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Smart Micro-controller Based Integrated Monitoring and Protection System for Three-Phase Power Transformer

Kristján Guðmundur Birgisson

Thesis of 60 ECTS credits

Master of Science (M.Sc.) in Electrical Engineering

May 2018

Smart Micro-controller Based Integrated Monitoring and Protection System for Three-Phase Power Transformer

by

Kristján Guðmundur Birgisson

Thesis of 60 ECTS creditssubmitted to the School of Science and Engineering
at Reykjavík University in partial fulfillment
of the requirements for the degree of
Master of Science (M.Sc.) in Electrical Engineering

May 2018

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Tough E. Questions, Examiner
Associate Professor, Massachusetts Institute of Technology, USA

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Abstract

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Örtölvu Byggt Öryggis og Eftirlitskerfi fyrir Þriggja Fasa Spennubreytir

Kristján Guðmundur Birgisson

maí 2018

Útdráttur

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Important!!! Read the Instructions!!!

If you have not already done so, LaTeX the `instructions.tex` to learn how to setup your document and use some of the features. You can see a (somewhat recent) rendered PDF of the instructions at `http://afs.rnd.ru.is/project/thesis-template/trunk/ruthesis/latex/instructions.pdf`. There is also more information on working with LaTeX at `http://afs.rnd.ru.is/project/htgaru/trunk/how-to-get-around-projects.pdf`. This includes common problems and fixes.

This page will disappear in anything other than draft mode.

I dedicate this to my spouse/child/pet/power animal.

Acknowledgements

So long, and thanks for all the fish.

Douglas Adams

Acknowledgements are optional; comment this chapter out if they are absent Note that it is important to acknowledge any funding that helped in the workThis work was funded by 2018 RANNIS grant "Survey of man-eating Minke whales" 1415550. Additional equipment was generously donated by the Icelandic Tourism Board.

Preface

This dissertation is original work by the author, Firstname Lastname. Portions of the introductory text are used with permission from Student et al.

The preface is an optional element explaining a little who performed what work. See `https://www.grad.ubc.ca/sites/default/files/materials/thesis_sample_prefaces.pdf` for suggestions.

List of publications as part of the preface is optional unless elements of the work have already been published. It should be a comprehensive list of all publications in which material in the thesis has appeared, preferably with references to sections as appropriate. This is also a good place to state contribution of student and contribution of others to the work represented in the thesis.

Contents

List of Figures

List of Tables

List of Corrections

List of Abbreviations

MSc	Masters of Science
PhD	Doctor of Philosophy
kV	kilo Volt
DC	Direct Current
AC	Alternative Current
HV	High Voltage
LV	Low Voltage
HC	High Current
LC	Low Current
CT	Current Transformer
GT	Generator Transformer
ST	Station Transformer
DT	Distribution Transformer
UAT	Unit Auxiliary Transformer
AT	Auxiliary Transformer
IT	Instrument Transformer
RT	Rectifier Transformer
NGT	Neutral Ground Transformer
ANSI	American National Standards Institute
M-C	Micro Controller

List of Symbols

Symbol	Description	Value/Units
V	Voltage	Volt
A	current	I
c	Speed of Light	$2.99 \times 10^{8}\,\mathrm{m\,s^{-1}}$

Chapter 1

Introduction

Electricity is one of the foundation of everyday life. Electricity is a widely used commodity in advanced countries and is being set up in third world countries. A quote from the Russian politician Boris Yeltsin is "We don't appreciate what we have until it's gone"[1]. The quote has meaning for multiple meanings and one certainly holds true for electricity. When it is operational everybody is happy but when it is non-operational, nobody is happy. There are workplaces that are very dependent on electricity for example hospitals, factories, emergency services. The loss of electricity can lead to money loss for the consumer if the power is not consistent or working for a long period time. Hallo Test

1.1 Power system

The set up for the basic power station is as follows

1. Electricity Generation
2. Step Up Transformer
3. Transmission Line
4. Step Down Transformer
5. Consumer

[1] `https://www.brainyquote.com/quotes/quotes/b/borisyelts371415.html`

The basic set up for a power systems can be seen in figure 1.1[2].

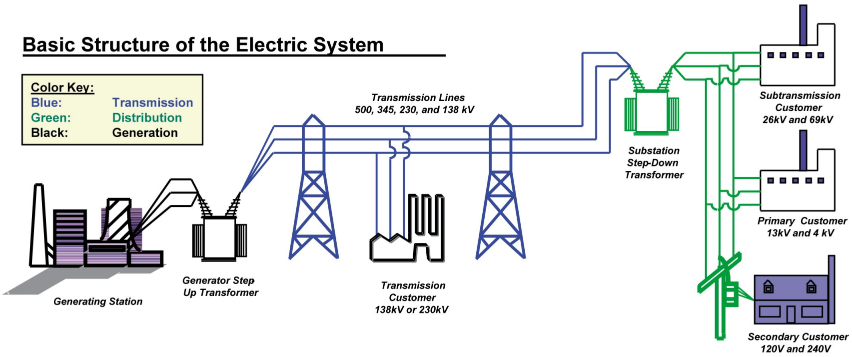


Figure 1.1: Structure of a Power System

The first step is the power generation that can be varied from oil, hydro, gas, nuclear, coal, wind, solar and other renewable sources as a single unit or a combination of multiple units. The World Eenergy Council[3] shows the usages of these electricity generations from the past 15 years which are changing as can be seen in figure 1.2[4].

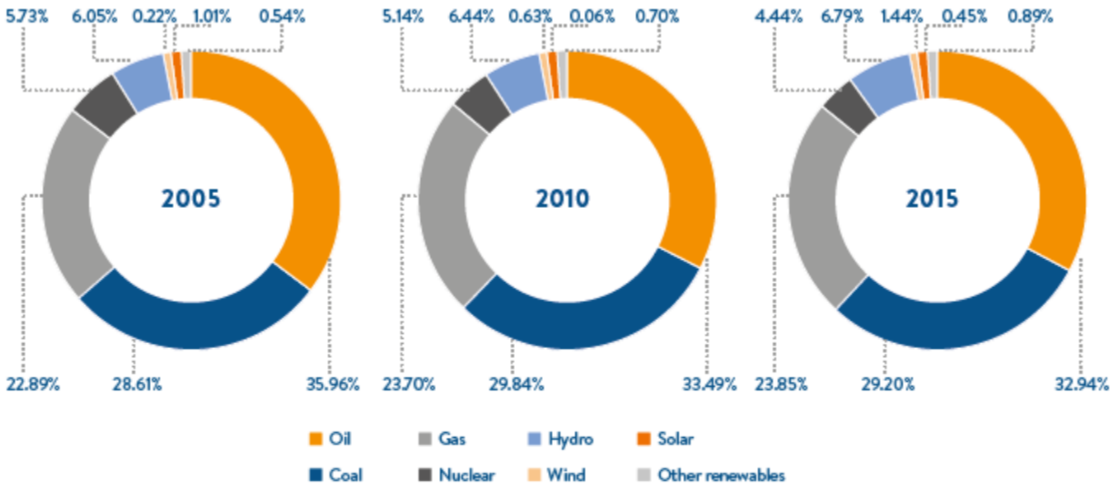


Figure 1.2: Electricity generation from 2005 to 2015

Step 2,3 and 4 there are two kind of transformers that are the step up and step down and the transmission line between them. Since in many instances the power generation is not in close proximity to where the consumer, then the electricity needs to be sent to the consumer.

[2]http://www2.econ.iastate.edu/classes/econ458/tesfatsion/Home458Team.htm

[3]https://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf

[4]https://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf

The voltage needs to be scaled up to be able to go through the transmission line, where the loss of voltage is inconsequential. When the distance to the consumer is reached than the voltage needs to be scaled down to be in working conditions. The consumer can also be directly connected with the transmission line for example factories with heavy electrical consumption. The regular consumer needs the voltage to be between 230 to 250 V in Europe and 110 V in America [5]. The electricity might have gone through multiples of transformers until it has reached its final destination.

1.2 Transformer

The transformer is one of the main units in a power structure, since they enable the power companies to send the voltage from the power generators over long distances and be usable for the consumer. The transformer is the most valuable unit and the the price and size of the transformer varies by manufacturer and some can cost millions of dollars [1]. The workability of the transformer is crucial and there-fore the maintenance and protection is of high importance. The failure of the transformer can be divided into two groups

1. Internal
2. External

It will be in more detail in next chapter about what failures are in each group.

[5] http://engineering.electrical-equipment.org/electrical-distribution/importance-of-voltage-criteria-for-consumer-distribution-system.html

1.2.1 Working of transformer

The workings of a power transformer is that two windings are on a single core to get magnetic coupling see fig 1.3[6]

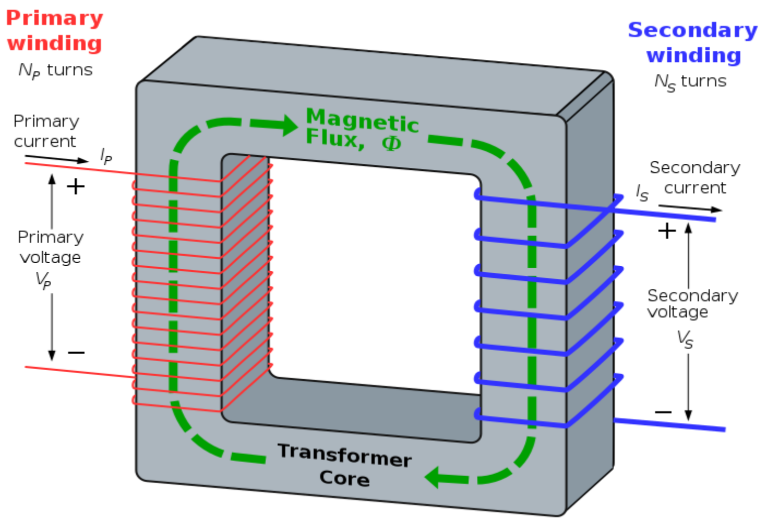


Figure 1.3: Ideal transformer with two winding on a single core

The windings are split into the primary (N_p) where the primary voltage (V_p) and current (I_p) goes through that produces magnetic field. Secondary windings (N_s) gets the magnetic field and creates electric current (I_s) and voltages (V_s) . The idealized model for the transformer is the following[2]:

$$\begin{aligned} \frac{V_p}{V_s} &= \frac{N_p}{N_s} \\ \frac{I_p}{I_s} &= \frac{N_s}{N_p} \end{aligned} \tag{1.1}$$

where the V_p and V_s are proportional to the number of windings in N_p and N_s. For a step up transformer then the windings would be $N_p < N_s$ and for a step down it would be other way around as the figure above shows how step down transformer windings would be.

[6] https://en.wikipedia.org/wiki/Transformer

1.3 Types of Transformers

There are few types of transformers used in power systems and are the following[7]

- Generator Transformer (GT)
- Station Transformer (ST)
- Distribution Transformer (DT)
- Unit Auxiliary Transformer (UAT)
- Auxiliary Transformer (AT)
- Instrument Transformer (IT)
- Rectifier Transformer (RT)
- Neutral Ground Transformer (NGT)

The GT is used in generating stations to step up the voltage for the use of transmitting the voltage with the transmission lines in the power grid. GT reduces voltage losses when transmitting the voltage over long distances and take much space so they are usually installed outdoors.

The ST is used for when the power plant is not generating power, to supply the auxiliary equipment necessary power to function in the power station.

The DT is a step down transformer that is used to lower the voltage to the supplier need.

The UAT is connected to the generator terminals and provides power to the generator auxiliaries of that unit. There is one UAT for every generating unit in power generating station.

The AT is used to step down the voltage to the low voltage loads in a power station where the voltage is lower than 1KV.

The IT is used in AC systems for protection system in power systems where they are connected line that has very high voltage and currents and lower the values to a more workable value. There are two types of IT and they are current transformer (CT) and potential transformer (PT). Where the CT steps down the current from HC to LC so low budget ammeter

[7] https://www.slideshare.net/vasanthancore/different-types-of-transformers-used-in-generating-station

can be used to measure the current and the current is safer to work with. PT is used to step down the voltage from HV to LV so that a low rating voltmeter can be used to read the values, the value can be 110 - 120 V. Using the CT and PT for measuring purposes in power stations lower the budget for measuring units. Where they take the current and voltage levels from very high rating that can be life threatening to a much safer values and readable values.[8,9]

The RT is a combinations of either diode or thyristors that are connected to the secondary side and change the AC to a DC. These transformer are used in industries where the supply of DC is significant for instance aluminium smelting factories where the furnaces need lot of power to operate.[10]

The NGT is used for resistance ground protection from damaging fault currents with low resistance. These devices are able to clear the fault within a few seconds and prevent the current to overheating on conductors.[11]

1.4 Objective of this thesis

The object of this thesis is to research, build and make a monitoring and protection system for a three phase power transformer by using sensors and micro-controller (M-C). The M-C will read data from the sensors that will be placed on tested transformer. The research will provide with that transformer failures happens to a transformer and what to look out for. There are optimal operating values for transformers but they depends on what kind and for what use it is for. If the values are not in the given optimal values the M-C will send an alarm and if needed cut off the power to the transformer before to much damage happens. The data collected in the M-C is sent to a program that will display the information for a human operator. The program will also allow the human operator to some control of the operation of the M-C.

[8] https://www.electrical4u.com/instrument-transformers/

[9] https://hubpages.com/technology/Differenet-Transformers-in-Power-Station

[10] http://www.studyelectrical.com/2015/11/what-rectifier-transformers-operation-and-application.html

[11] http://www.postglover.com/wp-content/uploads/downloads/2014/04/GT110-08_NGR_Trans.pdf

Chapter 2

Literature-review

The history of the transformer may be found in the early 1800's where the discovery of the property of induction and the invention of the induction coil. It was between 1880 to 1882 that Sebastian Ziani de Ferranti with William Thomas designed one of the earliest AC power systems. Lucien Gaulard and John Dixon Gibbs built the first step down transformer in 1882 with an open iron core that was first shown in exhibition in Italy 1884 but was not efficient enough to make and work with. In 1884, Ottó Bláthy, Károly Zipernowsky and Miksa Derí came up with the first closed built transformer with toroidal shape. It was not until William Stanley who went to the exhibition in Italy and saw the open iron core step down transformer. After the exhibition his boss George Westinghouse bought the patent to the Gaulard and Gibbs transformer design. George W. and William S. created a transformer that was more practical in production than the Gaulard and Gibbs. They changes the shape from toroidal shape that was hard to wind the wire around to a square shape that was much easier to work with. Mikhail Dolivo-Dobrovolsky a Russian born engineer who was working at AEG in Germany developed the first three-phase transformer that was used in the first powerful AC system[1].

[1] `http://www.edisontechcenter.org/Transformers.html`

2.1 The Working of a Transformer

Some characteristic of a transformer is that there are no moving parts, efficiency is very high and the frequency between windings are unchanged. [3] As from figure 1.3 it shows a single phase transformer. The core is made of magnetic materials that enable the magnetic flux ϕ when current goes through winding N$_p$. The flux created by N$_p$ goes through the core and connects with N$_s$. In a ideal transformer there is no loss in the transformer and is used for easier calculation, in real transformer there is energy loss in every step of the process but that is determined by the material used. The companies that make transformers have different ways of making the transformer and in many instances they are costume made for specific porpoise. From equation 1.1 it shows there is a correlation between the ratio of primary and secondary windings and the input and output of voltage and current. Since the transformer is a critical equipment for the use of distribution of electricity then a good protection system is needed to keep the transformer active. The time the transformer is connected it needs to stay on at all time unless it is taken out of service for some reason. The connection between windings on a transformer can be be wye (Y) or delta (Δ). There are 4 possible different ways of connection and are

- Y-Y (wye-wye)

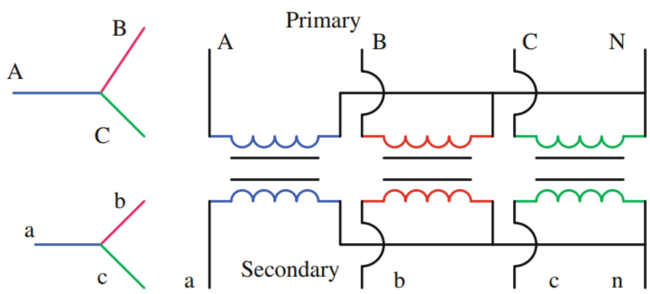


Figure 2.1: Y-Y connection diagram

- Y-Δ (wye-delta)

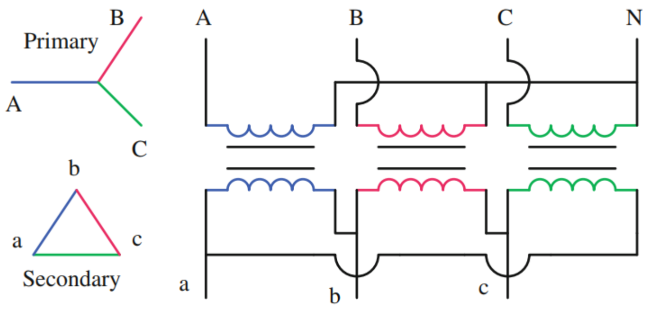


Figure 2.2: Y-Δ connection diagram

- Δ- Y (delta-wye)

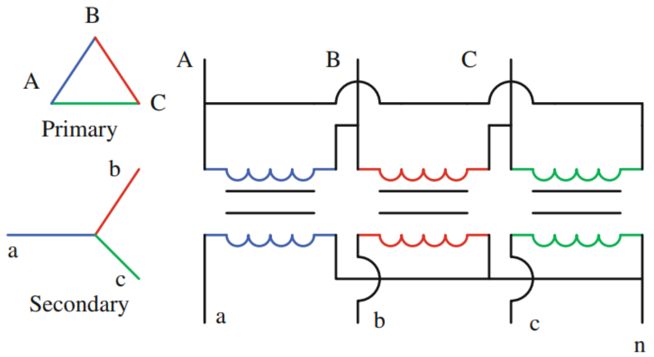


Figure 2.3: Δ-Y connection diagram

- Δ-Δ (delta - delta)

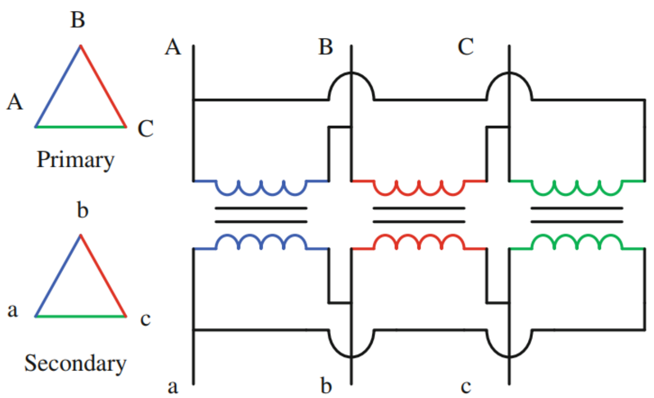


Figure 2.4: Δ-Δ connection diagram

The mainly used connection for a step down transformer is the Y-Δ (wye-delta) and for a step up is Δ- Y (delta-wye)[3][p. 88].

2.2 Transformer Protection

Since the transformer is very critical and expensive, the protection system needs to keep the transformer safe for operational use and here is listed some protective functions [4]

- Transformer Differential (87T)
- Restricted earth fault or ground differential protection (87GN)
- Instantaneous and inverse time Overcurrent (50/51)
- Ground instantaneous and inverse time Overcurrent (50G/51G)
- Current Unbalance/Negative Sequence (46)
- Over-excitation (24)
- Under-voltage (27)
- Over-voltage (59)
- Under-frequncy (81U)
- Thermal Protection (49)
- Breaker failure (50BF)

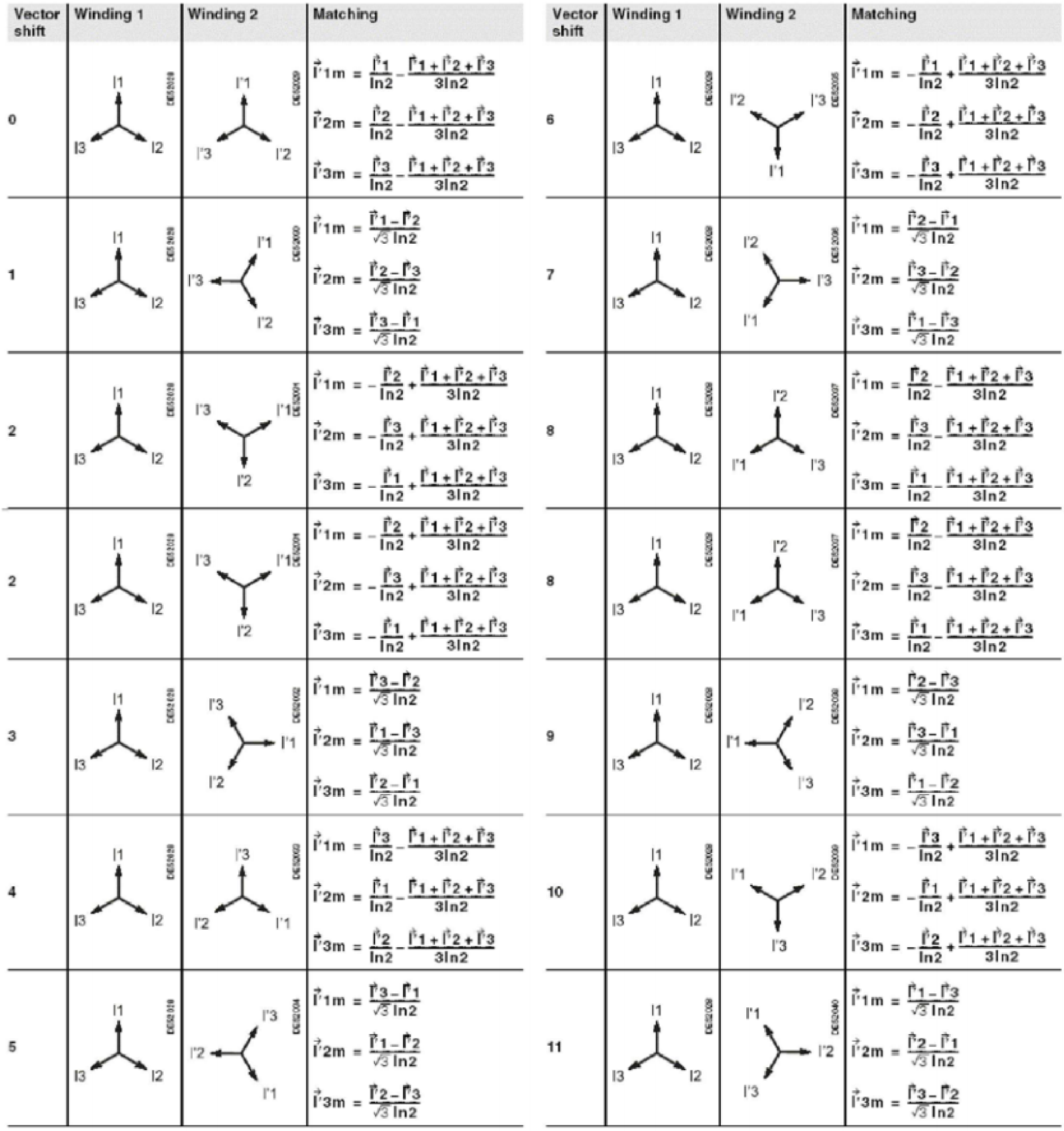
where the parenthesis numbers represent the ANSI device function.

2.2.1 Transformer Differential (87T)

Differential protection [5] uses sensors on the primary and secondary connections that compares the two currents of the same phase. If the currents equal each other than it is normal operation. If the currents do not equal each other then the transformer is not in working correctly. The currents have amplitude difference between the primary and secondary because of phase difference because coupling in the transformer and ratio of current transformation. The current matching of the primary winding is the same way of all vector shifts of the transformer.

$$
\begin{aligned}
I_{1m} &= \frac{I_{1p}}{ln(1)} - \frac{I_{1p} + I_{2p} + I_{3p}}{3ln(1)} \\
I_{2m} &= \frac{I_{2p}}{ln(1)} - \frac{I_{1p} + I_{2p} + I_{3p}}{3ln(1)} \\
I_{3m} &= \frac{I_{3p}}{ln(1)} - \frac{I_{1p} + I_{2p} + I_{3p}}{3ln(1)}
\end{aligned} \tag{2.1}
$$

Where I_{1m}, I_{2m}, I_{3m} is the matching value. I_{1p}, I_{2p}, I_{3p} is the current value from the primary windings. See figure 2.5 for matching value for the second winding respective from vector shift. [5][p. 6]



Vector shift	Winding 1	Winding 2	Matching
0			$\vec{I'}_{1m} = \frac{\vec{I'}_1}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_2}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_3}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
1			$\vec{I'}_{1m} = \frac{\vec{I'}_1-\vec{I'}_2}{\sqrt{3}\,In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_2-\vec{I'}_3}{\sqrt{3}\,In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_3-\vec{I'}_1}{\sqrt{3}\,In2}$
2			$\vec{I'}_{1m} = -\frac{\vec{I'}_2}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = -\frac{\vec{I'}_3}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = -\frac{\vec{I'}_1}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
2			$\vec{I'}_{1m} = -\frac{\vec{I'}_2}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = -\frac{\vec{I'}_3}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = -\frac{\vec{I'}_1}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
3			$\vec{I'}_{1m} = \frac{\vec{I'}_3-\vec{I'}_2}{\sqrt{3}\,In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_1-\vec{I'}_3}{\sqrt{3}\,In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_2-\vec{I'}_1}{\sqrt{3}\,In2}$
4			$\vec{I'}_{1m} = \frac{\vec{I'}_3}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_1}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_2}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
5			$\vec{I'}_{1m} = \frac{\vec{I'}_3-\vec{I'}_1}{\sqrt{3}\,In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_1-\vec{I'}_2}{\sqrt{3}\,In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_2-\vec{I'}_3}{\sqrt{3}\,In2}$
6			$\vec{I'}_{1m} = -\frac{\vec{I'}_1}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = -\frac{\vec{I'}_2}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = -\frac{\vec{I'}_3}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
7			$\vec{I'}_{1m} = \frac{\vec{I'}_2-\vec{I'}_1}{\sqrt{3}\,In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_3-\vec{I'}_2}{\sqrt{3}\,In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_1-\vec{I'}_3}{\sqrt{3}\,In2}$
8			$\vec{I'}_{1m} = \frac{\vec{I'}_2}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_3}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_1}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
8			$\vec{I'}_{1m} = \frac{\vec{I'}_2}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_3}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_1}{In2} - \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
9			$\vec{I'}_{1m} = \frac{\vec{I'}_2-\vec{I'}_3}{\sqrt{3}\,In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_3-\vec{I'}_1}{\sqrt{3}\,In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_1-\vec{I'}_2}{\sqrt{3}\,In2}$
10			$\vec{I'}_{1m} = -\frac{\vec{I'}_3}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{2m} = -\frac{\vec{I'}_1}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$ $\vec{I'}_{3m} = -\frac{\vec{I'}_2}{In2} + \frac{\vec{I'}_1+\vec{I'}_2+\vec{I'}_3}{3In2}$
11			$\vec{I'}_{1m} = \frac{\vec{I'}_1-\vec{I'}_3}{\sqrt{3}\,In2}$ $\vec{I'}_{2m} = \frac{\vec{I'}_2-\vec{I'}_1}{\sqrt{3}\,In2}$ $\vec{I'}_{3m} = \frac{\vec{I'}_3-\vec{I'}_2}{\sqrt{3}\,In2}$

Figure 2.5: Vector Shifts of the Transformer with 123 type phase-rotation sequences

2.2.2 Restricted earth fault or ground differential protection (87GN)

The 87GN ground protection is sensitive enough to detect internal ground faults. It uses low-resistance grounded .Fig 2.6 shows the set up and is able to detect ground faults without false tripping on external faults [6] [7].

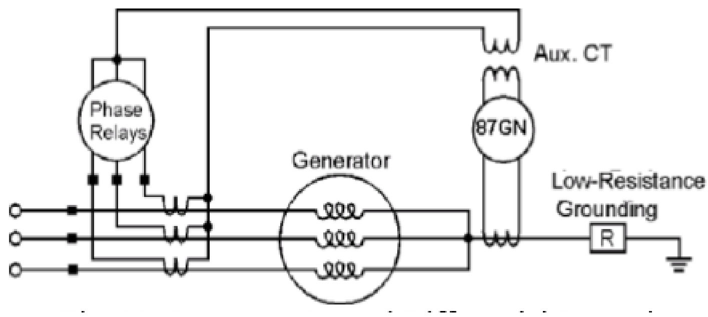


Figure 2.6: Ground Differential Protection

2.2.3 Ground instantaneous and inverse time Overcurrent (50G/51G)

Figure 2.7 shows the set up for the 50G and 51G where they work together for using 50G overcurrent relays that are positioned on each feeder and using 51G inverse time overcurrent on the grounded neutral sources. 51G provideds protection against exernal faults if the 50G has not isolated the fault. [6] [7].

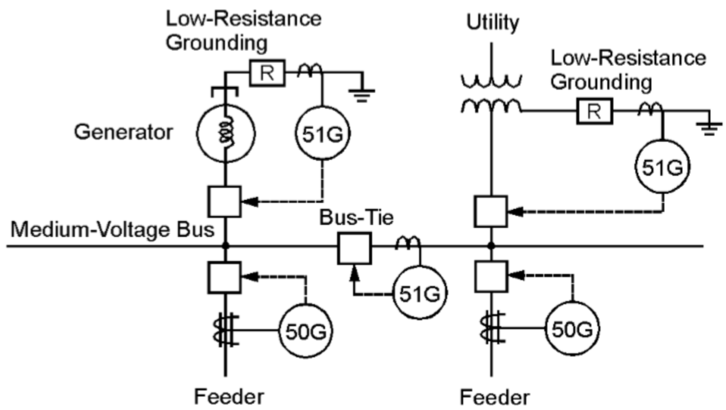


Figure 2.7: Ground time and overcurrent protection

2.2.4 Thermal Protection (49)

When the transformer is turn on the electricity flows through it, the loss of power in the transformer is turned to heat.

2.2.5 Transformer fault

The potential faults that happens in a transformer

Winding failure:

- turn-to-turn insulation failure
- moisture
- deterioration
- phase-to-phase and ground faults
- external faults (producing insulation failure

Tap changer failure:

- mechanical
- electrical
- short circuit
- oil leak
- overheating

Bushing failure:

- ageing, contamination and cracking
- flash-over due to animals
- moisture
- low oil

Core failure:

- core insulation failure
- ground strap burned away

- loose clamps, bolts, wedges

Miscellaneous failure

- Bushing CT failure
- metal particles in oil
- damage in shipment
- external faults
- poor tank weld
- over voltages
- overloads

2.2.6 Detection of transformer internal faults

Phase-to-phase

- transformer differential protection
- Buchholz relay
- overpressure device
- under-impedance/distance device
- HV fuses

Ground-fault, low impedance

- restricted ground-fault protection
- transformer differential protection
- Buchholz relay
- under-impedance/distance device

- HV fuses

Ground-fault, high impedance grounding

- restricted ground-fault protection
- sensitive ground-fault current protection
- neutral (residual) over-voltage protection
- Buchholz gas alarm

Turn-to-turn fault

- Buchholz alarm
- transformer differential protection

HV to LV winding flash-over

- transformer differential protection
- Buchholz relay
- overpressure device (sudden pressure relay)

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