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Practical analysis of various techniques used in inrush blocking and restraining of differential relays for transformer protection.

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Introduction

Current differential relays have been widely used for transformer protection and they have the ability to discriminate between internal faults and all other conditions. Nevertheless, the relays are prone to malfunctioning under certain circumstance such as over-excitation situations or magnetic inrush.

The inrush current occurs from increasing the excitation voltage which increases the flux in transformer core. Therefore, more current from the system is required to supply the flux. The characteristic of inrush current is determined based on the level of the flux and the period of power system cycle for the transformer core in saturation. There are three common events at which inrush current could occur:

1. Energization of the transformer: this is the most common event, where the current required to supply the flux may reach up to 8 times the full load rating of the transformer [1].

2. Fault clearing: during an external fault, the voltage in the system could be reduced which in turn decrease the excitation voltage of the transformer. After clearing the fault, the system returns to its normal voltage level. This return causes an inrush current as it forces a DC offset on the flux linkages. Normally, this type of inrush current is less than the previous case because of the absence of remnant flux in the core [2].

3. Sympathetic inrush: this type of inrush current takes place when a transformer is energized onto the system with already connected transformers. As depicted in Figure 1, energizing transformer 2 (Tx 2) causes a voltage drop across the source feeding transformer, which may lead to a saturation of this transformer in the negative direction. Thus, the inrush current will be produced in order to supply the flux [3,4].

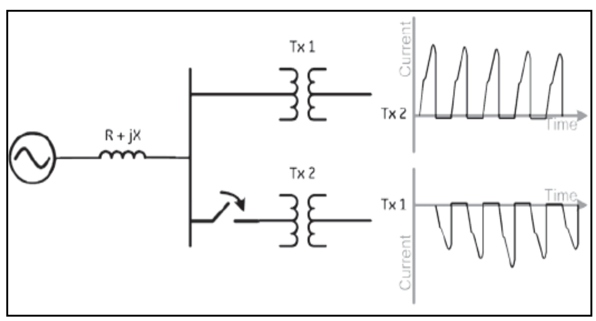

Figure1 Sympathetic inrush currents and waveforms.

Common methods for inrush blocking and restraint for differential relay

In order to prevent malfunctions of differential relays during inrush conditions, several methods are employed based on restraining or blocking signals derived from the current, voltage and flux [5].

The detection of harmonic contents and wave shape identification are the keystone for current-derived method for restraining the differential relay for a transformer [2,3]. The idea of harmonic blocking by using the 2nd harmonic was the initially proposed, followed by implementing the second and the fifth harmonics [7]. Even though this approach of restraining or blocking can ensure the relay security in case of inrush and over-excitation, it could also lead to malfunction for low harmonic conditions in the inrush current. Another technique depends on the length of the time intervals when the differential current is close to zero, and it is called “Gap detection”. The current intervals during inrush are normally greater than one-quarter cycle, and hence the relay is blocked [8]. In case of internal faults, the relay will operate because the current intervals are less than one-quarter cycle. However, the main drawback with such wave shape recognition technique is its failure to identify over-excitation condition.

As for the voltage-derived restraint, a voltage relay is used to block the differential relay when the voltage is high, but it is slower than harmonic restraint methods [9]. In the flux-restrained current method, the relay calculates the rate of change of the flux with respect to the differential current and then uses it as a restraint. This approach is based on the winding current which is unavailable for a delta winding transformer [10].

Recently, wavelet-based, neural network-based and vector-based technologies are suggested by several researchers for inrush blocking and restraining [7,8]. Wavelet-based technologies show good accuracy in their final operation outcome. However, it requires selecting appropriate wavelet for successful analysis and it is not vulnerable to noise and disturbances [7,9] .Despite of a high efficiency of classifying and identifying the problems of events at neural network-based technologies, it needs a large computational burden with large storage capacity for comparing, which seems until now not practical in implementing. Vector-based technologies have been successfully efficient for discriminating between magnetic inrush and internal fault. However, these methods are not validated for (CT) saturation condition during internal fault on the transformer [14].

The aim of this study is to analyse several inrush waveforms for transformer energizing which were collected from various locations. This breakdown of such waveforms performed based on selective current derived technologies for inrush blocking and restraining, because these methods are already applied in the selected utility. In addition, an evaluation table was created in order to select the most appropriate technique.

Methodology

Waveforms characteristics

Forty five inrush current waveforms were gathered from five substations for 220/66kv transformers at the Kingdom of Bahrain. These waveforms were recorded during energization of the transformers, an example of them is shown in Figure 2.

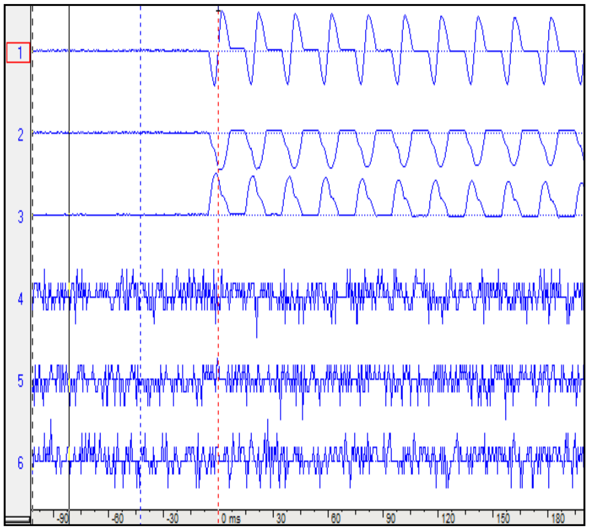

Figure 2 an actual waveforms for inrush current.

As shown in figure 2, the inrush current occurs in the HV side of the transformer, while at the LV side there are only distorted waveforms. In addition, the harmonic table reveals that the second harmonic recorded the highest percentage among the whole harmonies, which is one of main characteristic of inrush current phenomena during energization as depicted in the following table [15].

Table 1Harmonics values.

Channel Name: (1) IAS A Samp#: 324

Order	DFT Peak	DFT RMS	DFT Angle	% of Fund.	% of TrueRMS
1	173.985	123.026	273.131°	---	65.537%
2	180.069	127.328	263.924°	103.497%	67.829%
3	76.945	54.408	268.268°	44.225%	28.984%
4	19.420	13.732	319.102°	11.162%	7.315%
5	5.583	3.948	299.114°	3.209%	2.103%
6	8.028	5.677	214.527°	4.614%	3.024%
7	1.925	1.361	80.644°	1.107%	0.725%
8	5.759	4.072	57.879°	3.310%	2.169%
9	4.915	3.476	117.673°	2.825%	1.851%
10	3.969	2.806	131.597°	2.281%	1.495%
11	1.519	1.074	62.069°	0.873%	0.572%
12	0.849	0.601	20.323°	0.488%	0.320%
13	0.818	0.578	147.839°	0.470%	0.308%
14	0.710	0.502	281.288°	0.408%	0.267%
15	1.798	1.272	300.684°	1.034%	0.677%
16	0.910	0.644	297.544°	0.523%	0.343%
17	0.393	0.278	238.457°	0.226%	0.148%
18	0.594	0.420	255.688°	0.341%	0.224%
19	0.819	0.579	278.935°	0.471%	0.308%

True RMS: 187.719 Calculated RMS: 185.977 THD: 113.367%

According to several theoretical studies [15], the inrush current may reach up to eight to ten times of the rated full load current. In this study the waveforms are more than the rated current, but do not reach more than two times of the rated current. The waveforms were collected during energizing transformers with these characteristics: 220kV/66kV/21kV, 150 MVA, YNynd5 and 66/11KV, 20MVA, Dyn11.

The selected methods for the study

This study examined four methods for blocking or restarting the inrush current and they are as follows:

- **Gap detection:**

In this approach, the inrush current is characterised by the presence of a period during each cycle when relatively little current flows. By measuring the duration of the low current periods in any cycle (quarter of a cycle minimum), the relay is able to determine whether the differential current is due to magnetising inrush or due to a genuine fault [16].

- **2^nd^ harmonic Restraint:**

The relay typically senses the 2nd harmonic content of the current flowing into each phase of the transformer and adds to the slope characteristics which in turn raise the operating current [17].

- **2nd harmonic Individual blocking:**

The relay typically senses the 2nd harmonic content of the current flowing into each phase of the transformer and "blocks" restrained differential element of the individual phase in which harmonic contents are measured more than set value [17].

- **2nd harmonic Cross blocking:**

In this method, The relay typically senses the 2nd harmonic content of the current flowing into each phase of the transformer and "blocks" restrained differential element of the all phase if harmonic contents are measured more than set value in any of the phases [18].

The examination of above methods will be performed based on the procedures described in the following flowchart.

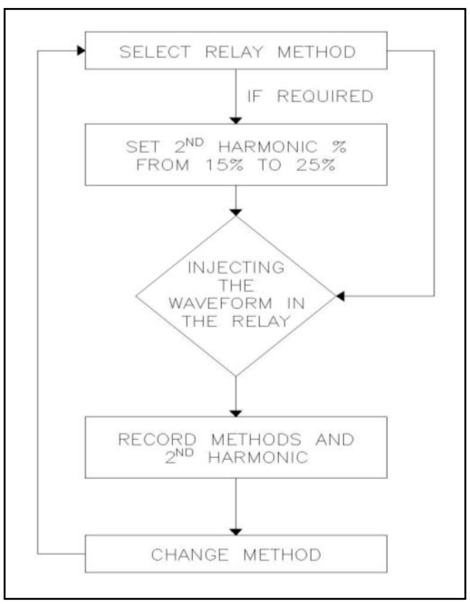

Figure 3 flowchart of the test procedure.

Equipment used for the experiment:

The waveforms were collected from SEL 487 E and KBCH 120 relays installed in different geographical locations of Bahrain. Omicron 256 plus was used to re-play all the scenarios with the help of their Trans play Modules.

The KBCH 130 relay was selected for analysing the gap detection method, while SEL 587 for analysis of 2nd harmonic blocking in individual and cross blocking modes. Both relays were applied with similar setting and almost identical slope characteristics. Figure 4 and Figure 5 show the operation characteristic diagram for both relays[16,17].

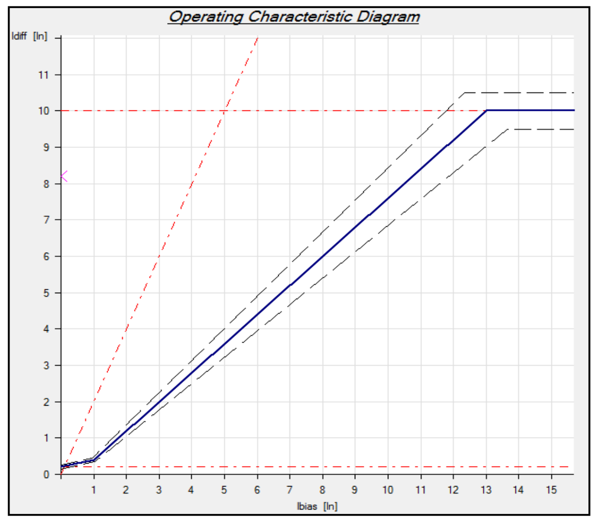

Figure 4 KBCH Slope Characteristics.

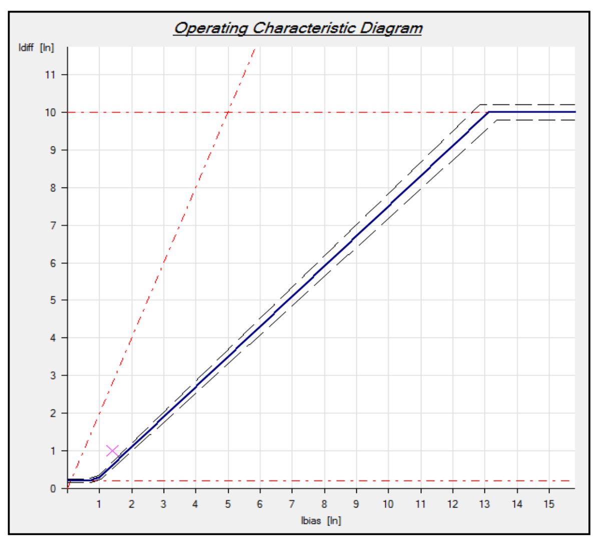

Figure 5 SEL 587 Characteristics.

Result and discussion

More than 45 inrush scenario were recreated and injected to relays under study and the results are in the following table.

Table 2 the result of the experiment.

2nd harmonic Setting (%)	Methods	Number of waveforms tripped
15	Restraint	**0**
	Individual Blocking	**0**
	Cross blocking	**0**
17.5	Restraint	**0**
	Individual Blocking	**0**
	Cross blocking	**0**
20	Restraint	**0**
	Individual Blocking	**0**
	Cross blocking	**0**
22.5	Restraint	**0**
	Individual Blocking	**1**
	Cross blocking	**0**
25	Restraint	**0**
	Individual Blocking	**3**
	Cross blocking	**0**
Not applicable	Gap detection	**4**

As shown in table 2, the gap detection method failed to detect inrush condition in 4 scenarios. However the relay would have detected these scenarios if the algorithm was modified for cross blocking or non-phase selective blocking. The results, also, show that if the 2nd harmonic setting was less than 20 % in any scenarios and the relays were using 2nd harmonic blocking, then the relay would be stable in both individual blocking and cross blocking modes.

Moreover, the relay was stable for the setting of 25% of 2nd harmonic with cross blocking and restraint modes. Whereas the relay operated three times in individual blocking method. This explain why the setting of the 2nd harmonic in differential relay is normally between 15% and 20% [19].

As for 2nd harmonic cross blocking and restraint methods, these modes proved well blocking tripping during inrush current. Nevertheless, its slower operation during internal fault is considered as a main disadvantage, which occurs because of the harmonic contents during faults. This drawback can be overcome by applying the gap detection method. Yet, this will make it prone to malfunction during the energization. When compared, the more accurate protection with the 2nd harmonic cross blocking and restraint modes are considered more important than the time gained by applying the gap detection method, particularly that the time difference is not very considerable.

The 2nd harmonic content has a considerable contribution during energization and its presence lasts more than 18 cycles, hence adequate setting shall be enabled for unrestrained differential element to clear any fault during energization. In addition, the magnitude of inrush current was measured in all waveforms in this study, and none of their values were more than two times of the rated current. This contradicts the simulation results obtained from various theoretical studies, which results from several factors, such as point of energization, presence of remnant flux and another main factor which is the transformer design and characteristics [20].

Conclusion

Based on the findings, the 2nd harmonics method with cross blocking and restraint modes proved to be the most efficient approach of blocking tripping during inrush current. Although they have the disadvantage of slower operation during internal faults.

Further research needs to examine accurate calculation of actual fault levels in order to optimize the setting of unrestrained element in differential relays during switched on to fault condition. In addition, this study sets ground for future work on performing statistical analysis of the magnitude of inrush current in different utilities and under different conditions, in order to evaluate the impact of lower setting for unrestrained elements.

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