Increased renewable power generation, HVDC interconnections and geomagnetic effects all lead to a direct current bias in the AC grid, which in turn increases noise and no-load losses in transformers

ABSTRACT

Increased renewable power generation, HVDC interconnections and geomagnetic effects all bias the AC grid with small direct currents, which leads to two negative effects on transformers (theory of half-cycle saturation): increased noise and increased no-load losses. A unique solution is the DC compensation system, which is an add-on to a transformer which eliminates the DC effects. Furthermore, there are dedicated steps available, from pure detection of the problem, preparation of the transformer and measurement, all the way up to a full compensation system.

KEYWORDS

DC bias, half-cycle saturation, geomagnetically induced currents, renewable grid effects

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Restoring efficiency, removing sound

Ready for DC in the grid with DC compensation and DC-ready transformers

1.The challenge

Power grid operators are required to constantly maintain and improve efficiency of their grid and power equipment. At the same time, growing public awareness and urbanization mean that noise pollution of the surrounding environment and neighborhoods has to be minimized. As a consequence, power grid operators are continuously specifying lower values of noise pressure and loss levels for power transformers. While these values are properly tested during the factory acceptance tests in a controlled environment, the actual situation in the grid may vary due to the impacts of direct current (DC). DC can occur from power electronics in the grid, HVDC interconnections, renewable power generation or small direct currents caused by geomagnetic effects.

Even normal geomagnetic activities can lead to DC currents in the range of some 100 mA to over 1 A in the transformers neutral point

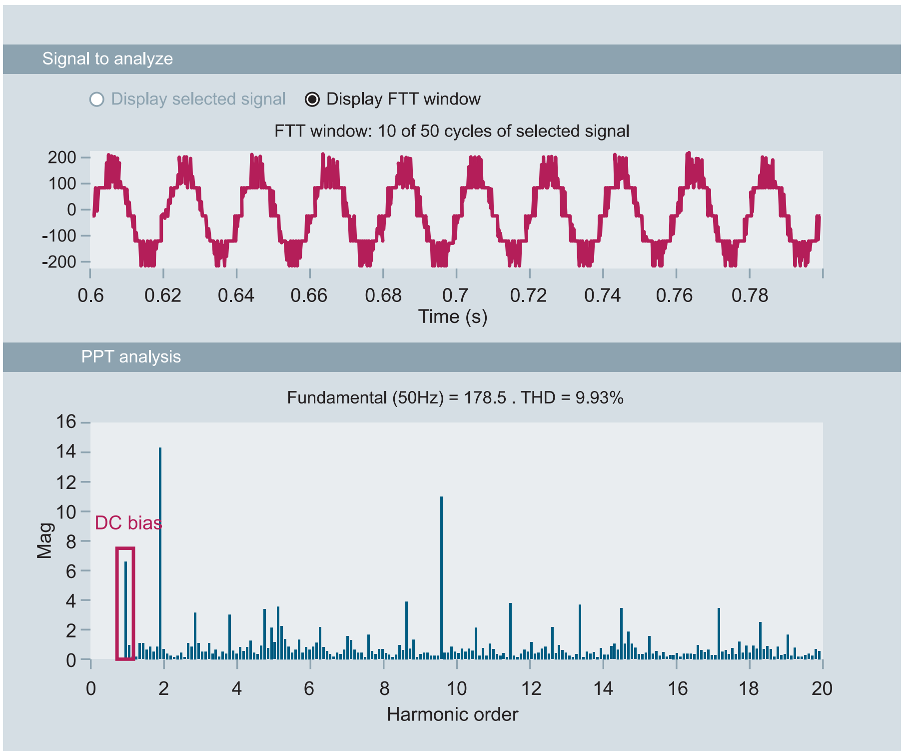

Figure 1. Example of DC bias caused by converters used in renewable energy generation

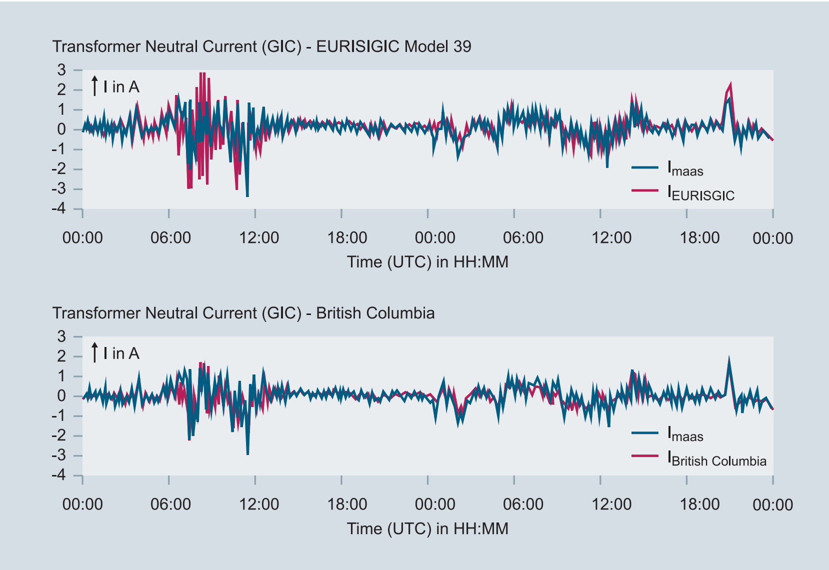

Figure 2. Modeled (red) vs. measured (blue) DC in the transformer neutral, from [4]

2. Reasons for DC bias in the grid

2.1 Renewable energy

In order to feed the electrical energy from renewable generation into the transmission grid, the application of converters is necessary. Usually, active switching elements such as thyristors are used for generating a sinus wave voltage by applying PWM (pulse-width modulation) inverters or multi-level PWMs. In Figure 1, it is highlighted that this can generate higher harmonic frequencies as well as DC offset (DC bias). Field studies were conducted jointly with utilities to prove the occurrence in the field [1, 2, 3].

2.2 Low geomagnetically induced currents in Central Europe

The effects of geomagnetically induced currents (GIC) on transformers are well known, especially in regions with higher latitudes. They range from increased noise and loss levels up to system failures and blackouts. A recent study by Thomas Halbedl et.al [4] has shown that small geomagnetic events can be a source of omnipresent small parasitic DC in the transmission grid. In Figure 2, the measured DC is always based on the same transformer, but modeled using the EURISGIC and the British Columbia Earth Model. Even normal geomagnetic activities can lead to DC currents in the range of some 100 mA to over 1 A in the transformers neutral point, as shown in Figure 2.

DC offset causes a "half-cycle saturation" of the core, which leads to peaks in the magnetization currents, significantly increasing noise and no-load loss levels

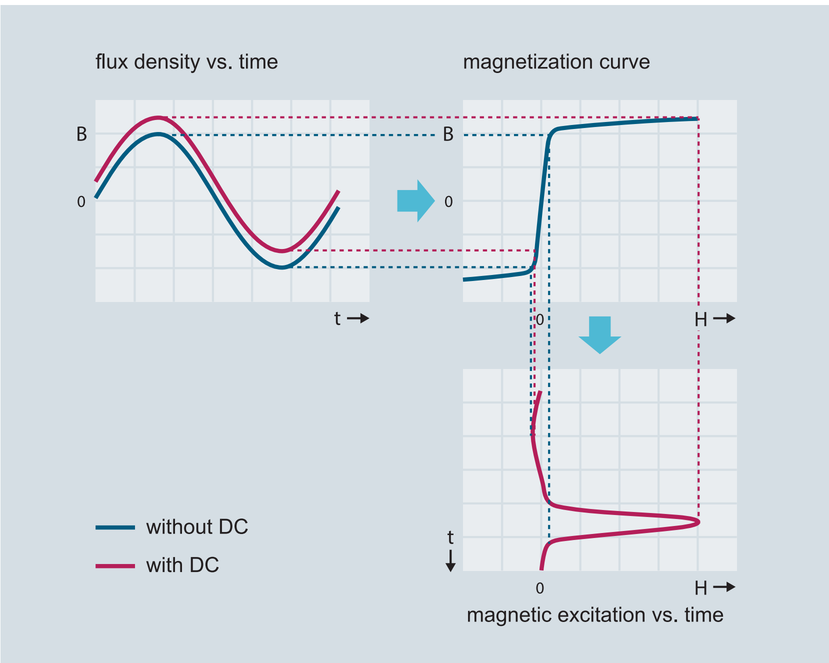

Figure 3. A principle of half-cycle saturation effect caused by DC flux offset: B proportional to U and H proportional to I

3.Theory and background

The DC offset causes a "half-cycle saturation" of the transformer core, which leads to peaks in the magnetization currents, as shown in Figure 3. These impacts significantly increase noise and no-load loss levels. Modern grain-oriented electrical steel has high magnetic permeability, and transformer cores are generally stacked in step-lap technology, which is an interleaved stacking of sheets at core joints that virtually leads to no air gap. For these reasons, transformer cores have a very high magnetic conductivity, and therefore, small currents are sufficient to excite the transformers to nominal flux density. While three-limb transformers are relatively insensitive to symmetric direct currents (same magnitude and polarity) in all phases (due to symmetric flux that has to close over air, resulting in high magnetic resistance), they react quickly to minor asymmetries (since asymmetric flux can close within the core, which has a very low magnetic resistance). Five-limb core transformers or single-phase transformers are also extremely sensitive to direct currents in the neutral point which distribute (almost) symmetrically to the phases. For instance, just a few hundred milliamperes of DC can result in a significant increase in noise and no-load losses (tested on several transformers with different core types, e.g. on a single-phase unit: 1st pilot project 230 kV / 134 MVA, core type 1-2, consisting of one main limb in the centre and two return limbs). Figure 4 shows that a DC of 500 mA may cause an increase of 13 dB (A) compared to the reference measurement in the test field without DC. For a human being, an increase of 10 dB is twice the perceived noise volume [5]. Furthermore, DC load causes an increase of up to 50 percent in no-load losses. Due to the magnetic conductivity of transformer cores, even a small DC impact can have major effects, including an increased reactive power current consumption and associated greater losses (see the line which demonstrates this high increase in Figure 4). Given a minimum lifetime of 25 years, the power equipment of today already needs to be prepared to cope with challenges posed by DC in the future. With an exponentially increasing renewable power generation comes a changing grid topology. The objective was, therefore, to develop a method to render transformers insensitive to DC loads. There is a capability to introduce DCC (Direct Current Compensation) preparation in a new transformer, which is called "DC ready". This enables quick retrofitting to a full DCC system at a later stage.

4.The solution

The approach developed is not based on eliminating the DC load, but rather on eliminating its effects on the transformer. The DC is therefore able to flow towards a certain location and will not be obstructed. The solutions for DC compensation for single-phase and three-phase units with three-leg cores as well as five-leg cores have been available since 2011 (with the first unit installed at a U.S. customer, close to San Francisco). Reference projects can be found all over the world, including Europe, Northern America, Africa and Australia, and an increase of DC in the grids in the future is expected in Northern America, Europe and Asia-Pacific, in particular.

The concept is not based on preventing the DC flow through the transformer windings, but rather on generating a magnetic field in the core to counteract the field produced by DC current. This magnetic field is generated by an additional winding: the so-called compensation winding. The required DC current is determined by sensors at the active part and controlled by a control unit, Fig. 7. The magnetic field generated by the DC current on the grid side and that generated in the compensation winding cancel each other out in the core, resulting in an AC field that equals the one in the transformer core during normal operation. The DC effects on transformer noise level can be nearly completely eliminated with the DC compensation activated. The same is also applicable for no-load losses. Thus, the noise and no-load losses decrease to almost original levels without DC present. It follows from this that active DC compensation is the solution of choice for continued low-loss and low-noise transformer operation when DC is already in the grid. Reliability of the system and especially of the sensor (all components in the active part) is equal to transformer lifetime. In case of malfunction, a notice of redundancy is given as well as maintenance hole for simple exchange.

500 mA DC may increase the noise by 13 dB (a 10 dB increase doubles the perceived sound level), and a DC load can increase no-load losses by up to 50 %

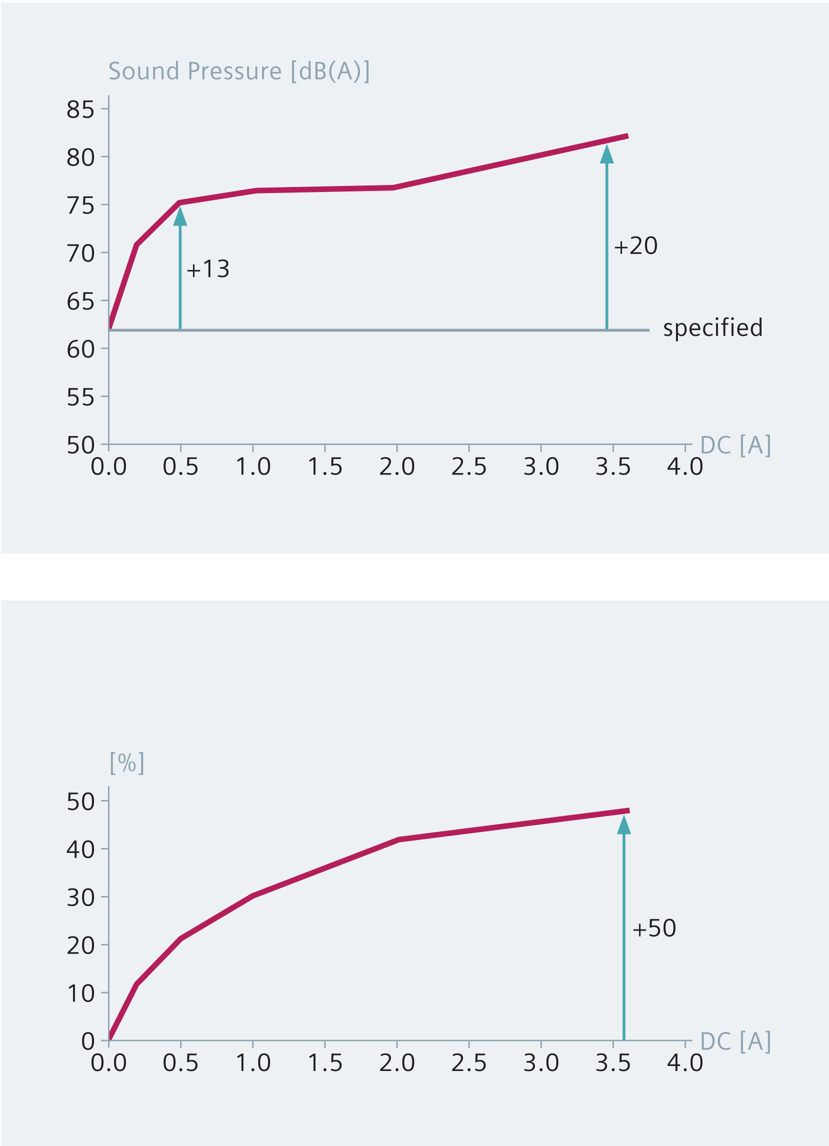

Figure 4. Change in sound pressure by increasing DC in HV (up); a relative change of no-load losses over DC load in HV (down)

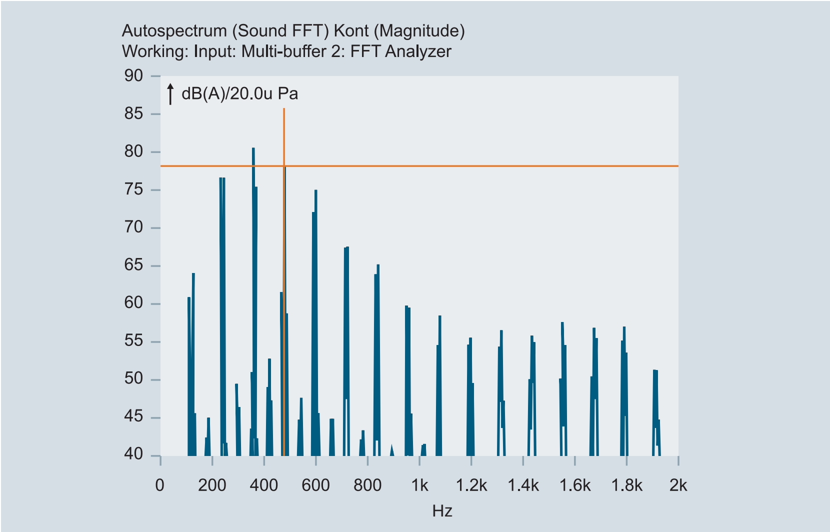

Figure 5. Example noise spectrum of transformer without DC bias (dominating even harmonics)

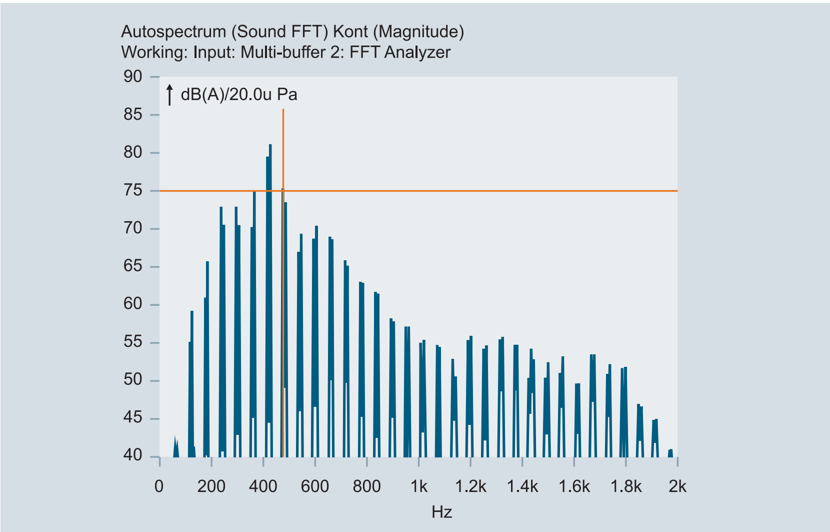

Figure 6. Example noise spectrum of transformer with DC bias causing even and odd harmonics

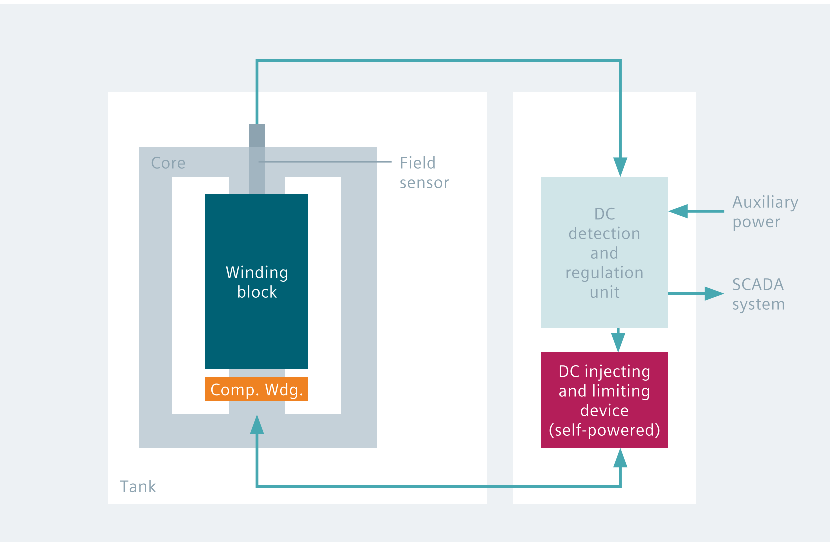

Figure 7. DC-ready transformer (left) and the upgrade package to a full DC compensation to the right (simplified)

External solutions for coping with DC would be:

- Low noise transformer without DCC – does not solve the DC effect
- Installation of external noise protection walls – highly expensive/not always possible
- Implementation of DC blockers – ineffective for DC asymmetric loading and depending on neutral accessibility, not effective for autotransformers (low and high voltage system galvanically connected, therefore re-routing the DC current)

5.The DC compensation approach

The DC compensation approach includes the following steps:

1. Detection in order to give first indication at installed transformers
2. Preparation of new transformer installations with cost-efficient DC-ready feature
3. Proving exactly the exposure of the prepared transformer to DC
4. Compensation in order to get down to usual noise and loss values

5.1 DC detection

Increased transformer noise and loss levels are usually the first indication of a DC bias in the grid and the transformer. The noise spectrum in particular can be used easily for an initial detection of DC bias in the transformer. In the noise spectrum of unbiased transformers, there will only be significant even harmonics (100, 200, 300… Hz in a 50 Hz grid). With a DC bias, the intermediate odd harmonics (150, 250, 350… Hz) will increase significantly, and thus can be used to quickly and easily detect a DC load in the transformer. Energized transformer fingerprints can be easily captured with a noise spectrum analyzer and they contain sufficient information to give customers heads-up information while they are planning to enlarge their grid with additional transformers.

5.2 DC-ready configuration

In order to be prepared for the changing grid topology and increasing renewable generation in the future, power transformers should be ready to cope with DC in the grid. Transformers can be designed “DC ready”, with the active part already

The compensation unit generates the necessary DC in the compensation winding for the counter magnetic field to offset the DC impact of both positive and negative DC magnitudes

equipped with all required components for DC compensation, such as compensation winding, internal measurement sensors and lead connections. The control unit is not included yet for DC-ready transformers, but it can easily be retrofitted with an out-of-tank installation later, based on the actual amount of DC in the grid. DC-ready transformers, therefore, have the following advantages:

- Easy plug-and-play retrofit of the control unit for DC compensation, matched with the actual amount of DC without any major rework of the transformer
- Capability to eliminate impacts of DC and set back the loss and noise levels to values measured in the factory – even in the event of changing DC amounts in the future
- DC-ready fleet and one full version in stock for quick reaction to a changing grid environment

5.3 DC measurement

A DC-ready transformer can be easily extended with an add-on device which allows measuring of the actual DC load of the transformer during normal transformer operation. This very detailed measurement gives evidence and determines the actual DC bias over time. This instrument can not only generate a snapshot (see DC detection), but also give a long-term measurement profile during a defined period of time. This helps to get an indication of feasible measures and compensation power of the DC compensation device.

5.4 DC compensation

A DC-ready transformer, already consisting of sensors and compensation winding, is connected to the compensation unit which is an external device that can be attached to the transformer or placed in the surrounding area. It generates the necessary DC in the compensation winding for the counter magnetic field to offset the DC impact at the installed unit, Fig. 7. In the grid, depending on the voltage level of the DC affected system, positive as well as negative DC magnitudes can be compensated. In transmission grids, usually, the compensation system is able to compensate single-digit amps in neutral.

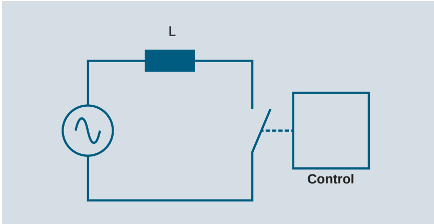

Figure 8. Principal functionality of the DC compensation

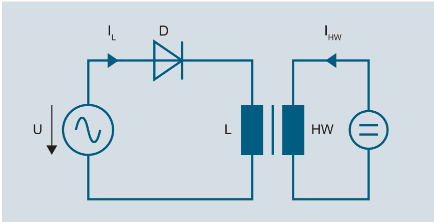

Figure 9. The construction principle of the compensation device

Figure 10. One possible placement of the compensation device on a power transformer

Figure 11. Siemens compensation device at Austrian Power Grid site

Authors

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There are solutions available for detecting and eliminating the negative effects of a DC bias on transformers

5.5 Principal functionality of the DC compensation

Periodically closing and opening the switching element generates DC-biased current impulses in the compensation winding where a current limiting reactor determines the maximum possible DC. The timing of the switching events is controlled by a control unit in order to eliminate the resulting DC flux in the transformer core. In Figure 8 illustrates the principal function of the DC compensation.

5.6 The construction principle of the compensation device

Since semiconductor based switches are vulnerable to overvoltage, they have been replaced by a transductor. With a defined DC bias in the secondary winding (HW) of the transductor and hence the DC magnetization of the transductor core, DC biased current impulses will be generated on the primary side (L) of the compensation device.

This solution has significant advantages in terms of robustness, availability and scalability. Another advantage is the combination of the switching element and current limiting reactor in a single electrical system, Fig. 9. During installation on site, generally, the device can be flexibly placed near the transformer. Figure 10 shows a 3D model of the compensation device placed in front of the transformer. The prototype test was conducted at a single-phase bank, where the compensation device was placed close to the cooling equipment. This is shown in Figure 11.

With a changing grid topology and increasing renewable generation, power transformers should be designed "DC ready" in order to cope with future DC challenges in the grid

Conclusion

The factors that influence DC bias in the grid are evolving due to geopolitical decisions on power generation (renewables) and already present environmental factors (low geomagnetic currents). The consequences of higher noise and loss levels interfere with global urbanization and environmental needs. Highly optimized transformers are even more inclined towards DC sensitivity. In order to solve these problems there are solutions available, ranging from detection to eliminating the negative effects on transformers.

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