Intelligent Protection of VSD Transformers

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Abstract — **Variable Speed Drives (VSD) protect themselves as well as the driven motors. In contrast, the isolation input transformer typically requires its dedicated protection. Unlike distribution and power transformers, the protection of VSD duty transformers need to consider several additional aspects, such as non-sinusoidal current with harmonic content, multi-winding design, phase-shifted converter windings etc. This paper aims to explain the challenges related to protection of VSD transformers. A guideline for reliable transformer protection based on good design practice is proposed. Finally the possibility to integrate the transformer protection into the VSD protection scheme is being explored.**

Keywords — transformer protection, phase shifting, Arc back, overvoltage transient, surge arresters, vacuum circuit breaker, variable speed drive (system).

I. Introduction

Vast majority of the medium voltage (MV) variable speed drive systems (VSDS) requires a dedicated input transformer (often called VSD transformer, rectifier transformer in IEEE or converter transformer in IEC). Power of such transformers ranges from approx. 500 kVA to 40’000 kVA with special cases exceeding 100’000 kVA. Input voltage is defined by the supply, typically ranging from 4 kV to 33 kV for dry transformers and up to 220 kV for oil transformers. Exception is just the small family of direct-to-line (DTL) drives that are transformer-less. A reliable transformer protection scheme is therefore essential for the functionality and availability of the overall VSDS. Power and distribution transformers usually have protection with a high level of maturity and reliability. On the other hand the VSD transformers differ in topology and operation that need to be considered in protection concept.

A. Reliability and Availability

Transformers belong among the most reliable power electric components. Their mean time between failures (MTBF) is generally in the range of several hundred or several thousand years. Despite this fact, a proper transformer protection is of utmost importance as a transformer failure can have fatal consequences.

Besides MTBF figures the mean time to repair (MTTR) is crucial for the availability of the drive system. At this point the designer shall make sure that there is no bottleneck in regards to availability. Specifications for the VSD often require various redundancies such as redundant cooling fans (n+1), redundant cooling pumps (2 × 100 % with automatic switchover) and sometimes also redundant semiconductors (n+1 in case of low-voltage components). The MTBF of a proven VSD is usually 10–25 years. Exact value depends on the product as well as the approach: theoretical calculation based on sub-component datasheets or feedback from installed base (figures from installed base typically more optimistic). Most of VSD failures can be detected very fast and fixed within few hours. In contrast, the VSD transformers seldom have redundant components and to fix an issue might take several weeks or months.

TABLE I.
Reliability and Availability of Transformer and Variable Speed Drive

VSDS component	Transformer	VSD
MTBF [years]	1'800	10
MTBF [hours]	15'768'000	87'600
MTTR [hours]	2'880	4
Availability	0.99982	0.99995

Of course, above data is statistical and a specific project might look different. However, it shall illustrate that although the MTBF figure of transformer is much higher than the MTBF of the VSD, there is also huge difference in the MTTR making the availability fairly similar. Also note that the transformer MTBF figures usually refer to all transformers built by the given manufacturer including less complex designs. When considering only the VSD transformers the MTBF figure is expected to be slightly lower.

Leading manufacturers make the VSD self-protective (features such as fuseless concept and arc resistant design) and easily serviceable in rare case of a component failure. Almost any kind of issue can be quickly fixed on site assuming that spare parts are available. When a transformer experiences a failure, it usually needs to be transported into a service shop. There it undergoes several tests to assess the severity of the issue. If the tests reveal that main components (magnetic core and/or some of the coils) are damaged and need to be replaced, the repair takes several months. Although the statistical availability is still well above 99.9 %, a plant downtime of several months would have devastating impact on the end user’s business.

B. Specific Protection Issues

For very critical applications a capital spare transformer might be a measure to minimize the risk. Regardless if there is spare transformer or not, the protection concept shall be designed in a way to ensure highest personal safety, quick fault detection with fast reaction time and reliable functionality in all possible operating conditions. It shall always be proved that the selected transformer protection concept is suitable for the given VSD application.

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Protection schemes for power and distribution transformers are used since decades and are very mature. On the other hand, protection of transformers used in the variable speed drive systems (VSDS) needs some extra concerns. There are certain points that differentiate them from the classical distribution and power transformers. Besides the differences in design, additional aspects such as current containing harmonic components, phase-shifted windings, common mode voltage etc. need to be considered. One of the key requirements on the VSDS is reliability and availability. The power semiconductors, heart of the VSD, are continuously developed and their reliability steadily increases. The VSD includes self-protecting functions and in rare case of a failure, the design usually enables a quick replacement of the faulty component directly on site in order to minimize the downtime. In contrast, a transformer repair may require shipping of transformer parts or even complete unit into the workshop. This means significantly larger downtime and severe consequence for the user. Therefore, a reliable transformer protection is essential to reduce the risk of a transformer failure and/or minimize the damages. This paper discusses various aspects related to the VSD transformers related to their reliable protection. The goal is to give a guidance and good design practice. Besides that the paper also explores the idea of having certain transformer protection and supervision integrated in the VSD control and protection scheme. Such philosophy would allow to have the protection of the complete VSDS centralized inside the VSD. The user benefits from simplicity, easier monitoring and supervision and reduced cost. Another goal is to gain increased reliability compared with conventional concept.

II. Protection of VSD Systems

Protection of the VSDS components is as important as the design of VSDS components. The protection schemes of system components such as transformer and motor have to be discussed in the early stage of the projects. In general, since the motor protection is already covered by the VSD protection, the main open topic is the protection of the input transformer. The user might be experienced with protection of distribution transformers. However, that concept might not be fully transferable to a converter duty VSD transformer. Some of the additional considerations are highlighted in this paper.

Availability is one of the key factors for the end user. Whenever a fault happens inside the VSD due to abnormal conditions, the faulty section (capacitor, semiconductor etc.) can be quickly identified and replaced with a spare part. However, when the VSD transformer experiences a severe failure, the repair takes a considerable amount of time. Often the repair of a transformer cannot be done on site and transport to a workshop is necessary. In the worst case, the transformer has to be replaced with a completely new unit. Needless to say that such event has severe consequences on the plant operation. Therefore it is very important to design the correct protection schemes for the VSD transformers to avoid the failures.

The classical VSDS consists of an isolation input transformer, VSD and electric motor. In some cases there might be also an output transformer between the VSD and motor to adapt the voltage. Depending on the project setup there are different suppliers for each VSDS component. In general, the VSD and motor protection is integrated into the VSD protection scheme. Therefore the customer does not necessarily specify the protection scheme of the VSD and motor. Typical motor protection functions implemented in the VSD are: overcurrent, current unbalance, overload, locked rotor, ground fault detection, overvoltage and others. However, the input transformer protection specifications depend up on the network conditions, operational scenarios, number of windings, vector groups, duty cycles etc.

The intended protected area for a given protective element is called zone. The VSDS is divided into two zones with respect to protection:

Zone-1: Transformer and line side cables

Zone-2: Variable speed drive, motor cables and motor

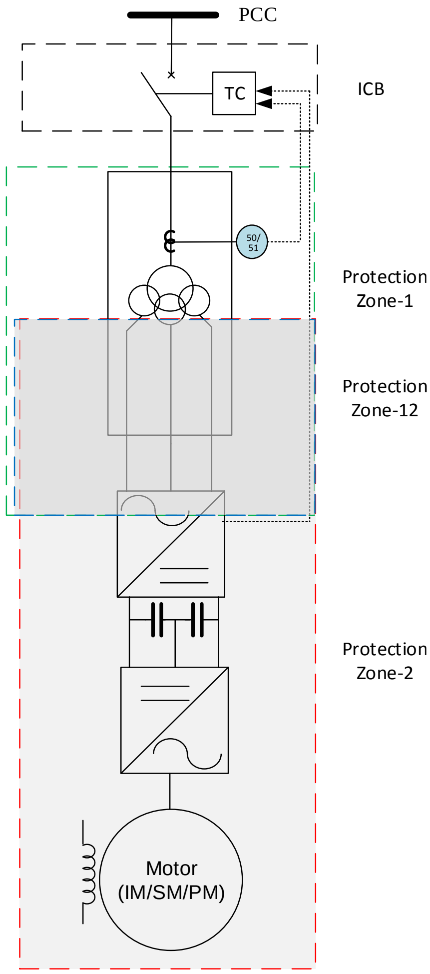

Fig. 1. Protection zones of variable speed drive system.

Alternatively, there might be three zones with the motor located in its own zone. However, the motor protection functions are usually satisfactorily covered by the VSD. Vibration monitoring, bearing supervision and pressure and leak detection are normally the only groups which are not covered by the VSD and require dedicated instrumentation. And even there is a trend to include some of those protection functions into the VSD or at least collect the signals centrally in the VSD.

The meaning of protection zones is to ensure the protection coordination inside a system or plant. It also helps to visualize the areas protected by the protection elements.

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Zone-1 typically includes following protection functions (with corresponding IEEE/ANSI codes [1]):

26T – Oil temperature (oil filled transformers)
49 – Thermal overload (optional)
49T – Winding temperature
50 – Instantaneous overcurrent
51 – Time delayed overcurrent
51G – Ground fault detection
63T – Buchholz relay (oil filled transformers)
63TP – Pressure relief device (oil filled transformers)
87T – Differential protection (optional)

Zone-2 typically includes following motor protection functions integrated in the VSD (with corresponding IEEE/ANSI codes [1]):

23 – Overtemperature protection
27 – Undervoltage protection
47 – Phase reversal protection
49 – Thermal overload protection
50 – Instantaneous overcurrent protection
51 – Time overcurrent protection
59 – Overvoltage protection

There is also an overlap area between zones 1 and 2. In this area the overcurrent protection is provided by the transformer protection relay while the earth fault protection is provided by the VSD integral protection.

III. Transformer Protection

A. General Considerations

Reliable transformer protection is essential to achieve high availability. The objectives of the protection schemes and devices are:

- To protect the personnel.
- To prevent the damage of the equipment due to short circuits within the equipment.
- To minimize the damage of the drive system components due to overloads.

The protection scheme shall fulfil the following characteristics:

- selectivity
- sensitivity
- speed
- security
- reliability

Standard protection functions were mentioned in the previous paragraph. Two basic protection groups are: Overcurrent and overvoltage groups of the protection functions.

B. Challenges in VSD Applications

When defining the protection concept of the VSD transformers, following things shall be additionally taken into account:

Current harmonic distortion

It shall be checked that the protection element (e.g. transformer protection relay) can work properly considering the harmonic distortion. The phase shift between secondary windings helps to eliminate (compensate) the characteristic harmonic currents. As a result, the harmonic distortion on the primary (HV) side of the transformer is usually very low and complies with the international grid codes. However, this cancellation takes place inside the transformer. The current flowing in the secondary (LV) windings is very rich in harmonics since each winding is feeding a 6-pulse diode rectifier bridge (see Appendix A). If the protection element is sensing such current, it shall have proper in-built filters or algorithms to ensure that non-sinusoidal current waveform does not result in a malfunction or false trips.

Multi-winding design

The VSDs are continuously developed and within the diode front end (DFE) family the trend is towards a higher rectifier pulse number in order to minimize the harmonics injected into the suppling grid and consequently to minimize the harmonic distortion. 12-pulse diode rectifier is often the minimum accepted pulse number; 24- or 36-pulse rectifier becomes a standard.

To meet the VSD requirements, transformers with 24-pulse or 36-pulse total reaction are nowadays a standard solution. While this evolution has a positive impact on the grid and other consumers (see Fig. 2), it makes the overcurrent protection more difficult. The increased rectifier pulse number brings challenges for implementation of the transformer overcurrent protection. The higher number of secondary windings, the higher sensitivity and selectivity is required. Depending on the network conditions and design voltage impedance it might be difficult to detect a fault inside the individual secondary winding based on measurement of the primary current.

The worst case for the fault detection by sensing the primary current is a phase-phase fault on one of the converter windings while the VSDS being at no-load condition. This is a realistic situation considering two faulty diodes inside the rectifier. The situation is even worse when a supply voltage variation is taken into consideration. At an undervoltage the fault current on the primary side becomes again few percent lower.

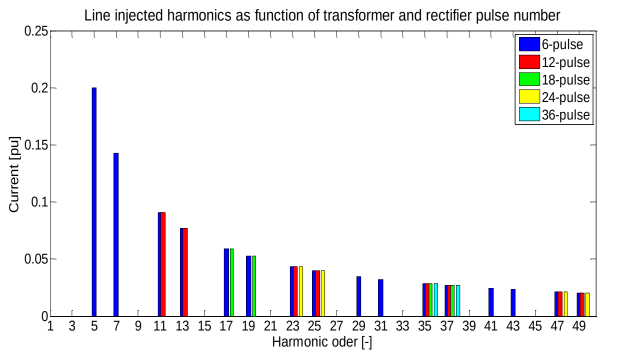

Fig. 2. Line side characteristic harmonics as function of the transformer pulse number.

The situation can be illustrated on examples of a 36-pulse transformer with 6 converter windings and 30-pulse phase shifting transformer for a multi-cell converter with 15 converter windings.

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<u>Case 1:</u>

Transformer rating	10’000 kVA
Transformer total reaction	36-pulse
Number of secondary windings	6
Transformer design impedance	8 % *)
Transformer max. impedance	8.8 % **)
Network short circuit power	200 MVA
Undervoltage	−10 %

*) One secondary winding shorted
**) Including IEC/IEEE tolerance

TABLE II.
SHORT CIRCUIT CURRENTS IN CASE 1

Fault current and fault power 36-pulse transformer with 6 secondary windings		3-ph short circuit		
		Rated voltage	Undervoltage	Short circuit power at rated voltage
Secondary SC current		10.38 pu	9.34 pu	17.30 MVA
Primary SC current	**0 % load**	**1.73 pu**	**1.56 pu**	**17.30 MVA**
	25 % load	1.94 pu	1.77 pu	19.38 MVA
	50 % load	2.15 pu	1.97 pu	21.47 MVA
	75 % load	2.36 pu	2.18 pu	23.55 MVA
	100 % load	2.56 pu	2.39 pu	25.63 MVA
Fault current and fault power 36-pulse transformer with 6 secondary windings		2-ph short circuit		
		Rated voltage	Undervoltage	Short circuit power at rated voltage
Secondary SC current		8.99 pu	8.09 pu	14.98 MVA
Primary SC current	**0 % load**	**1.50 pu**	**1.35 pu**	**14.98 MVA**
	25 % load	1.71 pu	1.56 pu	17.07 MVA
	50 % load	1.91 pu	1.77 pu	19.15 MVA
	75 % load	2.12 pu	1.97 pu	21.23 MVA
	100 % load	2.33 pu	2.18 pu	23.32 MVA

<u>Case 2:</u>

Transformer rating	10’000 kVA
Transformer total reaction	30-pulse
Number of secondary windings	15
Transformer design impedance	8 % *)
Transformer max. impedance	8.8 % **)
Network short circuit power	200 MVA
Undervoltage	−10 %

*) One secondary winding shorted
**) Including IEC/IEEE tolerance

TABLE III.
SHORT CIRCUIT CURRENTS IN CASE 2

Fault current and fault power 30-pulse transformer with 15 secondary windings		3-ph short circuit		
		Rated voltage	Undervoltage	Short circuit power at rated voltage
Secondary SC current		10.95 pu	9.85 pu	7.30 MVA
Primary SC current	**0 % load**	**0.73 pu**	**0.66 pu**	**7.30 MVA**
	25 % load	0.96 pu	0.89 pu	9.63 MVA
	50 % load	1.20 pu	1.12 pu	11.97 MVA
	75 % load	1.43 pu	1.36 pu	14.30 MVA
	100 % load	1.66 pu	1.59 pu	16.63 MVA
Fault current and fault power 30-pulse transformer with 15 secondary windings		2-ph short circuit		
		Rated voltage	Undervoltage	Short circuit power at rated voltage
Secondary SC current		9.48 pu	8.53 pu	6.32 MVA
Primary SC current	**0 % load**	**0.63 pu**	**0.57 pu**	**6.32 MVA**
	25 % load	0.87 pu	0.80 pu	8.65 MVA
	50 % load	1.10 pu	1.04 pu	10.99 MVA
	75 % load	1.33 pu	1.27 pu	13.32 MVA
	100 % load	1.57 pu	1.50 pu	15.65 MVA

From the above results we can see that with 6 secondary windings the fault current in the worst case scenario (2-phase fault on one secondary winding, no-load, undervoltage) is just in the range where it can be still detected with a conventional overcurrent relay (135 % rated current at undervoltage / 150 % rated current at rated voltage). The other case with 15 secondary windings shows that the fault current in the worst case condition is significantly below the rated current. Up to at least 50–60 % load the fault on single secondary winding cannot be detected without further counter-measures. The calculations considered grid short circuit capacity of 200 MVA, i.e. ratio of 20 between grid capacity and transformer rating. With lower ratio (weaker grid) the fault current further reduces.

Frequent transformer energizing

Frequent energizing of the input transformer is not directly related to the usage of the VSD, but rather to the application. Some applications require uninterrupted operation and are shut down only for a scheduled maintenance. On the other hand, there are applications where the transformer is switched on and off several times per week or even several times per day (e.g. pump storage power plants, marine propulsion, furnace applications, mill drives during maintenance inspection etc.).

The energization is associated with eventual switching overvoltages and of course with the inrush current phenomena. The inrush current occurs whenever the polarity and magnitude of the residual flux in the transformer core differs from the polarity and magnitude of the instantaneous value of the steady-state flux corresponding to the point on the B/H curve. The severity of the inrush current depends on the residual magnetizing flux, the source impedance and the closing instant of the upstream circuit breaker.

Very fast transient overvoltages

Besides the steady state voltage variation (e.g. within +/−10 % of nominal) there are voltage excitations classified as dynamic, transient and very fast transient overvoltages. The danger of the high frequency switching transients is well known and mentioned in the international standards, such as [3]. However, the topic gets sometimes forgotten during system integration of a particular project.

If the incoming circuit breaker is of the vacuum type (VCB), a switching overvoltage is generated when interrupting the current. Opening or closing a VCB can cause a prestrike or re-ignition, creating high frequency currents. The VCB is able to interrupt high frequencies causing virtual current chopping at levels near the peak currents.

These currents cause fast transient overvoltages that get trapped in the transformer windings due to its stored magnetic energy [5-9]. The transformer coils are exposed to very high dielectric stresses and the coil insulation might be unable to withstand such high magnitude and fast transients. Some transformer manufacturers even add exclusions into their warranty clause such as “*manufacturer warrants its product against any defects in workmanship and material, but only if the product is not exposed to voltage transients generated by high speed switching devices, such as SF6 and vacuum breakers*“.

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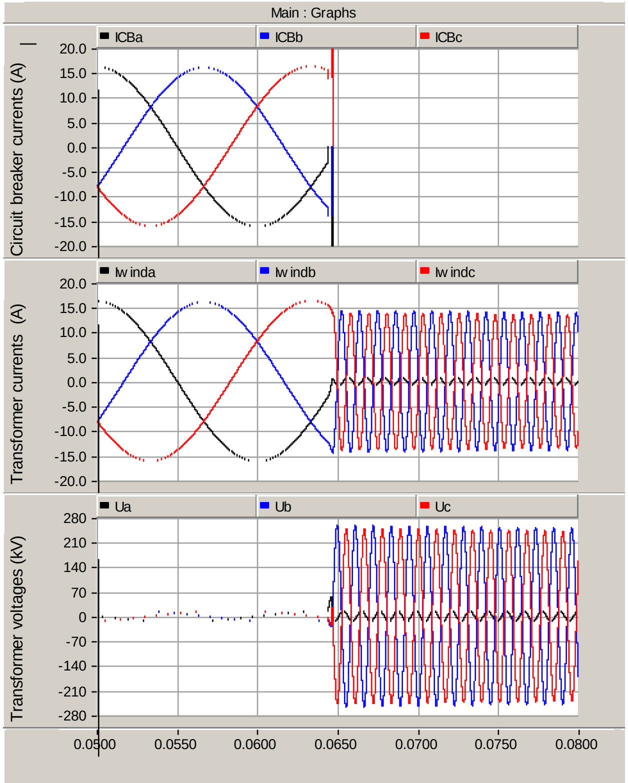

Fig. 3. Current interruption with vacuum circuit breaker.

The overvoltage is of a high frequency (hundreds of kHz up to 100 MHz), even higher than atmospheric overvoltages. Therefore the voltage rise time (dv/dt) is very high and it is a certain risk to excite an internal resonance inside the transformer. Captured on the site measurements the revealed rate of change exceeding 500 kV/μs. The standard waveform of the lightning impulse has the shape of 1.2/50 microseconds. The test infrastructure and procedure for the lightning and switching impulse testing is described in [14]. The standard withstand voltage test for very fast overvoltage transients is not explicitly given in the IEC standard [4] and shall be defined by the relevant apparatus committee. The testing waveform recommended by specialists for very fast transients, so called fast impulse test, has 10-times higher rate of rise than the lightning impulse, i.e. 0.12/5 microseconds. The voltage distribution over the winding turns is different and generally more critical for very high frequencies. The problematic was studied in detail, e.g. by CIGRE. See also Appendix B and C with measured and simulated waveforms.

The experience shows that such overvoltages, when appearing frequently, can affect the transformer and lead to an insulation failure. The dry type transformers seem to be more sensitive to those overvoltages while the liquid immersed transformers are more robust in this regard. Just increasing the BIL level of the transformer insulation might not be an appropriate solution. Instead, an effective overvoltage protection is needed.

Mechanical forces and stress

The dynamic short circuit test belongs to special tests and is very costly. A calculation is often accepted as alternative. Therefore the manufacturer experience and solid know-how is very important. Besides the thermal effects of a short circuit there are also the dynamic effects. The radial forces try to expand the outer winding and compress the inner winding. The axial forces act similarly in the axial direction. As the dynamic forces are proportional to the square of the fault current, they can reach fairly high values. External short circuits are not restricted to three-phase; they include line-to-line faults, DC faults and rectifier faults. It is important to consider especially the case of failure inside the diode rectifier. This type of failure increases the theoretical peak fault current by factor 1.5 compared to the traditional AC fault (eq. (1) and (2)). The phenomenon is called "Arc back" in the IEEE standard [2]. The dynamic forces in this case will be 2.25-times higher causing significantly higher mechanical stress.

$$\hat{I}_{\mathrm{AC\_fault}} = 2 \cdot \sqrt{2} \cdot I_{\mathrm{k\,(RMS)}} \tag{1}$$

$$\hat{I}_{\mathrm{Arc\_back\_fault}} = 3 \cdot \sqrt{2} \cdot I_{\mathrm{k\,(RMS)}} \tag{2}$$

When this case is not considered in the transformer mechanical design, it might lead to excessive forces. In case of fault in just one winding, the forces acting on the winding might catapult it in the axial direction. It is sometimes called 'telescoped winding'. It is proven that some transformer failures have been caused by this phenomenon as the standard industrial practice is to design transformers for the AC faults only.

Fig. 4. Axial short circuit failure due to dynamic forces (mechanical failure).

Such DC current generates forces with network frequency instead of two times network frequency. Additionally, it increases thermal stress of the short circuit current by 60 % and correspondingly reduces the required minimum tripping time to 40 % of the transformer nominal thermal short circuit requirement time. (IEC 2s, IEEE 1s). Having IEC rated transformer the minimum thermal tripping time is 800 ms and correspondingly IEEE rated transformer 400 ms. This may be difficult to reach with practical relay breaker combinations. Another challenge is the interruption of significant DC component.

Differential protection

The transformer differential protection can be easily done for a 2-winding or 3-winding transformer. As the number of windings increases, the complexity of such

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protection function increases as well. A large number of current transformers (CT) is required. For a 36-pulse transformer with 6 secondary windings it means 3 CTs on primary side and 18 CTs on the secondary side. For a transformer with 15 secondary windings as much as 45 CTs would be required. Besides that the phase displacement has to be considered as well. This might require additional summing CTs and a protection relay that supports such functionality. Further, if the differential protection shall protect not just the transformer, but also the cables, then the secondary side CTs shall be preferably placed at the input section of the VSD. This in turn means modifications on the VSD (mechanical adaptations). The overall cost is quite high and the solution might not be so reliable due to high complexity and amount of the components. There is also an increased risk of wrong installation and parameterization of such differential protection.

IV. Practical Solutions

This chapter provides several solutions and answers for the challenges related to the transformer protection. The focus is on reliability and simplicity and takes practical limitations into account.

A. Overcurrent Protection of Multi-winding Transformers

In order to detect a fault on the secondary side of a multi-winding transformer based on the primary current measurement, two methods can be used:

- Transformer design with multiple primary windings

There are typically two or three primary windings. These windings are paralleled internally, i.e. from outside it is no difference compared to the single primary winding. Each primary winding is equipped with a set of CTs. In this way the sensitivity of the overcurrent protection is increased (doubled for two primary windings, tripled for three primary windings).

- Protection relay with feedback from VSD

The modern digital protection relays are very powerful and provide lot of flexibility [10]. Most of them allow to change the parameterization dynamically. That can be used for the overcurrent pickup level. The VSD is sending a digital signal about the output power. It allows to set the overcurrent protection below the rated current at no-load and partial load without tripping the system at the full load operation.

Above solutions provide reliable overcurrent protection for challenging configurations with multiple secondary windings, higher transformer short circuit impedance and larger supply undervoltages (e.g. −20 % for power plant auxiliary drives). The concept has been applied in at least two projects so far and seems to work very well. The only pre-condition is a protection relay which allows to change the threshold based on the additional digital input. Most of the advanced relays available on the market support such functionality.

B. Frequent Energization of Transformer

Frequent switching imposes both electrical and mechanical stress on transformers. In case the transformer is expected to be energized frequently, a pre-magnetization is an efficient solution to mitigate possible issues. This is especially true for dry transformers that tend to be more sensitive. The solution can consist of a simple charging resistor or inductor. However, a more sophisticated and elegant method is a unit consisting of auxiliary transformer, switches, control, diagnostic and protection. The main input transformer is magnetized through one of its secondary windings by the auxiliary transformer before the main circuit breaker is closed. The pre-magnetization unit is controlled by the VSD and the logic is integrated in the start-up sequence. This solution has already become very common and is frequently requested by users.

C. Rectifier Diode Fault Supervision

As explained previously, the fault inside the diode rectifier, so called ‘Arc back’, causes a high peak fault current. This in turn means a high mechanical stress. There is a risk that the operator just resets the trip and switches the transformer against the fault repeatedly (unless there is an extra measure such as e.g. lock-out relay). After several trials the transformer can be mechanically and electrically damaged. When the diode fault can be detected in a reliable way, such scenario could be avoided. One solution is improved diode supervision. The voltage across each diode is measured. The voltage can drop just for a short time during commutation. If the voltage is missing for more than few milliseconds, it is evaluated as the diode fault. Details of the concept are described in [15]. The VSD then trips and displays a fault message to inform the operator about the issue. The reaction time shall be as short as possible to minimize the exposure to a high mechanical stress. Keep in mind that the transformer usually has limited withstand capability against occurring axial and radial forces. Early diode fault detection prevents multiple switching of the input transformer against the short circuit and can avoid mechanical damages inside the transformer.

D. Fast Switching Transient Protection

Vacuum circuit breakers can produce fast transient overvoltages inside of transformer windings. Simulations and field measurements revealed that the use of surge arresters might not be sufficient protection as surge arresters only limit the peak transient overvoltage while the rise time remains extremely steep. Dry type transformers are more sensitive to this issue while liquid immersed transformers tend to be more robust against transient overvoltages. The severity also depends on the transformer voltage class. Up to 12 kV class there are very few cases of failed transformers due to switching overvoltages and lot of experience due to a large installed base (vast majority of the integrated transformers belong to this category). Above 12 kV extra measures might be recommended. The higher the primary voltage, the more attention shall be paid.

Measure # 1: Type of circuit breaker

One measure on system level is to install an SF6 breaker rather than a vacuum breaker. This type of breaker creates a less severe switching overvoltage. Of course, the use of an SF6 breaker is not always possible due to various other requirements.

Measure # 2: Overvoltage protection

Two basic overvoltage protection measures are used: surge arrestors and RC snubber circuits.

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The surge arrestors are highly non-linear elements, usually of metal oxide resistor type, such as e.g. ZnO varistors [13]. The protective level of the surge arrestors must be coordinated with the BIL of the transformer (see [4] and [13]). They help to reduce the peak transient overvoltage, but do not influence the dv/dt rate. In contrast, the RC snubber capacitance aims to limit the dv/dt rate of rise. The series connected snubber resistance provides fast damping of the oscillations. It is obvious that both above means complement each other very well.

The insulation protection can be improved by using more effective arrangement of the surge arresters. Instead of the installation between each phase and ground the so called “Neptune connection” is very beneficial and easy to achieve. It inherently provides the phase to ground and phase to phase protection. More information can be found in [13].

Further, a special arrangement of varistors can overcome the overvoltage issue. It prevents re-ignitions during current chopping. It also protects against the resonance amplification because the transformer internal resonance is much less excited. The varistors require no maintenance and their life expectancy is the same as the transformer. However, it needs to be checked if this kind of protection is available for the VSD transformers or not.

E. VSDS Differential Protection

It was explained that a differential protection of a multi-winding transformer becomes very complex. The concept is suitable up to three or four secondary windings. For a higher number of windings it is still technically possible, but also very costly and does not necessarily increase the reliability. It might be a challenge to find a suitable protection relay that supports such configuration. Many current sensing devices are required and failure of any of them would likely trigger a false tripping and consequent shutdown. However, there is the idea of doing a differential protection of the VSDS; more specifically between the transformer primary side and VSD output. The current measurement on the transformer primary side is needed in any case for the overcurrent protection. The measurement at the inverter output is a standard part of the VSD and inherently available (no extra cost and no increase of complexity). It is therefore principally possible to make a combined differential protection of the input transformer, cables and VSD. This protection can be fully integrated into the VSD. In other words, the protection zones 1 and 2 could be merged into one single protection zone. In this way, the protection concept can be simplified and standardized. The main benefit for the user is one single interface in regards to the VSDS protection. A high level concept is shown in Appendix D.

The combined differential protection can be based on currents (traditional way) or it could eventually use the active power. The latter solves the problem of generally different power factor at the transformer input and VSD output.

Transformer input active power P_1

The calculation is based on the transformer input current I_1, supply voltage V_1 and primary power factor $\cos\varphi_1$:

$$P_1 = \sqrt{3} \cdot V_1 \cdot I_1 \cdot \cos\varphi_1 \tag{3}$$

VSD output active power P_2

The calculation is based on the VSD output current I_2, output voltage V_2 and output power factor $\cos\varphi_2$:

$$P_2 = \sqrt{3} \cdot V_2 \cdot I_2 \cdot \cos\varphi_2 \tag{4}$$

From implementation point of view it might be easier to calculate the VSD output active power P_2 from the motor torque $T_{\text{air gap}}$ and speed ω_{mot}:

$$P_2 = T_{\text{air gap}} \cdot \omega_{\text{mot}} \tag{5}$$

The VSD control usually calculates the air gap torque of the motor rather than the shaft torque. In such case the active power calculated according to (5) is the motor input active power which is equal to the VSD output active power (unless it is a special case with the output transformer etc.) Therefore the motor efficiency does not have to be considered and does not bring additional uncertainty.

The efficiency and losses in the transformer and VSD can be quite accurately calculated or estimated as a function of load so that the difference is considered in the differential protection.

$$\Delta P = P_1 - P_2 \tag{6}$$

$$\Delta P = P_0 + P_{\mathrm{L}} \cdot \left({S_{\mathrm{act}}}/{S_{\mathrm{R}}} \right)^2 + P_{\mathrm{VSD}} \tag{7}$$

where

- P_0 … transformer no-load losses
- P_{L} … transformer load losses
- S_{act} … transformer actual output power (kVA)
- S_{R} … transformer rated power (kVA)
- P_{VSD} … VSD losses

The transformer no-load and load losses can be directly obtained from the routine test report. The VSD losses shall be well known to the VSD manufacturer. It might be a function of several variables and can also be implemented in form of look-up table.

Like every approach also this one has certain inaccuracy and tolerance. Considering for example 0.5 % accuracy class of the current measurements, 2 % error of the supply voltage determination, 1 % error on the input power factor, 0.5 % error on the losses determination (ΔP) and 3 % error on the absolute motor air gap torque we get total inaccuracy of approximately 7 %. In order to keep some margin and avoid false triggering, 10–12 % active power difference could be used as threshold. Such tolerance shall be sufficient to allow a reliable detection of any severe failure within the protected area. Further improvement (if necessary) is a matter of an algorithm optimization in order to minimize the inaccuracy. It shall be repeated that also the classic differential protection has limited sensitivity, especially when considering a VSD duty transformer with multiple secondary windings having a relative phase shift.

The method of the combined differential protection might not be suitable for high dynamic applications where the instantaneous values of the current and active power rapidly change (e.g. rolling mill drives in metal works). However, it is well suitable for applications with limited dynamics such as most of compressors, pumps or fans.

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The proposed combined transformer and VSD differential protection has following advantages for the user:

- Current measurement already available (no extra sensors required)
- Protection of the transformer, cables between transformer and VSD and VSD itself (when CTs are located in the switchgear, then also the cables between switchgear and transformer are protected)
- Protection integrated in the VSD meaning that user has one single interface for the VSDS protection (all in one place).
- High level of standardization:
    - minimized project engineering related to the protection scheme,
    - minimized possible parameterization mistakes during project implementation.

In our opinion the proposed method is a valid alternative for the classic differential protection with all the advantages mentioned above.

V. Conclusion

The multi-winding VSD transformers are needed for most of VSD applications. The paper describes and explains the difficulties and challenges associated with protection of the VSD transformers. These challenges come mainly from the transformer topology using multiple secondary windings and the nature of the VSD as well as application specific issues.

The VSD has many self-protective functions and design allowing very quick replacement of a faulty component. These features minimize the repair time (MTTR). On the other hand a transformer failure might be the bottleneck in plant availability.

There are several recommendations given how to overcome those challenges and achieve a simple and reliable transformer protection concept. Asymmetrical fault conditions with high mechanical stress can be minimized by effective rectifier supervision. The insulation stress due to fast switching overvoltages is addressed by selection of a circuit breaker type and effective overvoltage protection. The stress during energizing is eliminated by the pre-magnetization process.

Some of these recommendations have already been used as a good engineering practice. Others, such as the VSDS combined differential protection, are novel and can enable new possibilities. The new concept of differential protection concept is presented as an alternative to the traditional transformer differential protection. It expands the protection zone of the traditional differential protection and simplifies the user interface. The concept does not require additional sensors. Instead, it utilizes already existing measuring equipment.

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Finally we would like to thank Esa Virtanen and Pasi Tallinen from ABB Vaasa for their extensive know how sharing on special transformers for VSD applications.

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Appendix A
Current waveform and harmonic distortion on HV and LV side of transformer

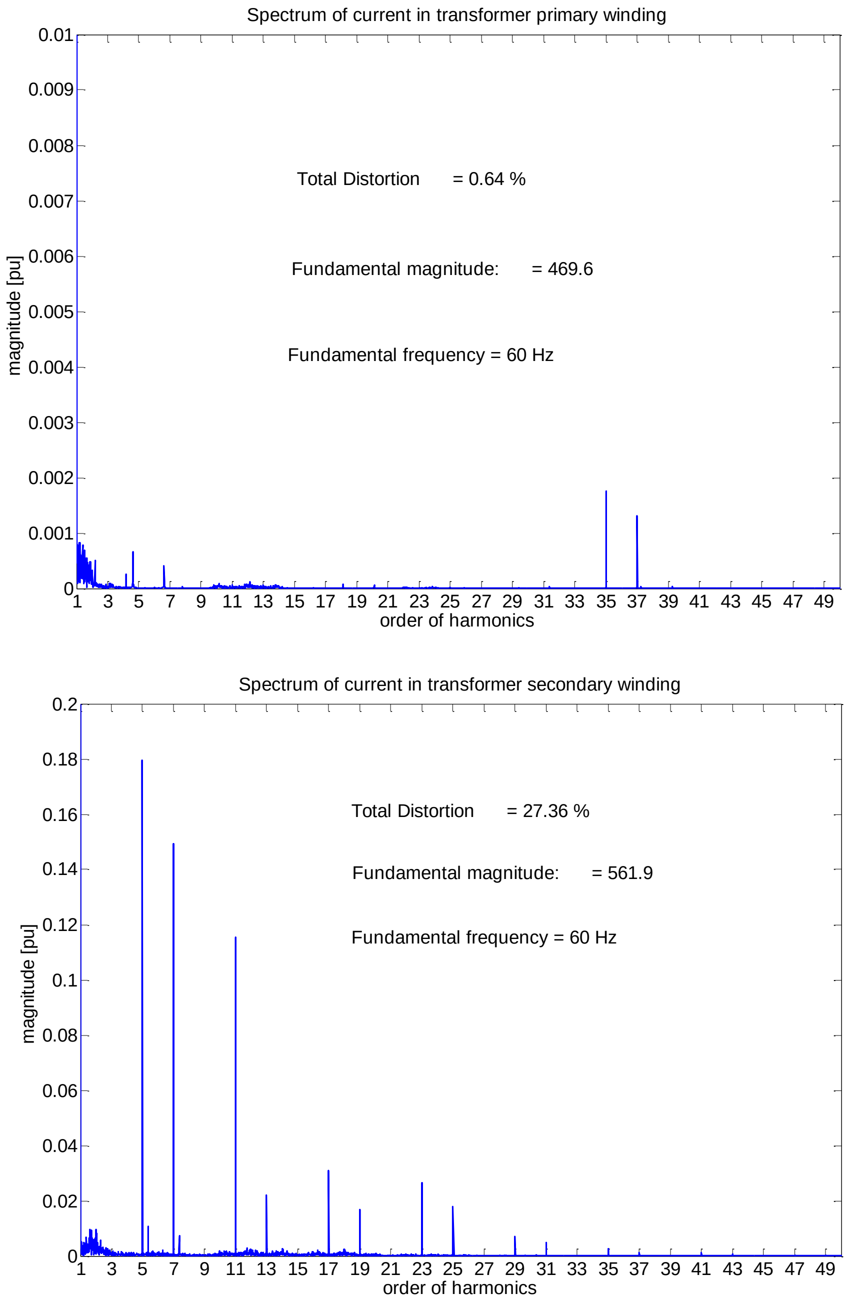

Fig. A-1: Current spectrum in transformer primary (HV) winding and transformer secondary (LV) windings; 36-pulse diode front end (DFE) type of VSD supplied by a 7-winding input isolation transformer.

Remark 1: Please note different y-axis scaling of upper and lower figure (HV side has THDi < 1 %, LV side has THDi > 27 %).

Remark 2: Vector group e.g. Yd11.33d11.66y0d0.33d0.66d1.

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Appendix B
Current chopping when opening vacuum circuit breaker (VCB)

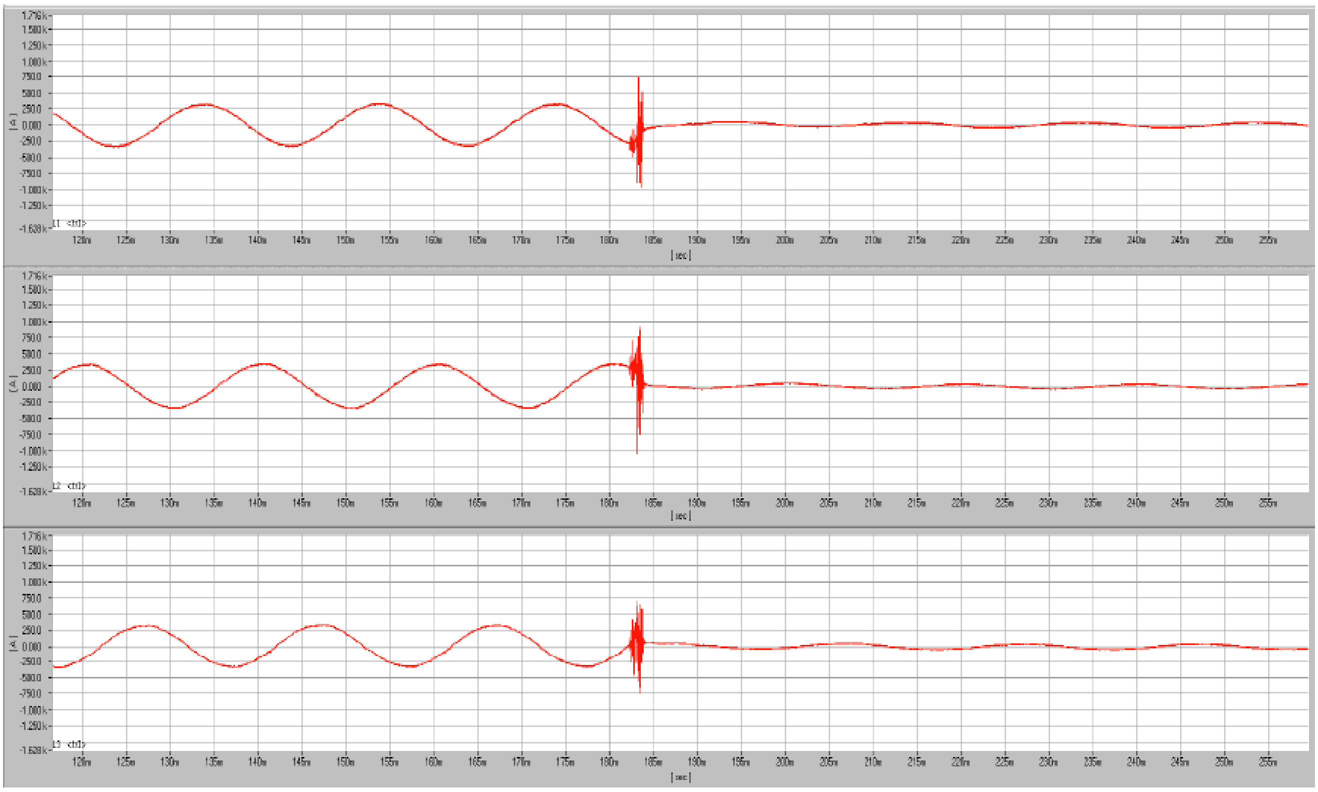

Fig. B-1: Current waveform at 35 kV bus while opening of vacuum circuit-breaker (real on site measurement).

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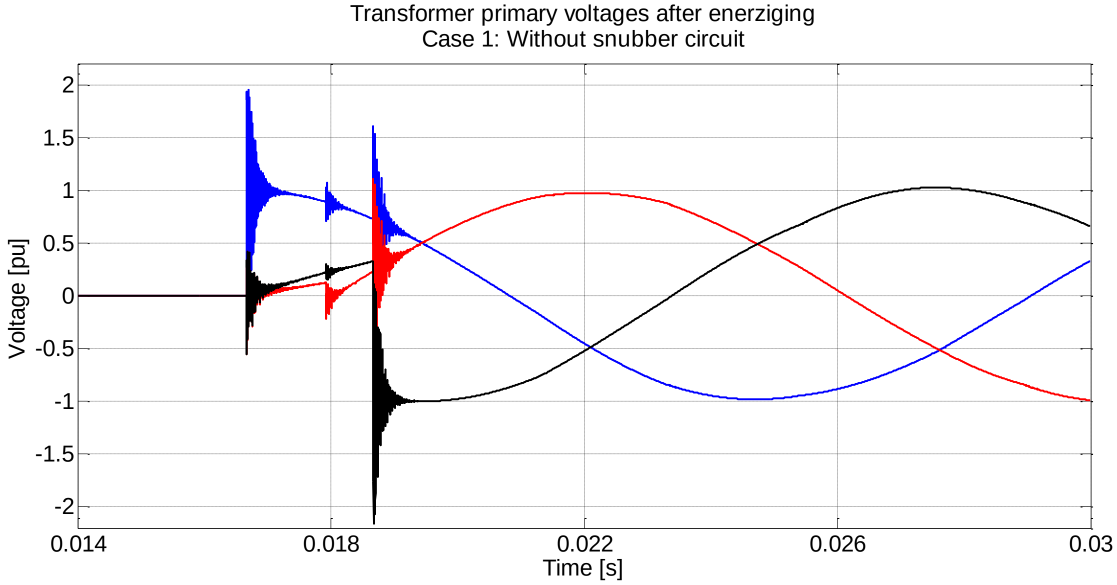
Appendix C
Transient excitation during energizing of transformer



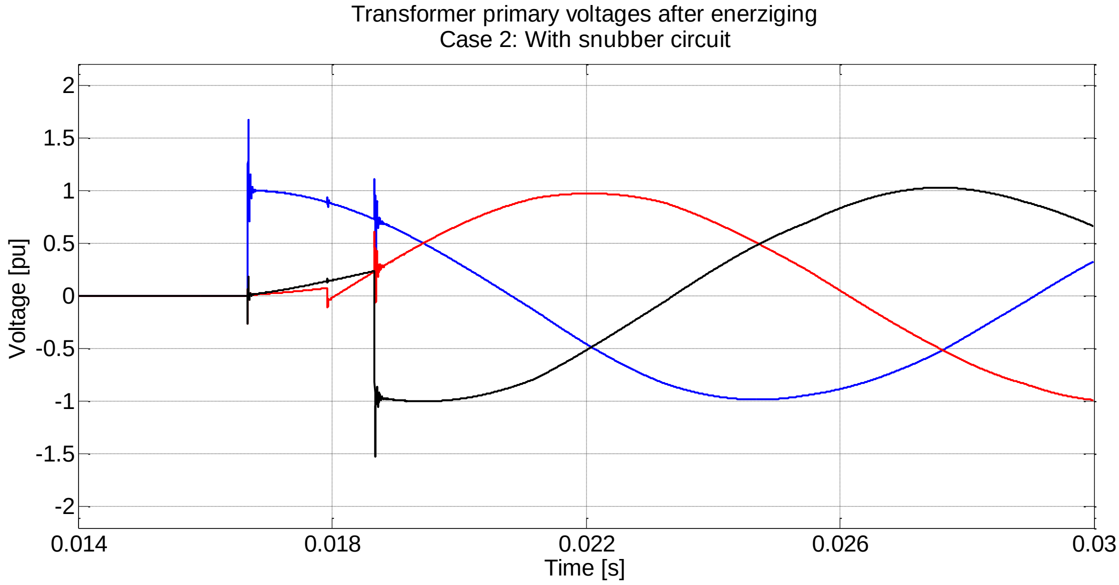


Fig. C-1: Transformer primary voltages during energizing process;
top figure – without overvoltage protection, bottom figure – with overvoltage protection.

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Appendix D
VSDS differential protection

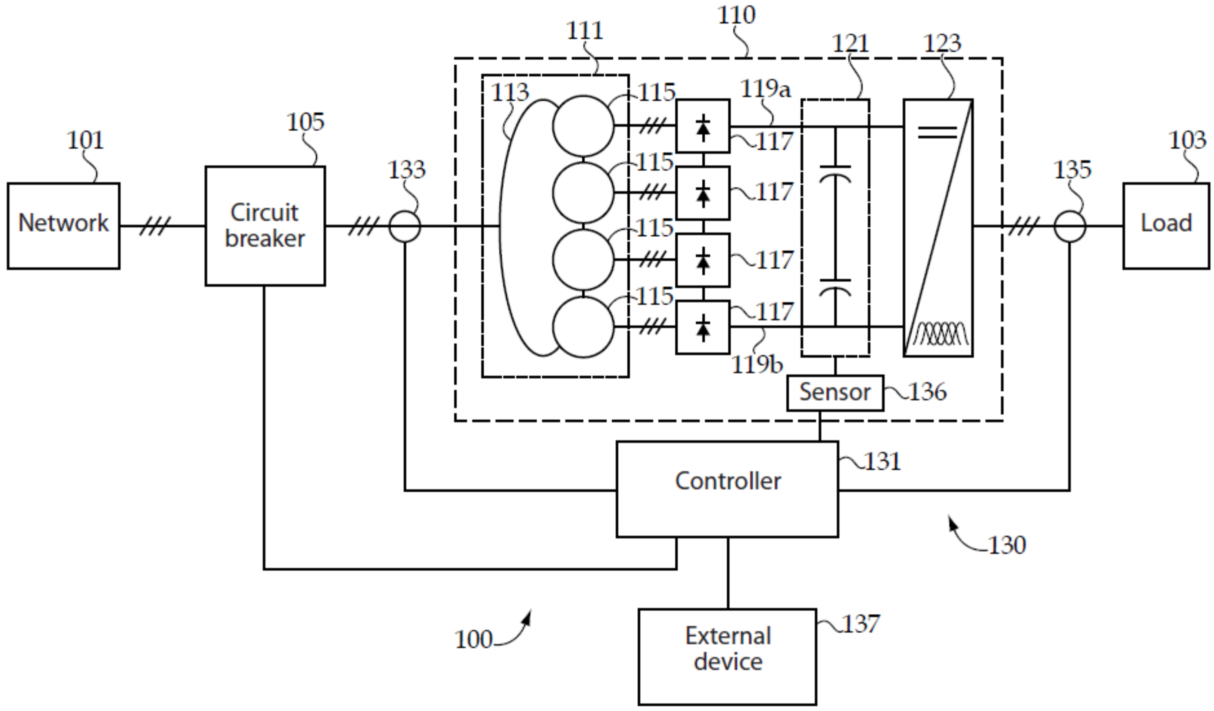

Fig. D-1: Combined VSDS differential protection; differential protection zone between measurement points 133 and 135 (extract from patent application [16]); current measurement 133 can often also be integrated inside the circuit breaker 105.

100 - System

101 – Power source

103 – Drive load

105 – Protective device (e.g. circuit breaker)

110 – Protected device (e.g. VSD)

111 – VSD transformer

113 – Primary winding of VSD transformer

115 – Secondary windings of VSD transformer

117 – Rectifier

119a,b – DC bus connections

121 – Capacitor based DC link

123 – Inverter

130 – Fault detection system

131 – Controller

133 – First set of current sensors

135 – Second set of current sensors

136 – DC bus voltage sensor

137 – External device

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