



Transformer Protection and Monitoring with Multifunction Relays Survey of German Practice

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Abstract

This paper describes the German practice with regard to the transformer protection and monitoring. In order to provide a representative overview, four large German utilities were surveyed. The results are provided in summarised form (tables and diagrams). Apart from general questions, the configuration of typical protection concepts and principles are emphasised. Regarding the numerical multi-function transformer protection arrangements, emphasis is placed on the evaluation of the properties and total perception with regard to the application of the numerous supplementary functions. Furthermore, statements regarding protection settings, engineering and commissioning are formulated. The current state with regard to monitoring is presented after the technical protection section. This current state is summarised.

Keywords: Digital transformer protection, Transformer monitoring, Relay application, German relaying practice

1. Introduction

Transformers are an important link between the individual voltage levels. On the one hand they provide for the voltage transformation and on the other hand the power transfer also is done via the transformers. The German transmission system is made up of the 380 and 220 kV voltage levels, is tightly meshed and has distributed power system in-feeds. The installed power system capacity is approximately 117 GVA. The distribution system is at the 110 kV voltage level and most of it (approximately 90%) is not solidly earthed (via Peterson coil). The remainder is effectively earthed (either solid or via low impedance). In-feeds from power systems are sometimes at the 110 kV level. The medium voltage system is the most expansive, and largely made up of the voltage levels 10 and 20 kV. Most of these systems are not effectively earthed. Some municipal cable systems have a low resistance earthing of the system neutral. In the course of renewable power generation, in-feeds to the medium voltage network occur for example via combined cycle power stations and wind parks.

The power stations primarily feed via unit transformer into the system. Most of these in-feeds are directly into the transmission system from where the distribution to the other voltage levels takes place.

In this paper, the protection and monitoring applications for system transformers is described, whereby only the transmission and distribution system is covered. To be able to provide representative information, 4 large German utilities were questioned during the preparation for this paper. The results are summarised in the following chapters.

Answers in connection with transformer faults and the frequency of faults were "few and far between". A final conclusion could therefore not be obtained in this regard. Individual statements for the following fault types were obtained:

- Winding short circuit

- Earth-fault
- Fault in the tap changer
- Fault on the bushing (had the highest incidence)

2. Transformer protection practice

In the transmission and distribution domain, the differential protection, next to the Buchholz protection, is the most important short-circuit protection function. Only low impedance measuring principles are applied which typically consist of the following components:

- Vector group and ratio compensation
- Tripping characteristic stabilised against error currents
- In-rush current and over-excitation stabilisation

The implementation differs, depending on the manufacturer and the technology. In the electro-mechanical and analog static relay types the CT ratio and vector group adaption was implemented with interposing transformers. These interposing transformers present a large burden to the main CT and resulted in a correspondingly large dimension for the primary CT. The implementation with numerical technology is far more elegant. In this case the CTs are directly connected. The compensation for ratio difference as well as vector group adaption is done mathematically.

The measuring principle of the stabilised differential protection is an electrical balance, whereby one side is the restraint component (stabilising), while the other side makes up the tripping component. With the older technology, this was implemented with direct connection. In numerical relays, this again is done with mathematical equations. With the analog-static relays, the stabilised differential characteristic with multiple slopes was introduced and also applied in the numerical devices. An increased sensitivity in the bottom end of the pick-up characteristic is obtained thereby. At the same time, the steeper slope avoids an over-function of the relay in the event of external short-circuits with high fault level causing CT saturation.

For the in-rush and over-excitation stabilising, the second and fifth harmonic are still the preferred criteria. Different filter designs, measuring-systems and pick-up thresholds are used in the various device generations. With electro-mechanical devices, it was initially attempted to cope with a measuring system on only one or two phases. Based on the experience gathered, later devices were then changed to have a measuring system on each of the three phases. As a result of the magnetising characteristic of modern transformers, the second harmonic component of the in-rush current is no longer so significant. Consequently the pick-up threshold had to be reduced and additionally a time limited cross-blocking had to be introduced. When the pick-up threshold is exceeded in at least one of the phases, all the other phases are temporarily blocked as well. The required duration of the blocking is derived during commissioning by measurements done during energising of the transformer.

Figure 1 summarises the statements above.

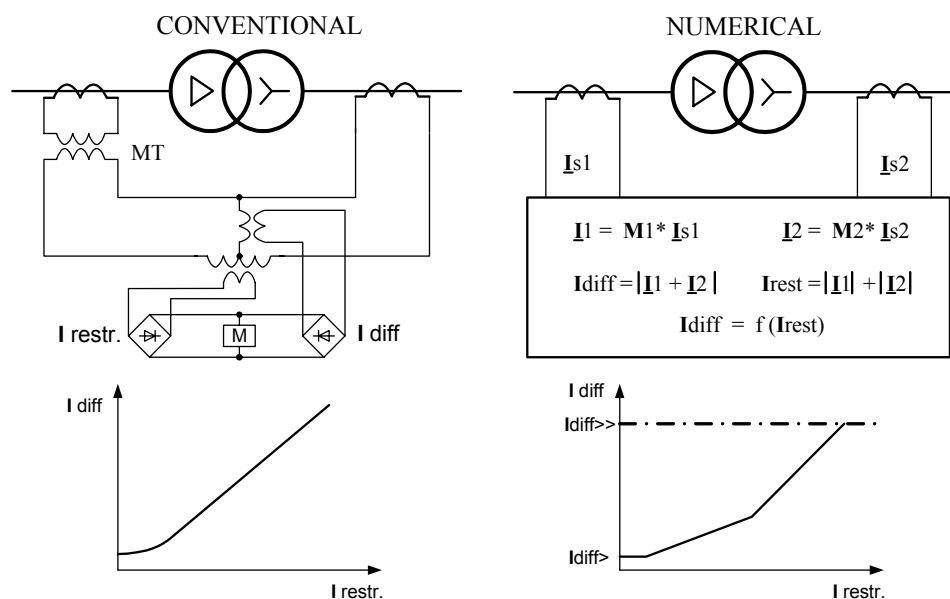


Figure 1: Differential protection principle with conventional and numerical technology

(MT: interposing transformer; M1; M2: matrix for correction of CT mismatching and vector group)

The survey with regard to the occurrence of the individual device technologies (refer Table 1) showed that there is still a significant number of electro-mechanical relays in service. The number of numerical protection devices has already passed that of the analog static devices and will increase in the course of further protection refurbishment projects.

Table 1: Relay distribution

Type of relay	UTILITY A	UTILITY B	UTILITY C	UTILITY D
Electro-mechanical	64%	60%	57%	27%
Analog-static	21%	11%	17%	0%
Digital	15%	29%	26%	73%

The next question related to the distribution of the transformers. Here, the percentage in the distribution system is naturally far greater than the percentage in the transmission system (see Table 2). Regarding the transformer types it must be noted that the number of applied auto-transformers is small and is therefore not further considered.

Table 2: Distribution of transformers

	UTILITY A	UTILITY B	UTILITY C	UTILITY D
Transmission (220; 380 kV)	16%	25 %	100 %	100%
Sub-transmission (110kV)	84%	75 %	no inform.	0%

The main protection is the same with all the utilities. Differential protection and the required Buchholz relays are always applied. Distance protection is almost always used as back-up protection in the transmission system. Only 1 utility indicated the use of over-current protection. Distance protection is always applied in the case of transformer banks. This results in the application shown in Figure 2.

The distance protection is usually set to reach up to 70% of the transformer impedance with a small time delay. From the other side of the transformer a corresponding reach into the transformer is also present so that 100% protection coverage with the back-up protection is obtained. The other distance relay stages are applied as back-up protection for the system and busbar protection.

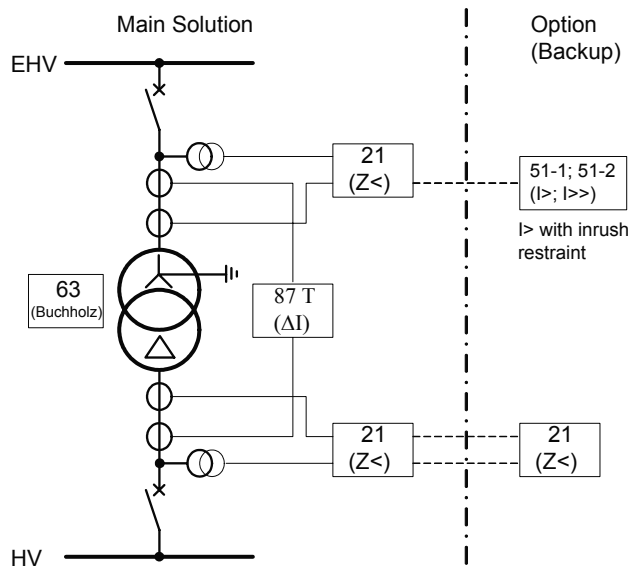


Figure 2: Transformer protection schemes for the transmission system

At the distribution level, the back-up protection concepts are similar to those of the transmission system. On the feeding end, over-current protection is however used as an alternative to the distance protection. Furthermore, one utility applies definite time over-current protection with reverse blocking logic at the low-voltage side. In this manner, a simple busbar protection is obtained. The over-current protection at the feeding end always has two stages. With the high set stage close-in faults with large fault current levels are detected. The normal over-current stage is set more sensitive and is co-ordinated with the time graded protection in the power system. In numerical relays, in-rush detection is considered to be state of the art.

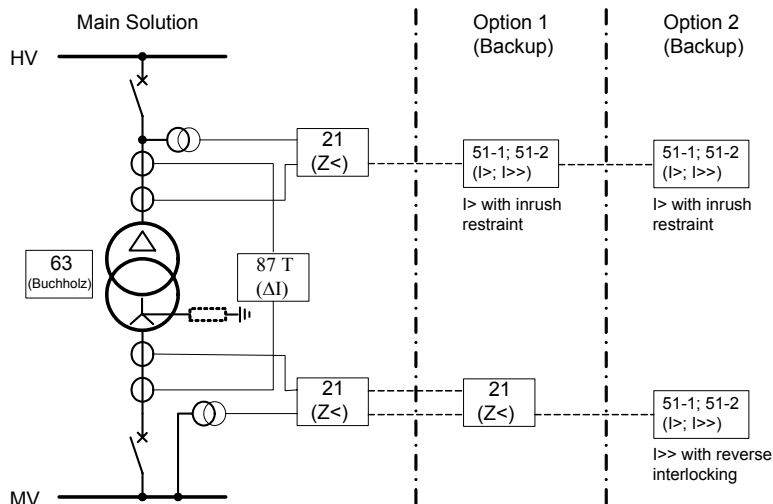


Figure 3: Transformer protection schemes for the distribution system

When applying the settings to the differential protection, the recommendations provided by the manufacturers are used as guidelines, in particular with regard to the settings of the tripping characteristic. The slope of the characteristic 1 (refer to Figure 2 on the right hand side) may be slightly increased on transformers with tap-changers. The pick-up threshold for the differential current is in general between 0,2 - 0,4 $I_{N,Tr}$. The pick-up threshold for the un-stabilised differential protection $I_{diff}>>$ is set above the current magnitude that is derived from the short-circuit impedance of the transformer. With the $I_{diff}>>$ -stage primarily close-in fault currents with very large current levels must be tripped.

As already stated above, the pick-up thresholds for the second harmonic are reduced. Where the typical pick-up threshold setting was still 18% in analog-static relays, nowadays this setting is typically 15% and lower. Blocking of the differential protection via the 5th harmonic is optionally applied. The recommendations provided by the manufacturer are used as a guideline for the setting (around 30%).

The protection tripping is routed to all the circuit breakers of the transformer if sufficient tripping contacts are available. Some utilities prefer to use two tripping contacts per circuit breaker. It is attempted to avoid failure to trip due to contact defect or broken conductors. This requirement was also maintained for the numerical protection. The breaker failure protection function is largely allocated to the busbar protection system.

In connection with the Buchholz tripping, opinion with regard to numerical protection systems is divided. One section applies direct tripping of the circuit breaker by the Buchholz protection with additional coupling of an alarm to the numerical protection. In this manner, event-recording (time stamped by the numerical protection) and simultaneous triggering of the disturbance record is possible. In order to save auxiliary relays (reduction of components) the other users connect the Buchholz trip via the back-up protection. The tripping and event-recording is then done with the back-up protection.

Primary testing during commissioning has proven very successful. The test transformer is energised by the 380V 3-phase supply and feeds onto the HV side of the transformer. The low-voltage side of the transformer is short-circuited. With conventional protection additional measuring instruments are connected to measure the differential and stabilising current while observing the relay response. By crossing-over two currents a trip is provoked so that the trip circuit is checked. With numerical protection, the operational measured values are usually checked and finally a trip is obtained by reversing the star-point polarity in the protection. Connection changes in the current circuits are not necessary.

Testing of the differential protection on unit transformers is done in a similar manner, the only difference being that instead of the test transformer, the generator itself is used as a source for the test currents. This is common practice in Germany.

The in-rush current blocking is tested by multiple transformer energising sequences. If the setting threshold is already very low, the time limited cross-block function is activated.

3. Advantages of the numerical technology from the users point of view

With numerical differential protection devices, as already stated in chapter 2, the fundamental protection principle has remained largely unchanged. It was merely modified and refined. The processing is entirely done via programmed mathematical algorithms. The implementation in the devices from various manu-

facturers only differs marginally. Numerous supplementary protection and other additional functions are new to the numerical devices.

In Table 3 the perceptions of the basic properties of numerical transformer protection systems are shown. The responses were weighted on a scale from 0 to 5. Where 0 to 1 indicate “not important” to “negligibly important” and the scale 4 to 5 indicates “important” to “very important”. The bold line indicates the average value and the grey area the spread of the answers.

The flexible protection settings were indicated in the range between 3 to 5 by the user. The average is approximately 3,5. This is probably due to the application of standard setting values. The higher setting sensitivity of the devices is hardly used, as boundaries are defined by the CTs and it is desirable to avoid an over-function of the device due to too sensitive settings. The numerous additional measured values were hardly mentioned. The measured values from other bay devices are utilised. The response to the remote setting option was divided; the average however is between 3 and 2. The remote access of disturbance records was given a somewhat higher value.

Table 3: Weighting of the characteristics of multi-functional numerical transformer differential protection relays (scaling: 0 not important and 5 very important; bolded lines: average value, grey areas: variations)

	0	1	2	3	4	5
Flexible settings of protection functions						
Higher sensitivity						
No external matching transformers						
Short tripping time for Idiff>> stage (approx. 10 ms)						
Additional protection function in the differential relay (I>, I ² t, U>, I ₂ >, U/f>, ...)						
Additional measuring functions (U, I, P, f, ...)						
Lower current transformer requirements						
Detection of CT saturation (at external faults)						
Integrated fault recording						
Integrated event recorders						
Commissioning support (e.g. Diff., Restr. - values, angles)						
Self - monitoring						
Integrated free programmable Logic						
Flexible masking of binary inputs and outputs						
Remote reading of fault records (via modem)						
Remote setting of protection						
General remote access by protection experts						

The self-monitoring is given the highest rating of importance. It is closely followed by the user-defined logic. This is one of the latest new developments in numerical protection. The flexible routing and allocation of binary in and out-puts was valued in an equivalent manner. This allows for excellent adaptation to the specific situation in each plant and the operating philosophy of the user. Commissioning tools that are also included received an equally high rating. On the one hand, “working” with the devices is simplified and on the other hand this feature results in time and consequently cost savings. Similarly important is the direct CT connection without the need for additional external circuitry. The interposing transformers have always been a source of errors in the past. The event recording and related time stamping as well as the disturbance recording option was also weighted positively. Both features are essential for fault analysis and also serve as a useful commissioning aid. The additional protection functions included in the devices received a positive response. They may be applied in different manners and in particular result in a reduction of the number of different devices that are applied.

The fact that smaller CTs are sufficient, as well as the integrated saturation detectors, was given a slightly lesser weighting. This is due to the fact that numerical protection systems are increasingly replacing electro-mechanical protection systems and the existing CTs can be still be used.

Opinion was divided on the question as to the tripping time, in particular that of the high-set tripping stage Idiff >>. The average response is identical to that given for the higher sensitivity and is considered

to be “not so important”. Naturally it is expected of the protection to securely cover internal close-in faults with CT saturation.

It was further enquired which supplementary functions are really used in practice. Three classifications were provided for the answers – “frequently”, “sometimes” and “not used”. The results of the survey are summarised in Table 4. Furthermore, the results were sub-divided into the voltage levels 220 kV, 380 kV and 110 kV. The 4 utilities were designated with the letters A, B, C, D. The most frequently made selections are shaded grey. Although the supplementary protection functions were given a very high rating in Table 3, they are not very frequently applied in practice. For the over-excitation protection it must be stated that this protection function is typically used on unit transformers in power stations and is only seldomly applied in other areas of the power system. The earth over-current protection is hardly ever used for transformer protection.

The frequency protection however is very often used at the sub-transmission level. Here the frequency is measured at the medium voltage side and causes tripping of the circuit breaker on the medium voltage side when the threshold is exceeded. It is also significant to note that the thermal over-load protection is only seldomly used. Only 2 utilities apply this function at the transmission level and none of the utilities use this at sub-transmission.

With regard to the operational measured values, the answers were unanimous. This functionality of the protection is not used. External devices are used for obtaining the measured values. The disturbance recording as well as the logic functions are used. With regard to the logic, one utility expressly stated the possibility of coupling and processing the Buchholz alarms.

Table 4: Application of the supplementary functions

Functions	220 kV and 380 kV Transmission			110 kV Sub-transmission		
	Fre- quently used	Some- times used	Not used	Fre- quently- used	Some- times used	Not used
Over-voltage protection $U >$	A	C	B, D		B	A, C
Earth-fault protection $U_0 >$	A, B	C, D		B		A, C
Over-excitation protection ($U/f >$)	A		B, C, D			A, B, C
Thermal overload protection		A, B	C, D			A, B, C
Frequency protection		C	A, B, D	A	B, C	
Negative sequence protection		A	B, C, D		A	B, C
Earth-fault protection for earthed transformer neutrals		B	A, C, D		B, C	A
Restricted earth-fault protec- tion		B, C	A, D		B, C	A
Disturbance recording	D	A, B, C			A, B, C	
Operational measured values			A;B;C;D			A, B, C
Integrated logic functions	C	A, B	D		A, B, C	

4. Monitoring of the transformer

To obtain information regarding the current practice, questions regarding the monitoring were also posed. The questions were deliberately not detailed and the classification was done in a similar manner to Table 4 with the three categories “frequently”, “sometimes” and “never used”. In this regard no differentiation in respect to the voltage level was done. The results are given in Table 5. It is noteworthy that one utility did not respond to all questions.

Most questions received the response “sometimes used”. This indicates that monitoring has not yet obtained a high level of acceptance. The first two questions referred to monitoring systems in general. There are some installations on large transformers, but there is no clear statement with regard to the future application. Therefore it is all the more gratifying that the Hotspot calculation contained in the latest protection devices has been widely accepted. Based on the phase currents, and via a coolant temperature measurement, the relative aging is calculated and cyclically summated according to the specification IEC60354. In parallel, the hotspot temperature is determined [1], [2]. Threshold values can be determined at which an alarm is issued or a trip is generated.

The classic monitoring procedures such as oil analyses are mostly carried out. Paper analyses and electrical offline tests are however not very frequently done.

Table 5: Survey results regarding transformer monitoring
(1) pilot applications; 2) not yet foreseeable)

	Frequently used	Some times used	Not used
Present practice with regard to transformer monitoring		A; B; C ¹⁾	D
Future significance of transformer monitoring		A;B;C ²⁾ ;D	
<i>Details:</i>			
Hotspot calculation according to specification (integrated in the protection)		A, D	B, C,
Oil analyses (Gas in oil, water content, colour, ...)	B, D	A	
Paper analyses (e.g. moisture in paper)		A, B, D	
Electrical offline tests (winding resistance, insulation resistance, tan δ .)		A, B	D

5. Conclusions

The German utilities apply the classic low impedance differential protection as the main protection principle next to Buchholz protection for transformers. Distance protection is the predominant back-up protection. Alternatively, over-current protection is also applied. With regard to numerical protection devices, functions other than pure protection functions, such as self monitoring, disturbance recording and the flexible logic including the routing and allocation of binary inputs and outputs were rated highly. It was stated that the commissioning tools are especially meaningful. The numerous additional measuring functions on the other hand are hardly used.

Although the additional protection functions included in the numerical transformer protection equipment found wide acceptance, they are not very frequently applied in practice.

The transformer monitoring is only applied here and there. With regard to future developments of the monitoring, the answers indicate a certain “wait and see” attitude. The classic monitoring techniques are applied instead, whereby the gas analysis is dominant.

Literature

- [1] Differential protection 7UT6. Device manual No. C53000–G1176–C160–1, Siemens AG, 2003
- [2] Standard IEC60354: Loading guide for oil-immersed power transformer. Second edition 9/1991