-second scale. Typical details to be considered are 10^{-4} to 10^{-6} of the dimensions and 10^{-9} to 10^{-12} of the vol-

Figure 4. 1.35GW solar PV plant Konya Karapinar (Turkey).

Choice	Challenge
High Voltage	More expensive construction, more insulation material, bigger dimensions
	Risk of breakdown, full breakdown requires measures and partial breakdown (corona in air) gives additional energy losses
	Reactive power (capacitors) becomes important when AC is used instead of DC
High Current	Forces on conductors which lead to bending and breaking
	Heat generation, leads to losses and maybe melting
	Reactive power (inductors) become important when AC is used instead of DC as well as induction effects like the skin effect

Table 1. Challenges when using high voltage or high current.

Figure 5. 700MW TenneT offshore transformer substation.

ume/weight of the high voltage component. It is obvious that the highest electrical field strength is determined by the peak value of the voltage. For all operating conditions the allowable electrical field strength should be (much) less than the breakdown field strength of the insulation material, percentages between 4% to 60% of the breakdown value are common. Because of the use of high voltage, the physical dimension of equipment increases and more insulation material is needed. Typical high voltage component dimensions are 1.5m per $100kV_{peak}$, e.g., a 400kV cable termination or transmission insulator string on a pylon is $\sqrt{2}/\sqrt{3}*4*1.5 \approx 5$m.

If a breakdown of the insulation material occurs, a short circuit current starts to flow, often one or even several magnitudes bigger than the nominal current. The short circuit current must be interrupted as fast as possible to prevent dangerous situations with consequential mechanical and thermal damage.

If High Current is chosen, precautions must be taken to cope with the mechanical Lorentz force [N/m] that occurs between two conductors, $F=2*(I_1*I_2)/d$, with currents I_1 and I_2 in kA and conductor distance d in dm. The Lorentz force is quadratic with the current, parallel currents create attracting forces and opposing current create repelling forces. Note that for

Figure 6. High voltage equipment for AC (left) and DC (right) cable testing at KEMA Labs.

AC the forces are dynamic and pulsate with 100Hz between zero and the maximum value determined by the peak current.

A power of 1000MW can be transmitted or connected with a high voltage of 400kV and 2.5kA or alternatively 10kV and 100kA can be used. Note that for the latter case the conductors have to withstand a tremendous force of 10,000N/m when placed 20cm apart. To prevent excessive heating caused by the ohmic I^2R losses, a big conductor area is needed. If a practical current density of $1A/mm^2$ is used a $100{,}000mm^2$ conductor area (35cm ø) is needed to reach an acceptable loss of 1.5MW per kilometer. Compared to the high voltage choice, much less insulator material is needed, although a lot more conductor material is needed. Insulator material is cheaper than conductor material.

Following the reasoning given above the conclusion is obvious: the choice for High Current is not an option to transmit or connect large amounts of electric power, for this High Voltage is the logical, practical, and economical choice.

Outlook

In high power applications often components or modules are series connected to allow for higher voltages or parallel connected to allow for higher current. The engineering challenge is how to guarantee an even voltage distribution or current distribution. What happens with the voltage or current distribution when one of the components or modules fails? Does the component or module fail as a "short" or as an open circuit? Can the remaining components or modules cope with the new voltage or current stress?

High voltage and high current do not scale, and a common mistake is to think that you can unlimited stack well engineered low voltage units to create a high voltage unit and parallel numerous low current units to create a high current unit.

Figure 7. Prof. Peter Vaessen at the ESP High Voltage

"There is a renewed interest and bright future – a renaissance – in high voltage technologies and research, as it is a key enabler of the electricity grid as backbone of the future power system."