Restricted Earth Fault Protection (64R) in Resistive Grounded Transformer

(Comprehensive Analysis)

Abstract

Transformer is considered vital equipment in transmission and distribution network. Power Transformer is typically considered the costliest equipment for any substation/switchyard project and is expected to serve a lifecycle of 35 years[*]. Considering the significant cost associated with power transformers and the relatively long outage time in case of failure of the same equipment, it is emphasizing the importance of implementing effective protection strategies to prevent or mitigate such events.

Below listed are the commonly used protections for power transformers[†]:

- Backup over current (50/51) and earth fault (50N/51N) protection.
- Differential Protection (87T).
- Restricted Earth fault protection (64R).
- Thermal overload protection (49).
- External Trip function (i.e. Buchholz relay, Pressure Relief Valve etc.).

The protection of power systems and the grounding of electrical equipment are interdependent. It is important to note that the type of grounding that is chosen for a power system can have a substantial impact on the selection of the protection scheme.

Power Transformer HV (high voltage) and LV (low voltage) winding can have multiple configurations like star or delta on either side. With both the windings system grounding can also have multiple cases such as solid, resistive, reactive or grounding transformer. Each of the selected configurations has a certain impact on the protection system and the same shall be ensured in the Design and Engineering phase of the project.

In the case of a power transformer having Delta-Star configuration with resistance or reactance grounding, whenever in zone line to ground fault occurs at the low voltage (LV) side, certain difficulties are encountered with regard to the implementation of differential protection. These challenges include the following:

- The magnitude of reflected fault current at the HV side varies with the location of the line to ground fault at the LV side.
- Up to some extent the reflected fault current at the HV side in case of ground fault[‡] at LV side winding, is less compared to the relay setting.
- The sensitivity of differential protection is inadequate to ensure complete winding protection.

This paper aims to examine the aforementioned technical challenges and suggest a mitigation method.

[*] According to CERC (Central Electricity Regulatory Commission) norms.

[†] We have considered 6MVA, 11/6.6kV as Power Transformer for case study purpose.

[‡] ground fault has the meaning Line to Ground fault (in zone) in this paper.

Problem Statement

In a power system, the transformer is grounded through a resistor, reactor or using grounding transformer and the single line to ground fault current at the LV side is limited by means of the type of grounding method utilized. By limiting the ground fault, the transformer differential protection is not enough sensitive to protect the complete winding as the reflected fault current varies with fault location and up to some extent reflected current at HV remains below the settled value.

Background

Consider a Delta-Star transformer with a neutral grounding resistor.

I_{1Phase} = High voltage (HV) side current per phase.

I_{2Phase} = Low voltage (LV) side current per phase.

N_1 = Number of turns of HV winding.

N_2 = Number of turns of LV winding.

T = Turn Ratio.

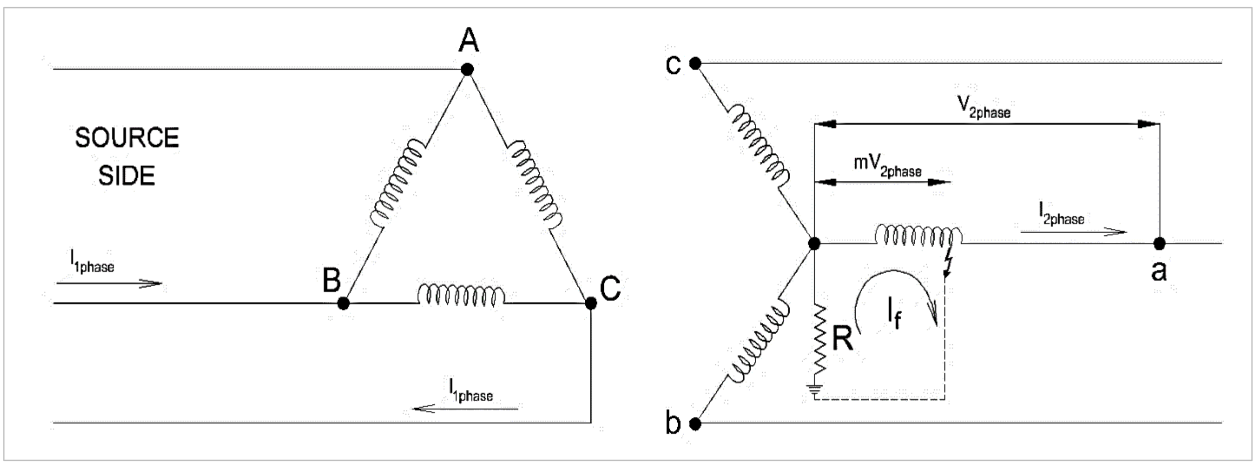

Figure 1: Power Transformer Winding Configuration

Transformer turn ratio:

$$\frac{I_{1Phase}}{I_{2Phase}} = \frac{N_2}{N_1} \qquad (1)$$

$$I_{1Phase} = \frac{N_2}{N_1} \times I_{2Phase} \qquad (2)$$

$$I_{1Phase} = T \times I_{2Phase} \qquad (3)$$

For an internal L-G fault at fraction 'm' from the neutral:

$$\text{Fault current } I_f = \frac{m \times V_{2phase}}{R} \quad (4)$$

Where,

m = Distance from neutral to the fault location.

R = Neutral Grounding Resistor.

Due to the L-G fault at LV winding, the effective turn ratio (T_e) of the transformer is computed as:

$$T_e = \left(\frac{N_2}{N_1}\right) \times m \quad (5)$$

$$I_{2Phase} = I_f = \frac{m \times V_{2phase}}{R} \quad (6)$$

Reflected fault current at HV (delta) side:

$$I_{1Phase} = T_e \times I_{2Phase}$$

$$= m \times T \times I_{2Phase}$$

$$= m \times T \times \frac{m \times V_{2phase}}{R}$$

$$I_{1Phase} = m^2 \times T \times \frac{V_{2phase}}{R} \quad (7)$$

From the equation (6) and (7) we can state that:

$I_{2Phase} \propto m$
$I_{1Phase} \propto m^2$

The above equations describe the relationship between HV and LV side currents in a transformer during a line-to-ground fault in LV winding.

The equations demonstrate that the LV side fault current is directly proportional to the distance from the neutral, while the HV side fault current is proportional to the square of the distance from the neutral. This relationship is further illustrated in the below graph.

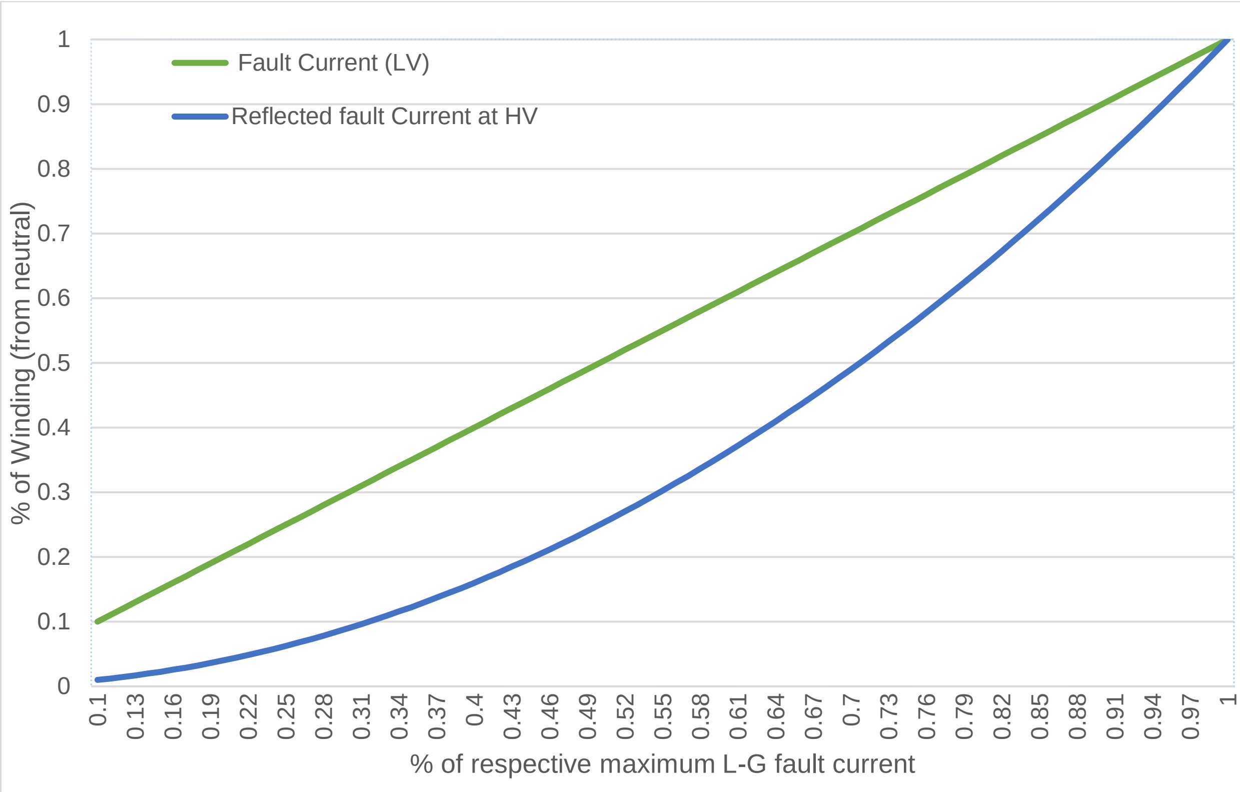

Figure 2: % effective winding vs LV and reflected HV fault current

Case Study

Transformer Rating	=	6MVA
HV Winding	=	11kV
LV Winding	=	6.6kV
Vector Group	=	Dyn11 or Dyn1
NGR	=	15.877Ω
HV CT ratio	=	350/1A
LV CT ratio	=	550/1A

Voltage per phase at LV side:

$$V_{2Phase} = \frac{V_{2\ line\text{-}line}}{\sqrt{3}}$$

$$= \frac{11000}{\sqrt{3}}$$

$$= \quad 6351V$$

Rated current per phase at LV side:

$$I_{2phase} = \frac{V_{2phase}}{R}$$

$$= \frac{6351}{15.877}$$

$$= 400A$$

Turn Ratio:

$$T = \frac{V_{2phase}}{V_{1phase}}$$

$$= \frac{6351}{66000}$$

$$= 0.1667$$

Using equation number (7), reflected fault current per phase at HV side with 100% winding (m=1):

$$I_{1phase}^{max.} = m^2 \text{ x } T \text{ x } \frac{V_{2phase}}{R}$$

$$= 1^2 \text{ x } 0.1667 \text{ x } \frac{6351}{15.877}$$

$$= 66.67A$$

The reflected fault current on HV side is a function of fault location 'm' and can be calculated for various fault location in transformer winding.

Sr.No.	m (%)	I_{2phase} (A)[§]	I_{2phase} / I_f	I_{1phase} (A)[**]	I_{1phase} / I_{1max}
1	0.05	26.24	0.05	0.45	0.003
2	0.10	52.48	0.10	1.81	0.010
3	0.20	104.97	0.20	7.21	0.040
4	0.30	157.46	0.30	16.36	0.090
5	0.40	209.95	0.40	29.09	0.160

Unprotected Region

§ Refer equation (6).
** Refer equation (7).

Sr.No.	m (%)	I_{2phase} (A)§	I_{2phase} / I_f	I_{1phase} (A)**	I_{1phase} / I_{1max}
6	0.50	262.43	0.50	45.45	0.250
7	0.60	314.92	0.60	65.45	0.360
8	0.61	320.17	0.61	67.65	0.372
9	**0.62**	**325.42**	**0.62**	**69.89**	**0.384**
10	0.63	330.67	0.63	72.16	0.397
11	0.70	367.41	0.70	89.09	0.490
12	0.80	419.90	0.80	116.37	0.640
13	0.90	472.39	0.90	147.28	0.81
14	1.00	524.87	1.00	181.82	1.00

Unprotected Region

Protected region

If we consider pick up for differential first stage is 0.20pu (20%):

Hence, relay pick up current,

$$I^{st} = \text{Pick up setting} \times \text{CT ratio}$$

$$= 350 \times 0.2$$

$$= 70A$$

The differential relay will only issue a trip command when it senses more than 70A current with a pre-defined time delay (typically instantaneous). In the event of a single line to a ground fault occurring in the LV winding up to 62% from the neutral of the transformer, the reflected fault current in the HV side is found to be less than 70A, which cannot be sensed by differential relay with given pick up settings. Therefore, up to 62% of winding from neutral remains unprotected, while the remaining 38% is protected by differential protection against line-to-ground fault.

Mitigation

One of the possible solutions is to implement a Restricted Earth Fault-REF (64R) protection at the LV (star) side of the power transformer. REF protection is an effective solution for impedance and solidly grounded transformers, as it can easily detect and respond to line-to-ground faults, thereby providing essential protection for the unprotected winding.

References

- Network protection and Automation Guide by Alstom.
- Monograph of IEEEMA articles of Dr. K Rajamani, Rev 05, 2022.

White Paper	*Restricted Earth Fault Protection (64R) in Resistive Grounded Transformer (Comprehensive Analysis)*
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This white paper will help to understand constrains with system grounding selected and mitigation plan to select proper protection for Power Transformer. This document is prepared only for reference to understand protection system concept. Intent of this document is not to show any project specific calculation/scheme, which can be utilized directly in project. We welcome readers to share their observations, suggestions, or queries on our email id specified.