Distribution transformer protection

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Table of Contents

1 Introduction

I have come across protection designs that have set the HV over current pickup to 100% of the transformer's rating, and other designs setting the pickup to 160%. This document discusses why all these design options are acceptable, under some circumstances, and this Engineers view on what protection is required for a HV transformer and the justification for my view.

2 Security and reliability

HV and LV design are two different worlds. Protection security and reliability are weighed very differently.

A reliable system will always trip if there is a fault. If the relay system can't do its job, you simply trip the system. Protection is more important than supply.

A secure system will only trip if there is a real fault. You cannot reduce supply security, because you have a failed protection system.

When you are designing a LV protection system, in many cases you have the option of designing a system that is fail safe, if the digital protection relay fails you trip the system. The protection is more reliable, but the supply is less secure. Even for LV systems this is not always the case, for example AS3000:2018 clause 2.5.1.4 allows the omissions of over current devices for safety reasons. An example given is a lifting magnet. Also, if protecting building safety systems, it can be argued fail safe design is not an option, this is addressed in AS/ANZ3000 by insisting you connect safety circuits before the customer's main breaker.

On the HV side, security matters. Tripping for a minor issue like a protection relay failure is not an option. This leads to HV engineers thinking about primary, secondary and tertiary protection, and regular testing of HV protection schemes to prove the protection system still works.

3 Primary, secondary, and tertiary protection of a transformer

As you often need security of LV supply after the transformer, transformer protection needs to take a leaf out of HV protection philosophy, one should think about primary, secondary and tertiary protection. Just as one achieves high reliability in the rest of the HV network, one should not be looking at fail safe primary protection, but a system that will only trip if the fault condition arises and then use testing to prove the system works as one does with HV protection.

3.1 Primary protection

It is the author's view that primary protection of a transformer should always be provided by transformer temperature sensors, for example, PT100. Unlike the HV relay providing thermal modelling (ANSI 49), PT100'S protection has the following advantages:

1) No matter the overload type (single phase or three phase) the temperature rise of the transformer is reflected if the transformer manufacturer strategically place the temperature sensors.
2) Doesn't require you to know the thermal constants of the transformers.
3) Thermal protection relays such as the BWDK-32/42 series provide protection that is independent of the HV relay. Thus, you have independent relays for primary and secondary protection.

The BWDK-32/42 can be set up to trip the LV or HV breaker, both options will remove the load. As transformers are seldom run in an environment that is equal to the maximum allowed ambient temperature the LV protection will often trip first on current overload, which is what you want it the BWDK-32.42 is tripping the HV breaker.

3.2 Secondary thermal protection

It is best if the LV breaker is set up to provide secondary thermal protection. As this breaker is often set up as a shunt trip it is also **not** fail safe. It is generally set up for the maximum rating of the transformer, at the design maximum ambient temperature. This is generally forced upon the engineer as the utility uses the LV breaker to limit supply.

If a transformer is part of a HV installation and it is accepted the temperature sensors are the primary protection, then the LV breaker can be set with a margin to make sure the temperature sensors trip first. This gives greater security of supply and better utilization of the transformer if the ambient temperature is less than the design maximum ambient.

This cannot be done if the transformer has multiple breakers connected to the secondary and the sum of the breaker settings is greater than the transformer rating. In this case the HV thermal protection should be set closer to 100%, and if one of the loads is close to the transformers rating it is impossible to set the LV protection to trip first, if you treat the HV protection as the primary protection.

If you treat the HV breakers thermal protection as the secondary thermal protection (and set a reasonable margin), with the transformers temperature sensors used as the primary protection, tripping the LV breakers, then it is possible to still have the LV trip first.

3.3 Tertiary thermal protection

If there is one LV breaker then the HV over current protection should be set up so it will discriminate with the LV protection.

To get discrimination between the LV and HV overcurrent protection, the HV overcurrent protection pickup must be set in the order of 140% of the transformers rating. The margin required depends on the protection curves and these should be plotted using the engineers favorite application for such purposes. Utility engineers have been seen to use 160%. This has a solid historic base as the fuses used to protect transformers were selected with a rating in that order.

If there are multiple LV breakers and the sum of the thermal overloads is greater than the transformer rating then the HV breaker becomes the secondary protection, this has been discussed above.

4 Over Current and Short Circuit protection

AS3000:2018 well recognizes there is a difference between overcurrent and short circuit protection with clause 2.5.3 dealing with overcurrent and 2.5.4 short circuit. Even though removing short circuit protection makes no sense, as a shorted supply is both dangerous and useless, AS3000:2018 clause 2.5.4.5 allows it under some circumstances. It is difficult to see where removal of short circuit protection is acceptable. What is acceptable is relying on secondary short circuit protection if the primary protection relay fails.

Overcurrnet protection may be at the supply end of the cable or at the load end (see AS3000:2018 clause 2.5.3.3).

8 Problems with transformer over current protection on the primary side.

There are issues with placing the over current on the transformers primary side.

1) You do not want a LV fault to trip out the HV protection as it is often difficult to get the HV breaker reset.
2) The LV phase to neutral current will become a phase to phase current (see section 5.1 and

5.2.).

If the system is designed with multiple connections to the transformers LV side and the sum of the LV breaker overcurrent settings is greater than the transformers full load current then LV overcurrent protection cannot be provided and overload protection on the HV side needs to be considered.

5 LV short circuit protection using the HV protection.

For the connection between the transformer terminals and the main switchboard under some circumstances, AS3000:2018 allows the use of double insulation as an option to short circuit protection.

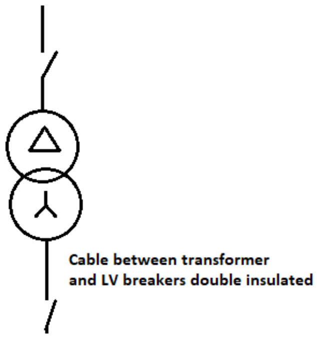

Figure 1 Cable between transformer and LV breaker

The cable between the transformer and the LV breaker should be protected by the HV protection. To do this the HV protection must see the LV fault. To see the fault current the fault must be reflected to the HV size at a magnitude that can be seen by the HV protection.

A secondary single phase fault ends up being seen on the primary side as a phase to phase fault, with a magnitude of $(TX_{ratio}*I_{fault})/sqrt(3)$. The next two sections aim to provide insight as to why.

5.1 Sequence current explanation.

When there is a phase to neutral fault the out-fault current flows in one phase and the in fault current flows in the Neutral.

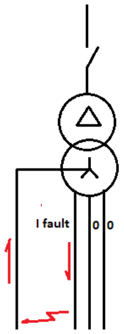

Figure 2 Single-phase fault

If the fault is in the red phase, the symmetrical component equations are:

$I_R = I_{R0} + I_{R1} + I_{R2} = I_{fault}$
$I_Y = I_{Y0} + I_{Y1} + I_{Y2} = 0$
$I_B = I_{B0} + I_{B1} + I_{B2} = 0$

The currents can be drawn as phasers, these can be added up as vectors, that is phasers have a magnitude and direction. The solution has three sequence phasors equal in magnitude. On the primary side the symmetrical phasers offered by the fault add up as shown below.

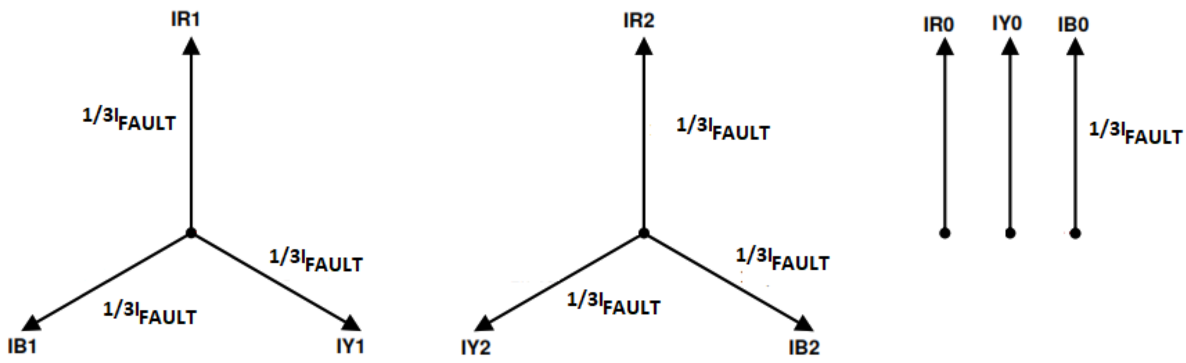

Figure 3 Secondary side symmetrical components.

Moving the phasers around so they are head to tail.

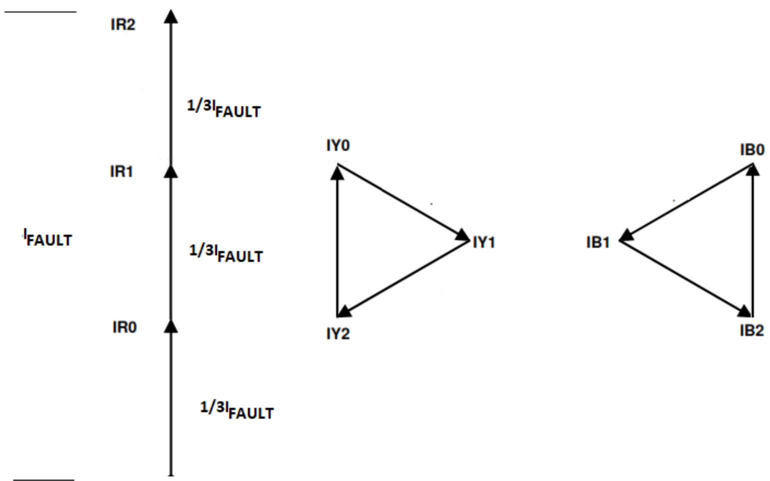

Figure 4 The symmetrical phasers add up as required.

If the magnitude of the symmetrical component is 1/3 of the fault current the symmetrical components add up as required, that is the fault current on the red phase and zero currents in the other two phases.

To see what happens on the primary side we need to consider what happens to symmetrical components when they pass through a star delta transformer.

The zero component rotates in the delta, they heat up the delta winding but are never seen on the primary side. The positive sequence currents will be shifted 30 degrees anticlockwise as they pass through the transformer [1], the negative sequence components shift 30 degrees clockwise.

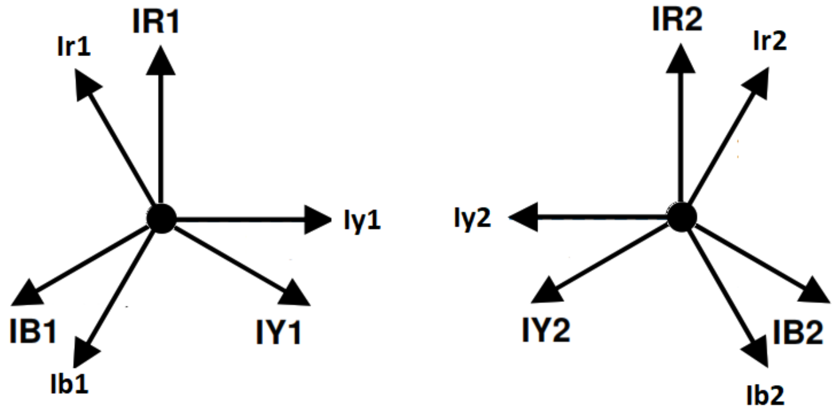

Figure 5 Positive sequence anticlockwise, negative sequence clockwise. Zero sequence gone.

Adding up the phasors you end up with the following.

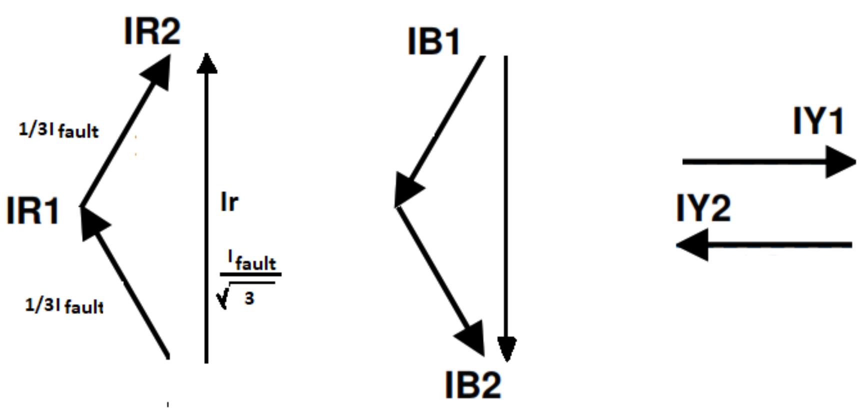

Figure 6 Summation of the primary side sequence currents.

5.2 Power argument

Symmetrical components can be used to show how the single phase fault is reflected to the HV side. Once we have established the line to neutral fault on the secondary ends up being seen as a line to line fault on the primary we can justify the magnitude using power-in must equal power-out argument (ignoring losses):

Vout = VP-N

Vin = VP-N* *ratio*sqrt(3)* (it is line to line)

Vin*Iin = Vout*Iout (power in equals power out)

Let Iin =Iout/*ratio*sqrt(3)*

VP-N**ratio*sqrt(3)* * Iout/ *ratio*sqrt(3)* = Vout*Iout

Cancel the *ratio*sqrt(3)* term and you have equality.

5.3 Single phase fault level

The zero-sequence impedance matters as the zero-sequence current must equal to the first and second sequence currents if two phases are to be zero and one nonzero. The zero-sequence current depends on the transformers zero sequence impedance.

Unfortunately, the zero sequence impedance is not found on a transformer name plate. The zero sequence impedance depends on the number of legs, the winding arrangement and on which circuit you are consider (high or low voltage). A typical three phase distribution transformer has three legs, has a star delta arrangement and our interest is the zero sequence impedance seen on the star side. The issues are discussed in IEC standard 60076-8.

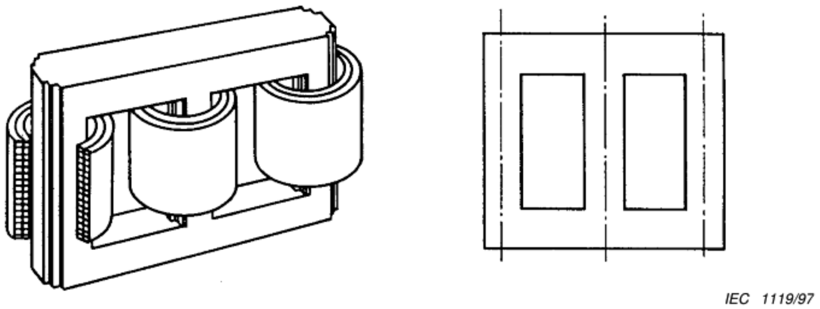

Figure 7 Three limbed magnetic circuit ([2] figure 1)

For a Dyn transformer 60076-8 gives the zero sequence impedance as a_1Z_{12}, with 0.8 to 1 given as the range of a_1 ([2] table 1). Setting a_1= 1 makes the three-sequence impedance the same and gives us the lowest fault current, which is of interest when trying to determine if protection will pick up.

5.4 Line to Neutral impedance.

The transformers per unit impedance can be looked upon as the percentage of voltage that must be applied to get the rated line current.

$Z\%V_{LN}/I_L = Z_{LN}$

$I = S_T/(\text{sqrt}(3)*V_{LL})$

Take S_T=1MVA , V_{LL}=415volt, V_{LN} = 240), $Z_{\%}$=5% impedance

I_L= 1,000,000/(sqrt(3)*415) = 1391 amps

Z_S= 0.05*240/1391 = 0.0086 ohms.

For the delta case the 5% is applied to 415, so

Z_D = 0.05*415/1391 =0.015

And

Z_D/Z_S = sqrt(3)

The single-phase cable loop impedance is also higher than the three-phase loop impedance. Three phase current goes on one phase and comes back on two. The single-phase current goes out on one and comes back on the neutral, for a system with a neutral cable size equal to the phase cable size. The three phase impedance can be multiplied by 2/sqrt(3) to give the single phase impedance. [4 table 40 notes]. That is:

$Z1_{cable} = Z3_{cable}$* 2/sqrt(3)

Where:

Z1 is the single-phase loop impedance and

Z3 is the three-phase loop impedance

When compared to three phase faults, the lower internal transformer impedance and the high cable impedance means the single phase fault current falls off faster, and this is the one to watch when working out the maximum distance a LV breaker can be from the transformer.

5.5 HV pickup above LV pickup.

We can't go too low with the HV pickup as we want the LV breaker to trip before the HV breaker for a fault after the LV breaker. Fortunately, LV instantaneous pickups are being set lower as people start to understand the ark-flash risk. The days when I_{sd} being set to 8 have gone.

5.6 Fault Pickup

Remembering that most faults are not bolted, relay pickup should be set to half the calculated fault current for bolted faults [3 page 3].

5.7 What reduction in cable length to see single phase fault

If we are looking at overload we only have to deal with the line to neutral overload current on the secondary changing into a line-to-line current overload on the primary, and the transformer ratio.

This is generally not an issue as attempts are made to limit out of balance loads because they produce circulating current in the transformer delta.

Our interest is line to neutral faults. Three issues have been discussed in previous sections, if we assume the 0,1 and 2 sequence impedance are the same which gives a conservative results as we are looking for minimum fault currents.

1) The line to neutral fault current is seen as a line-to-line fault current, reduce by a factor of sqrt(3). See section 5.1 and section 5.2.
2) The cable loop impedance, increase impedance by a factor of sqrt(3)/2. See section 5.4.
3) The ratio of the transformers internal single phase impedance to internal three phase impedance, transformer impedance difference of sqrt(3). See section 5.4

If the neutral cable impedance per length is the same size as the line cable, the reduction in length needed for the primary pickup to see the same fault current is.

Sqrt(3)* sqrt(3)/2 * SQRT(3) = (sqrt(3)*3)/2

Thus, as an example, if the primary protection can see a three fault at 100 meters, the single phase fault can only be seen for:

100*2/(3*sqrt(3)) = 38 meters.

Reference number	**Reference**
[1]	The Use of Simple drawings to determine fault currents. Lee Wai Meng https://www.onengineers.com/wp-content/uploads/2019/06/chapter-14.pdf
[2]	IEC 60076-9 First edition 1997-10
[3]	Symetrical Components for power system engineering. J.Lewis Blachburn, ISBN10 000-8747-8767-6, ISBN13 978-0-8247-8767-7
[4]	AS/NZS.1.1:2009