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Mitigation of flux produced by geomagnetically induced currents (GIC) on power transformers with delta windings

Henrik Jönsson
Victor Lovén

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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Abstract

Geomagnetically induced currents (GIC) arise in our power system due to fluctuations in the earths magnetic field, which commonly is caused by space weather events. These currents may result in core saturation for transformers that get exposed. The purpose of this project is to clarify the possibility of reconnecting the delta connected tertiary windings in order to mitigate the saturation that is caused due to GIC. Laboratory studies were performed on different types of transformers, which later were simulated and compared to the experimental results, in order to verify the credibility of the simulations. This will allow us to trust the results of the simulations performed on a large transformer to a greater extent.

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List of symbols

ε Electromotive force, EMF

R1 Resistance in series with battery

R2 Resistance in parallel with battery and R1

Φ Magnetic flux

Ugic Battery voltage representing GIC

L Inductance between breaker and load transformer

ZN Wire inductance and resistance between compensation windings and ground

α GIC rise time for an uncompensated transformer

β Amount of compensation

Terminology

AC Alternating Current

CME Coronal Mass Ejection

DC Direct Current

EMF Electromotive Force

FFT Fast Fourier Transform

GIC Geomagnetically Induced Currents

GMD Geomagnetic Disturbance

MMF Magnetomotive Force

Primary winding wye connected winding to which the power supply is connected to

rms Root Mean Square

Secondary winding wye connected winding which is the side of the transformer that is loaded.

SVC Static Var Compensator

Tertiary winding Delta connected tertiary winding

Compensation winding Open delta connected tertiary windings, with one end connected to secondary zero and the other to ground.

p.u Per unit

Chapter 1

Introduction

1.1 Background

Geomagnetically induced currents, GIC, arise in the power system as a result of space weather events. These currents are of very low frequency and can be viewed as a quasi DC current in the power system. The consequence of a DC current entering a power transformer is half-cycle periodic saturation of the core. This periodic core saturation results in heating, harmonics and reactive power losses. Studies have been done in order to investigate mitigation possibilities, among them is a patent by Mats Alaküla and Sture Lindal [1] that eliminates the flux offset in the core, by installing flux compensation windings. Inventions like this have generated interest to further develop ways of mitigating the impact.

Wye-wye transformers usually have delta connected tertiary windings in order to manage zero sequence currents. This study will evaluate the impact of reconnecting these tertiary windings into flux compensation windings, that will, at least partially, mitigate the flux offset.

1.2 Purpose

The objective is to investigate the influence of GIC on a wye-wye connected transformer with delta connected tertiary windings. These tertiary windings will be re-configured and used as DC flux compensation windings, both in simulations and laboratory studies. These will be evaluated by comparing them with simulations of optimal DC flux compensation windings. The implementation of partial flux compensation windings has never been both simulated and tested before in one study. If this method proves to function well enough, implementation will be more cost effective compared to custom made transformers to prevent the impact of GIC.

1.3 Scope of work

This work consists both laboratory studies and simulations, that will be evaluated and compared to each other. The laboratory study will mainly be performed on three 800VA single phase transformers, but also on one 2.4kVA three legged 3-phase transformer and one 2.4kVA five legged 3-phase transformer. Both the aspect of the steady state and transient behaviour will be evaluated. The simulations will mainly focus on the comparisons of the laboratory single phase transformers and the modelling of the single phase transformers in order to achieve a reliable simulation model that can be up-sized to a 400MVA transformer.

Chapter 2

Theory

This chapter deals with the theory of the how geomagnetically induced currents (GIC) enters the power system and some theory about the system. First, a brief introduction on space weather disturbances and how these cause geomagnetic disturbances. Further the GIC in the power grids are discussed. Followed by the negative effects GIC have on the power system and in particular on high power transformers.

2.1 Geomagnetically induced currents, GIC

GICs are low frequency currents, which are induced in power systems by geomagnetic field variations that are a result of space weather disturbances. The frequency is so low, compared to the frequency of the power grid, that it can be considered as quasi-DC. This phenomenon was first noticed over 150 years ago, when the telegraph system was effected by GIC [2]. Back then this was the most advanced infrastructure and this disturbance resulted in massive problems. Today, in our current, complex power system, these geomagnetic field variations can still cause huge problems as this report will show.

2.1.1 Cause

Solar activity The cause of GIC are solar storms and space weather events. These events start at the surface of the sun when the suns magnetic fields collide and large clouds of plasma are thrown out in to space. These clouds of plasma do sometime travel in the direction of Earth. Depending on the direction of the magnetic field inside the cloud of plasma it has different impact on our magnetosphere. This can generate electric fields which drives an electric current between the magnetosphere and the ionosphere. Due to the orientation of the earths magnetic field the currents are most intense in the auroral ovals. Since this magnetic field changes an electric current is induced in conducting structures such as the power system [3],[4].

Charged particles heading towards earth As a solar storm erupts on the sun, particles will head out into space. Some of which will head towards earth and hit the magnetosphere. The first thing to hit us is the light that is sent out from the solar flare, as it travels with the speed of light. Shortly after that, the solar energetic particles will hit, as they are travelling close to the speed of light. However the speed of the solar energetic particles can vary, usually it hits earth 20-30 minutes after the eruption. The coronal mas ejection (CME), which travels a lot slower, will hit the earth after 1-4 days. If a person would be in space and get hit by a solar storm, the particles could do great damage to the human body. Luckily, we are protected from these particles by the earth's magnetosphere and atmosphere. Generally, solar storms do not have any impact on the human body at our planet, however it can have a great negative impact on our technological infrastructure. Some examples of space weather consequences on Earth is the collapse of the Hydro-Québec power system on March 13, 1989 due to geomagnetically induced currents, where over 6 million people were without power for 9 hours. Another example of the impact of space weather is the power outage in Malmö, Sweden, 31st of October 2003. This power outage was also due to GIC [5].

2.1.2 Geomagnetic induction

The Geomagnetic disturbance (GMD) results in GIC in the powers system, pipe lines and other long conductors. The currents are related to the magnetic field changes, which can be explained by the variation of flux Φ over time resulting in the EMF ε. See $Faraday's\ law$ [5].

$$\varepsilon = -\frac{\delta\Phi}{\delta t}$$

In order for current induction to take place, according to Faraday's law, the magnetic field has to vary through a closed loop. The power lines themselves do not make a loop, as all of them are vertical, slightly above the ground and the geomagnetic disturbance also act vertically to the ground. However, the power lines do make an entire closed loop together with the earth. The upper half of the loop is represented by the power lines, that are eventually grounded through transformers and the lower half of the loop is the earth.

The magnitude of the GIC depends of different key variables: length of power lines, power line direction, the magnetic flux variation and soil conductivity.

Power line length The length of the power lines matters, as with longer lines a larger current can be induced. However, when the line length gets too long the GIC as a function of the line length reaches a steady state. This behaviour is visible in Figure 2.1 [5].

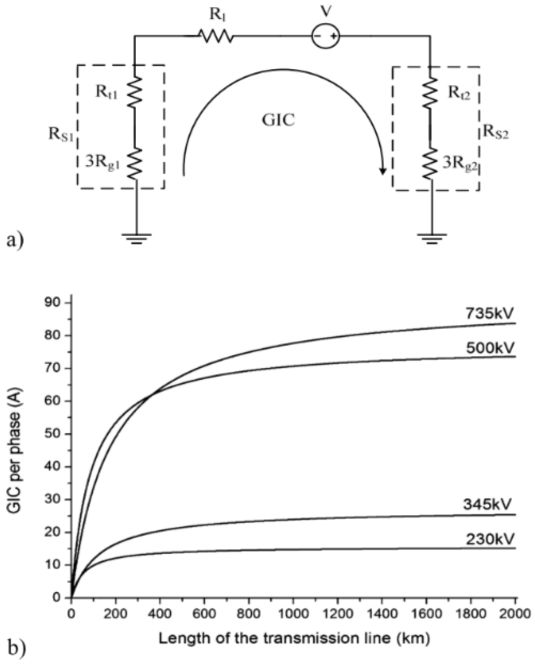


Figure 2.1: (a) Example circuit of a transmission line connected to two substations, with grounding at the transformer neutral points. (b) Graph of induced GIC with respect to the length of the power lines in kilometers, [5].

Power line direction The direction of the power lines also matters, as the magnitude of the GIC depends on the perpendicular component of the lines and the geomagnetic field variation. However, since the geomagnetic disturbances are not guaranteed to be homogeneous and straight the prediction of which power line direction that is worst can be hard to predict.

Magnetic flux variation Finally, the magnitude of the electromagnetic field variations also makes a difference on the amplitude of the GIC, larger variations induce more current. This is also visible in Faraday's law. In other words, larger magnitude and higher frequency of the field results in higher induced currents. However, the Soil conductivity also impacts the amount of GIC that is induced to the system, [5].

2.1.3 Effect

The induced GIC flows along the transmission lines and to ground through the transformer windings. This GIC produces a quasi-DC offset in the magnetization of the transformer core which results in three primary negative effects. Transformer heating, reactive power losses and waveform distortion [8, 9]. A saturated core indirectly heats the transformer since the flux has to travel through other paths which are not designed to handle magnetic flux. This saturated core also results in waveform distortion (ie. increased harmonics) which eventually may cause misoperation of protection relays. The waveform distortion also increases the reactive loading of the system and can contribute to voltage collapse [9].

Saturation The partial core saturation occurs when the variation of magnetic flux and current is no longer symmetric around zero, which is a result of the GIC entering the transformer through the power lines. With no DC-offset, the transformer is able to work in a non-saturated area of the magnetizing characteristic, see Figure 2.2, at all points of the sinusoidal current. However when the transformer is subjected to a DC-offset, the sinusoidal current and magnetic flux will no longer be symmetric around zero, but instead asymmetric around the DC-offset.[9] This leads to larger current and magnetic flux in the half period with the same current and magnetic flux direction as the DC-offset. Hence, smaller current during the other half period. The half period with reduced current and magnetic flux is not a problem, however the half period with increased current and flux may saturate the core. The core is not saturated for the entire half period, but only for the small part where the magnetic flux from the AC source, added to the magnetic flux from the GIC is larger than the maximum flux that the core can handle, without getting saturated. As the core gets saturated it loses a lot of its magnetic abilities, which leads to lower inductance of the transformer, resulting in larger winding currents, in the form of current spikes [9], see Figure 2.2.

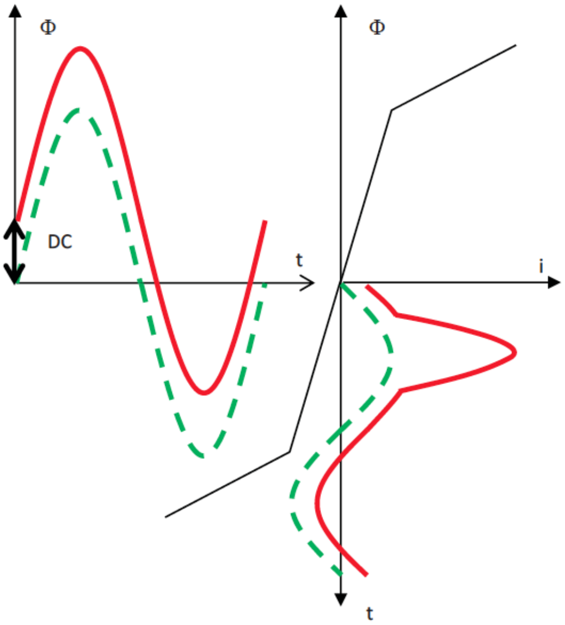


Figure 2.2: Mapping from magnetic flux to current through the magnetizing characteristic typical for a transformer but with hysteresis neglected. Operation in linear range (dashed) and with half-cycle saturation (solid) shown.[9]

As the core enters magnetic saturation it can not carry any more magnetic flux, hence the permeability of the core drops and the reluctance, which is the magnetic resistance, increases. This results in the flux finding new paths outside of the core where the reluctance is lower. The flux will therefore flow through the transformer oil, tank, housing and nearby structures.
By mitigating or fully eliminating the flux induced by the DC offset the impact of GIC would be eliminated in the transformer [9]. There is a patent [1] that eliminates the flux induced by the DC offset, however this patent comes with a great economic cost, as the transformers would have to be replaced by transformers with an extra winding that specifically eliminates the flux induced by the DC offset. As for now, wye-

connected transformers have delta-connected tertiary windings, which is implemented in the transformer in order to handle zero sequence currents. These tertiary windings could be used to mitigate the flux induced by the DC offset, this has similarities to the patented compensation windings, which is also delta connected [1]. Since the number of turns of the tertiary windings are not optimal, the DC flux will not be completely eliminated, but if reduced enough to prevent the core from getting saturated, the negative effects of the GIC would disappear, or be mitigated if partially compensated.

Heating In case of saturation and the flux finds new paths outside of the transformer core, hotspots accrues in the transformer and nearby structures. The transformer oil and housing are not designed to carry AC magnetic flux which will result in eddy currents in the structures, this will increase the temperature of the transformer. If the core is exposed to enough DC-offset, which forces the flux out from the core, this will result in overheating of the transformer that may cause permanent damage. A damaged transformer will need maintenance or replacement before being put into service again. Taking a power transformer out of service will result in increased system loading during the time that the transformer is inoperative, which may last several days and much longer if the supply of nearby spears is exhausted [9].

Reactive power losses As GIC is entering the transformer, the rms value of the distorted current waveform will increase. This increment results in higher reactive losses in the transformer, which results in the power transformer drawing more reactive power, this stresses the system.
Systems near voltage collapse are characterized by drawing great amounts of reactive power, hence this increment brings the system closer to a blackout.

Harmonics and waveform distortion The normally sinusoidal AC current and flux become distorted due to the transformer saturation produced by GIC. This distorted waveform causes relays to operate in order to protect the system from over currents and over voltage. However, these operations can be unwanted since the relays are tripping on a distorted waveform and not the fundamental value of the peak value. In some cases, such as the Quebec blackout in 1989 and Malmö blackout in 2003, this false tripping of relays disconnects equipment that weakens the system, such as a Static Var Compensator (SVC) or a transformer [9].

2.2 Zero sequence currents

Zero sequence currents, which are AC current components being the same in all three phases, are present when an unsymmetrical fault to ground occurs. For instance a line to ground fault.

While ungrounded transformer windings block zero sequence current from the terminals, windings that are grounded, typically wye connected, can carry such current. When transformers saturate, they draw a third harmonic current, which is of zero sequence type. Instead of drawing this current from the network, which is undesirable, it can be supplied by delta connected windings. Wye-wye transformers are therefore normally equipped with a delta connected tertiary winding for this purpose. It may even be ”buried” with no terminals available on the outside of the transformer. Transformers with a delta connected main winding do not need tertiary windings.

2.3 Mitigation Method

2.3.1 Series capacitance

Series capacitance are sometimes installed on long transmission lines, they reduce the total series reactance and make the lines seam electrically shorter, which increase transfer capacity and improves stability. A nice side effect of this is that it blocks the flow of GIC, since DC currents can not pass throw a capacitor.

2.3.2 Transformer type

To give transformers different abilities they are constructed in different shapes and sizes. Three commonly used transformer types are single phase transformer, three legged 3-phase transformers and five legged 3-phase transformers. Especially when looking at DC flux which is a zero sequence flux.

Single phase transformer A three phase transformer can be achieved with three separate three legged single phase transformers, see Figure 2.3. Each transformer has primary-, secondary- and tertiary windings on the middle leg. This allows the flux from the GIC to return in the outer legs, allowing the DC flux to flow.

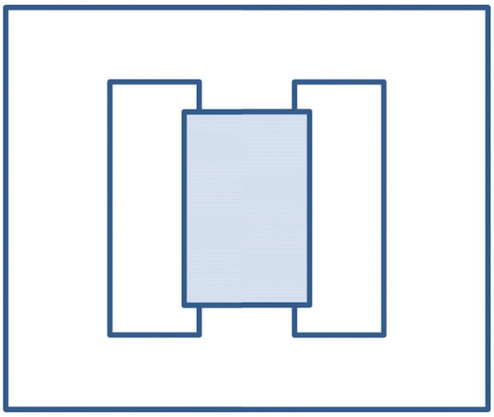


Figure 2.3: Single phase transformer. The blue area is primary, secondary and tertiary windings, the white area is the core

Three legged 3-phase transformer This type of transformer is good against GIC, since the GIC is symmetrically added to all phases and there by the flux from the GIC is forced in the same direction in all three legs, see Figure 2.4. The structure does not allow any flux to easily return in any leg but has to return in the surrounding material, transformer oil, housing and air.

Construction of a transformer with three legs produces a structure that becomes taller than a five legged transformer of the same power. This can sometime prevent the transformer, during transportation, to pass under highway bridges, effecting the choice of transformer type.

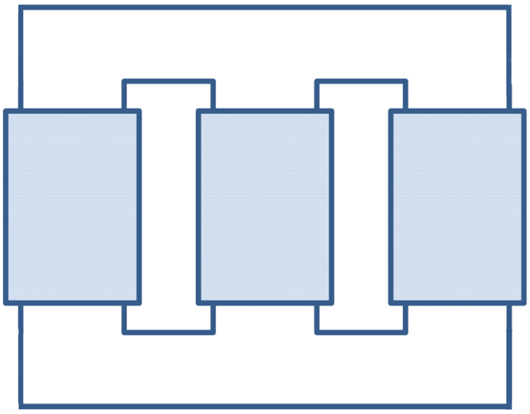


Figure 2.4: Three legged transformer. The blue area is primary, secondary and tertiary windings, the white area is the core

Five legged 3-phase transformer The five legged transformer is just like the single phase transformer bad against GIC. The flux generated from GIC which simultaneously gets induced in the three middle legs and the flux has a return in the outer legs, see Figure 2.5.

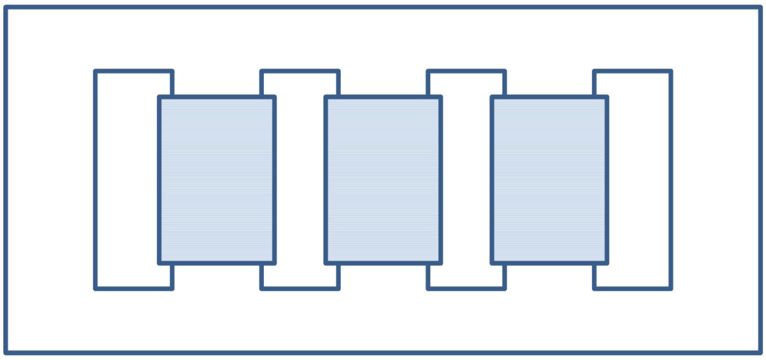


Figure 2.5: Five legged transformer. The blue area is primary, secondary and tertiary windings, the white area is the core

2.3.3 Compensation windings for GIC immunity

As mentioned in the section above, it is possible to fully compensate the negative effects of the GIC. This is patented by Mats Alakühla and Sture Lindhal [1]. The idea of the patent is to use tertiary windings with one third of the voltage of the main windings in order to fully compensate for the flux produced by the GIC. The windings would have to be delta connected and opened in one point, so that one end is connected to the neutral point of the main windings and the other end is connected to ground. It is very important that the compensation winding is connected so that the GIC in the compensation winding travels in the opposite direction around the core than in the main windings. If not, it would double the effects of the GIC instead of canceling it. The problem with this solution is that there are no such windings present in any transformers, which mean all new transformers would have to be built in order to implement this solution.

2.3.4 Partial compensation with tertiary windings

If the tertiary windings that are already existing in a wye-wye connected transformer could be opened and connected between neutral and ground, this would be very similar to the patented solution. However, it will only partially compensate the DC flux. This is due to the fact that the already implemented tertiary windings does not have the optimal number of turns to fully compensate for GIC disturbances. These windings are originally installed to compensate for zero sequence currents, but can be modified to also compensate for GIC. In order to do this compensation, the delta connected tertiary windings will be opened and connected to the common zero of the windings of which the GIC enters the system in one end, and connected to ground in the other end. As shown in Figure 2.6

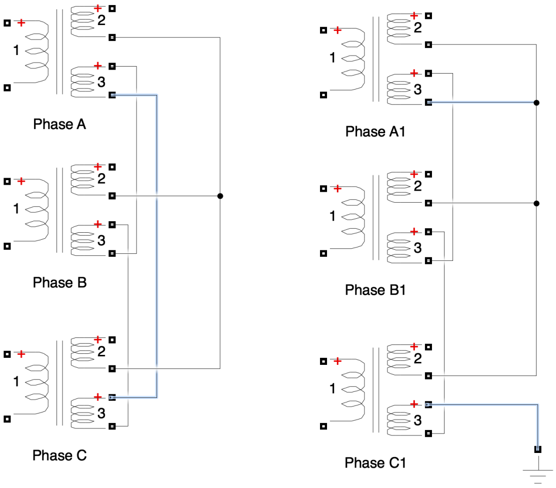


Figure 2.6: Third winding in each phase as delta connected tertiary (left) and as patented compensation winding to reduce impact of GIC (right).

This allows the GIC that travels in parallel through the main windings to continue in series through the tertiary windings. This results in a three times larger DC current in every tertiary winding, than in the main windings. Hence a perfect GIC compensation would be acquired if the tertiary windings had a turn ratio being one third of the main windings. The compensation ratio is linear to the number of turns in the tertiary windings. If the tertiary windings would have one sixth of the turns of the main windings, instead of one third, it would only mitigate the flux induced by the GIC to half of what it would have been without compensation. In the same way, if the number of turns of the tertiary windings would be the same as that of the main windings, it would overcompensate. This means the tertiary windings would create a flux three times bigger than the main windings, but in the opposite direction. Which would result in a flux that is twice as big as with no compensation at all, but in the opposite direction.

2.3.5 Closing open delta with a capacitor

Losing the compensatory effects for zero sequence currents when reconnecting the tertiary windings can potentially be avoided by connection of a capacitance where the delta was opened. In other words, connect a capacitance between the zero point of the high voltage windings and ground. This allows the AC, in other words the zero sequence current to flow in the original delta winding while the DC, or GIC can flow in the new connection in order to mitigate the DC induced flux. What could be potential problem with this type of connection is that it can result in resonance, as there are both capacitive and inductive components.

Chapter 3

Equipment

This chapter will describe and motivate the equipment and power supplies that has been used. It will also provide the transformer parameters and show the experimental circuit, Figure 3.1 where the GIC enters the system in the form of DC.

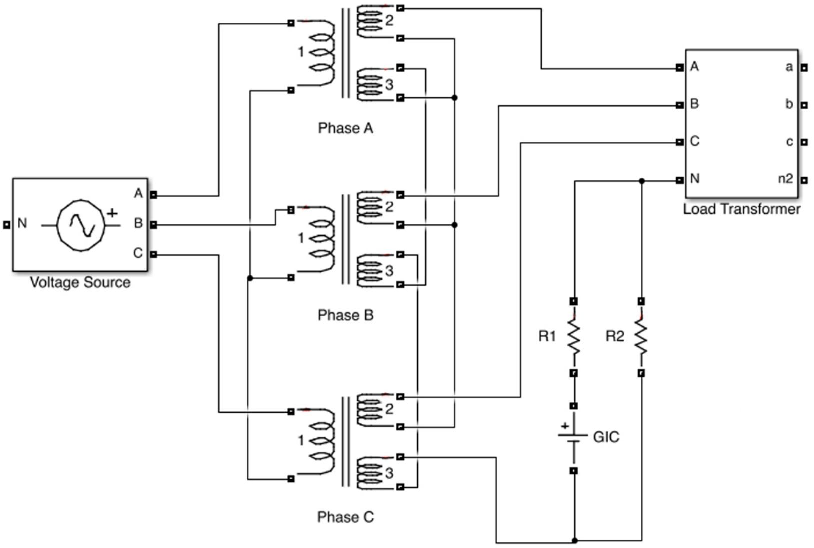


Figure 3.1: Experimental circuit used for injecting DC into transformers

3.1 Measuring equipment

All laboratory measurements were done with a *Rigol DS*1054 oscilloscope. To measure the currents two Fluke AC current probes and one *Kyoritsu AC/DC* clamp adapter model 8113 were used. The voltages were measured with one *Tectronix P*5200*A* differential probe and one *Esselite Studium* differential probe.
Apart from these probes, five *Biltema Art.*15 − 124 and two *MetraHit* 16*s* multimeters were used to measure and observe voltage and current.

3.2 Transformers

The single phase transformers bellow are three identical E-core transformers, see Figure 3.2. They are specially designed with a tertiary windings that can be connected at $42V$ and $73V$, see Tables 3.1, 3.4. The study also uses the fact that a connection can be put between the $42V$ point and $73V$ point, in order to get a $31V$ connection. Each of the single phase transformers are rated 800VA, resulting in a 2.4kVA 3-phase system when connected together.

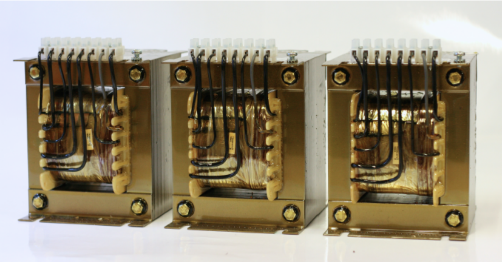


Figure 3.2: Single phase transformers

Table 3.1: Parameters of single phase transformers

Power	800VA
Frequency	50 - 60Hz
Primary	0 - 127 - 220V
Secondary	127V / 5.2A
Tertiary	0 - 42 - 73V / 1.8A
Dimensions H x W x D	150 x 125 x 125mm

The three legged 3-phase transformer is custom made as well, with the same possibility for the tertiary connections as the single phase transformers above, see Figure 3.3 and Tables 3.2, 3.4 for transformer parameters.

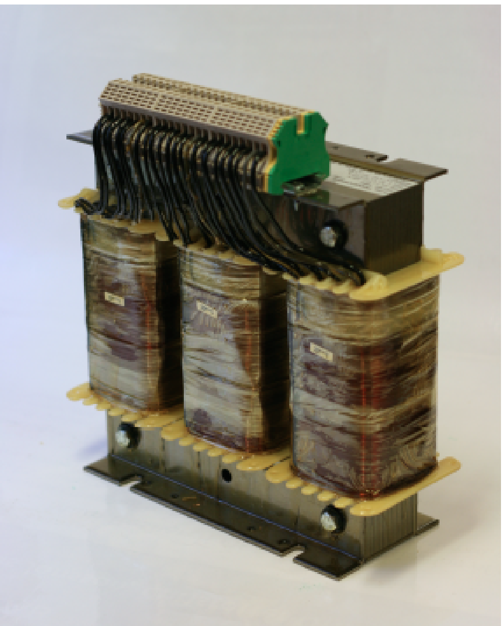


Figure 3.3: Three legged 3-phase transformer

Table 3.2: Parameters of three legged 3-phase transformer

Power	2400VA
Frequency	50 - 60Hz
Primary	0 - 127 - 220V
Secondary	127V / 5.2A
Tertiary	0 - 42 - 73V / 1.8A
Dimensions H x W x D	255 x 280 x 85mm

The five legged 3-phase transformer has the exact same specifications as the three legged 3-phase transformer. The only aspect that separates the two different transformers is the number of legs. see Figure 3.4 and Tables 3.3,3.4 for transformer parameters.

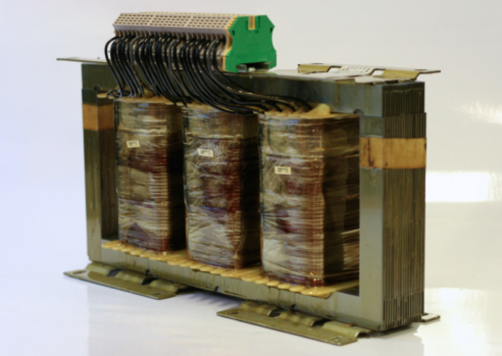


Figure 3.4: Five legged 3-phase transformer

Table 3.3: Parameters of five legged 3-phase transformer

Power	2400VA
Frequency	50 - 60Hz
Primary	0 - 127 - 220V
Secondary	127V / 5.2A
Tertiary	0 - 42 - 73V / 1.8A
Dimensions H x W x D	213 x 400 x 85mm

Table 3.4: Transformer parameters

	Single-phase [p.u.]	3-legged [p.u.]	5-legged [p.u.]
RDCP220	4.473*10ˆ-2	4.770*10ˆ-2	4.786*10ˆ-2
RDCP127	1.422*10ˆ-2	1.754*10ˆ-2	1.745*10ˆ-2
RDCS127	1-622*10ˆ-2	2.029*10ˆ-2	2.024*10ˆ-2
RDCT73	0.225	0.2735	0.2792
RDCT42	0.1318	0.1680	0.1472
RwP220	1.409*10ˆ-2	4.721*10ˆ-3	4.651*10ˆ-3
RwP127	7.8781*10ˆ-3	8.6241*10ˆ-3	8.6081*10ˆ-3
RwS127	8.934*10ˆ-3	9.5641*10ˆ-3	9.4511*10ˆ-3
RwT73	0.1064	0.1414	0.1409
RwT42	5.4531*10ˆ-2	7.8281*10ˆ-2	7.7681*10ˆ-2
Rm	49.47	40.38	33.12
LlP220	1.155*10ˆ-5	2.024*10ˆ-7	6.328*10ˆ-7
LlP127	9.274*10ˆ-6	7.739*10ˆ-6	8.011*10ˆ-6
LlS127	3.441*10ˆ-6	3.596*10ˆ-6	3.515*10ˆ-6
LlT73	6.620*10ˆ-5	9.132*10ˆ-5	9.508*10ˆ-5
LlT42	4.316*10ˆ-5	6.357*10ˆ-5	6.314*10ˆ-5
Lm	5.421*10ˆ-2	6.779*10ˆ-2	2.951*10ˆ-2

3.3 AC supply to transformers

Before conducting tests on the transformers the voltage quality of the AC supply was investigated. In the laboratory two different power nets were available, one $230V$ $50Hz$ grid which which is the public network. The other system, $127V$ $50Hz$, is a local net transformed in the building from $230V$ to $127V$ and is used for laboratory studies and tests. There is also a third option, generate the power directly from a $200kVA$ generator.

3.3.1 Public $230V$ grid

First, tests were conducted with the $230V$ grid as a direct power source to three single phase power transformers, as shown in Figure 3.5. The wave form is quite nice, but without a variac the voltage can not be controlled. Some complications also occurred early on, as the DC offset did not work well with direct grid connection. As the only route for the DC after passing the transformer, is to go straight out on to the power grid, when putting the DC on the high side of the transformers.

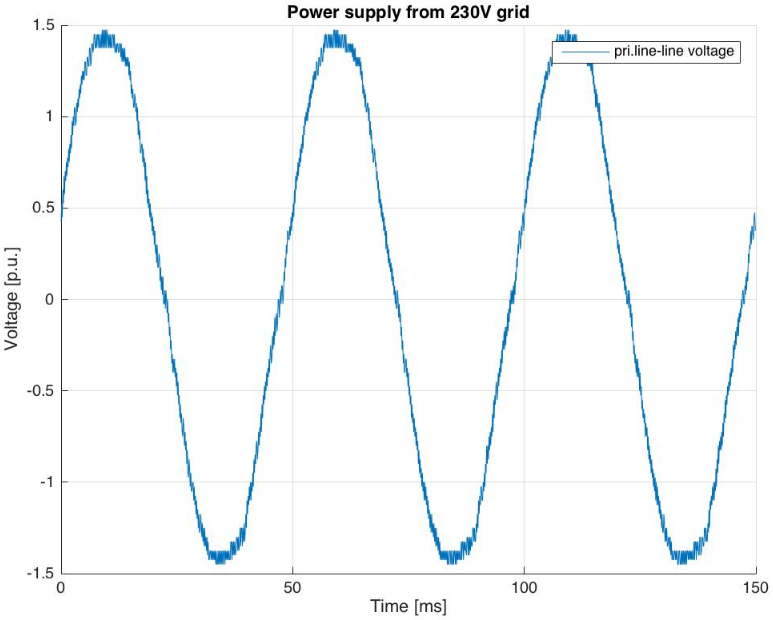


Figure 3.5: $230V$ Grid as voltage source on primary side of the transformer. $3.5A$ DC offset on secondary side.

3.3.2 Public $230V$ grid and Variac

To allow amplitude variations of the voltage on the primary side of the transformer, a variac was connected between the grid and the three single phase transformers. The variac has a common zero for the primary and secondary side, which is also common with the zero of the power grid. For tests with DC offset on the primary side of the transformer, the DC current will find its way out to the grid. The voltage on the primary side of the variac contains a large amount of harmonics, see in Figure 3.6, as the power grid that feeds the variac is connected to other machines in the building. The secondary side voltage of the variac is even worse than the primary side, as slight saturation of the variac occurs when the load is high. The secondary side voltage also drops drastically when loaded or when a DC flows through the secondary side of the single phase transformers, indicating considerable series impedance in the variac.

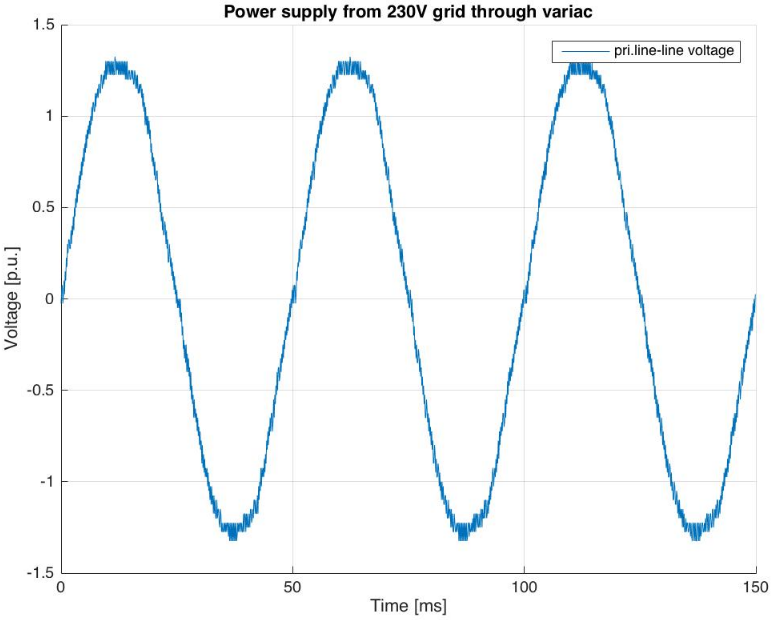


Figure 3.6: Variac as voltage source on primary side of the transformer. $3.5A$ DC offset on secondary side.

3.3.3 From $127V$ grid to variac to step up transformer

A poor primary voltage may cause harmonics in the final result, therefore it is very important to use a power source which is as ideal as possible. In order to find a good primary voltage the $127V$ grid of was connected to the variac, which in turn was connected to a step up transformer, which is connected to the three single phase transformers. This improved the secondary side voltage of the variac as the supply grid had a smother sinusoidal form, as well as the variac did not get saturated. However, the voltage of the secondary side of the step up transformer had a poor waveform, see Figure 3.7, therefore it may contaminate the final results. However, this way of feeding the transformer also allow us to drive big DC current on the primary side of the transformer, as it is galvanically isolated from the net through the step up transformer.

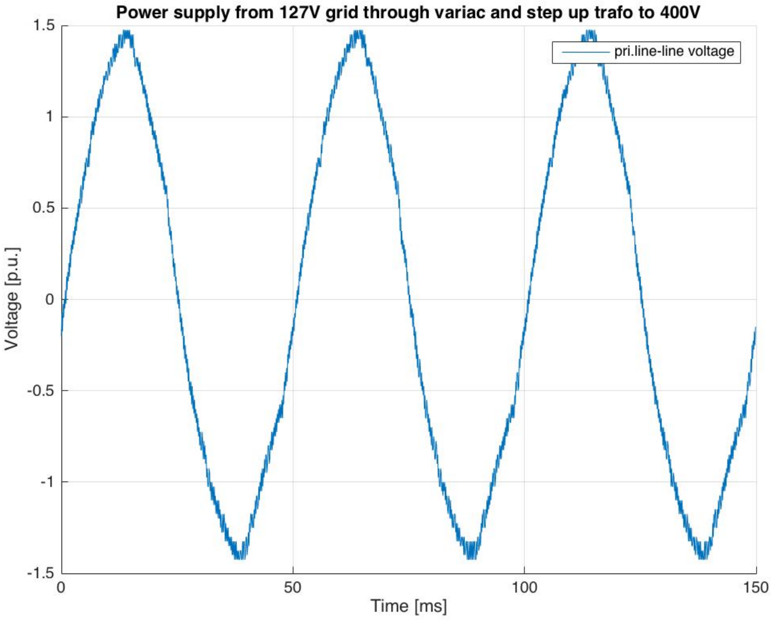


Figure 3.7: 127 grid to variac to step up transformer as voltage source on primary side of the transformer. $3.5A$ GIC on secondary side.

3.3.4 $200kVA$ synchronous generator

To conduct more precise measurements with a true sinusoidal voltage instead of the contaminated voltage in the power grid, see Figure 3.5, 3.6, 3.7. The test system is supplied from a $200kVA$ synchronous generator powered by a $50kW$ DC motor. This supply proved to have a very clean sinusoidal voltage and no obvious inductance problems, see Figure 3.8. It also allowed us to do tests with DC offset on the primary side of the transformer, as a small DC offset was no problem for the generator. Therefor, it was decided to conduct all following measurements using this synchronous generator.

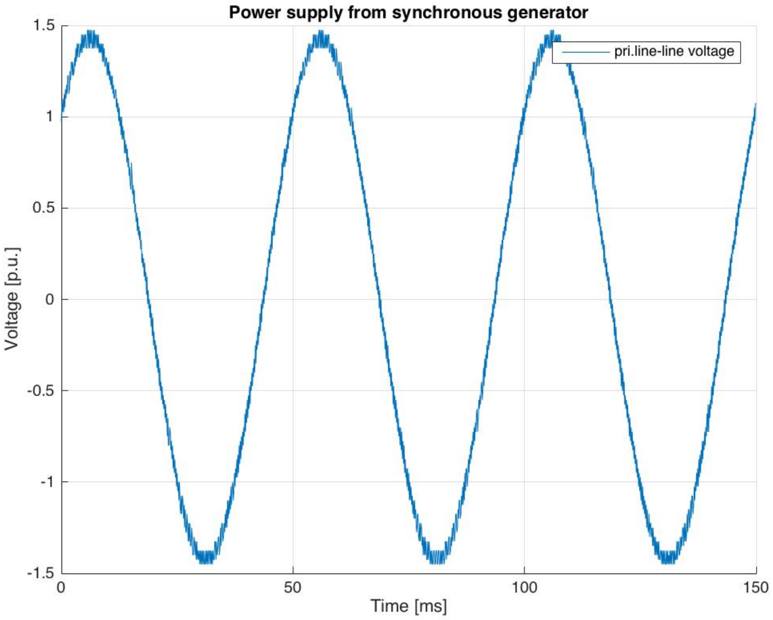


Figure 3.8: $200kVA$ generator as voltage source on primary side of the transformer. $3.5A$ GIC on secondary side.

3.4 Power supply and load

AC power supply All of the final results were taken with a $200kVA$ synchronous generator as power supply, since this was the power supply that provided the least contaminated voltage. Apart from this synchronous generator, both the $127V$ grid and $230V$ grid was used and driven though a variac and step up voltage transformer. However, the voltages produced from these different power supplies were a lot more contaminated, compared to the synchronous generator. This topic is further discussed in section 4.1.

DC power supply As for the DC power supply, two $12V$ batteries were connected in series in order to create the DC offset. To easily configure the amplitude of the DC current, the batteries were connected in series with an adjustable resistance. In order not to drive a large AC current through the batteries, the batteries and resistor were connected in parallel to another adjustable resistance, this one lead parts of the AC past the batteries.

Test system load A lot of different loads were used as well. The load commonly used was an $ASEA$ transformer, which was connected to the secondary side of the transformer during the experiments, see Figure 3.1. Apart from the $ASEA$ transformer, one $ASEA$ load capacitor and one $Tramo-etv$ load inductor was used. The resistors connected in parallel and series with the battery can also be seen as a load, since some of the AC current flowed here as well.

Chapter 4

Experiments - steady state

4.1 Hysteresis curve for transformers

The hysteresis curve shows the magnetic characteristics of the transformer, both in the saturated and unsaturated area. In order to determine the hysteresis curve of the transformers, measurements were made of the primary current and secondary voltage. Two methods were used in order to obtain the hysteresis curve. The first and most simple one was to phase shift the voltage 90° and plot the shifted secondary voltage on the Y-axis and the primary current on the x-axis (Figure 4.1). The second method was to numerically integrate the secondary voltage. A plot was made with the integrated secondary voltage on the Y-axis and the primary current on the X-axis (Figure 4.2). As the figures show, the voltage almost stationary for very high and low currents meaning the flux almost completely stops to increase as the core reaches the boarder to saturation.

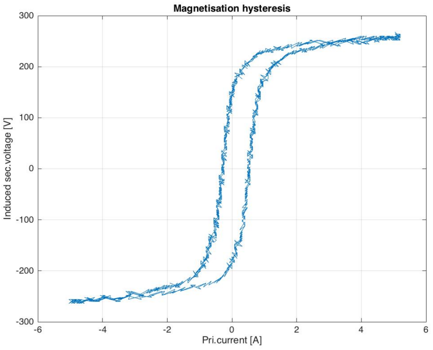


Figure 4.1: Phase shifted voltage for a single phase transformer

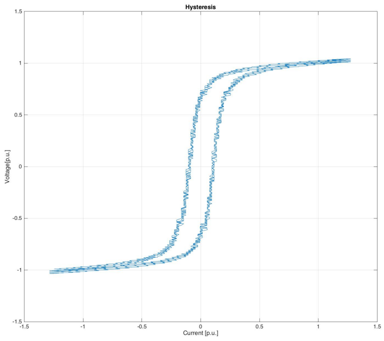


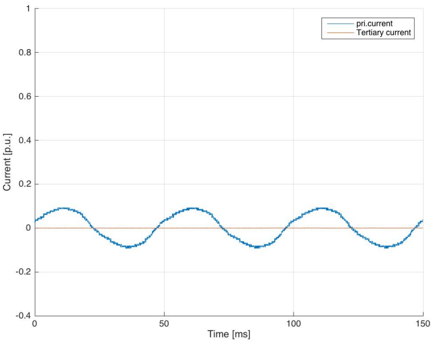
Figure 4.2: Numerically integrated voltage for a single phase transformer

4.2 GIC impact in transformers

As the GIC flows through the transformer windings, either on the primary or secondary side, depending on where it was induced, it will create a flux with the same direction in every phase of the core, as this DC flux acts equally in every phase. As this behaviour creates a flux offset in the core, the core will easily become saturated when the flux from the AC and the flux from the DC offset have the same direction. A number of tests were performed on each transformer in this section in order to compare the transformers behaviour with and without a DC offset.

4.2.1 Single phase transformers

The single phase transformers were tested with and without GIC, see Figure 3.1 without any compensation windings, in order to see the impact the GIC has on the transformers without any attempts of mitigation.



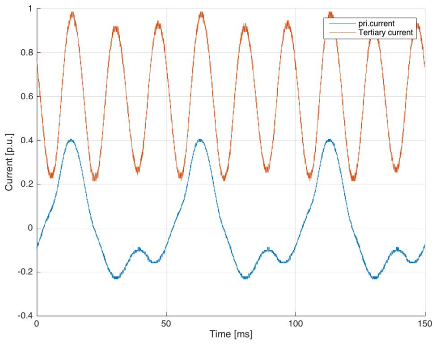


Figure 4.3: Primary and tertiary current without GIC and compensation

Figure 4.4: Primary and tertiary current with $3.5A$ GIC, without compensation.

Comparing Figures 4.3 and 4.4 shows that, the GIC has a considerable impact on the primary current, as the DC offset partially saturates the core and the AC waveform gets distorted. In Figure 4.4 a third harmonic is visible in the tertiary winding current. This third harmonic is a result of the saturation of the transformer cores. When a transformer is driven into saturation the AC waveform becomes distorted and contains both even and odd harmonics, [11]. This second harmonic is present in the primary current, but is really hard to distinguish in the waveform. Therefore, a Fast Fourier Transform (FFT) was performed to determine the spectral content of the waveform. This clearly shows the presence of the 2nd harmonic (100Hz), (Figure 4.5). Note that deep saturation does not give rise to a third harmonic, but rather to a sixth harmonic in the tertiary winding, this is slightly visible in Figure 4.5.

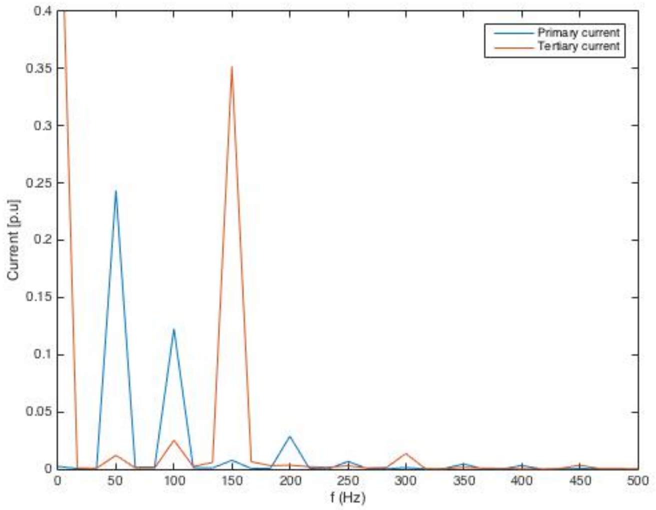


Figure 4.5: FFT without compensation

The phenomenon that causes the third harmonic, of the tertiary current, is the saturation of the fluxes in three legs of the transformer, which are phase shifted 120°. As the three tertiary windings are connected in series, the same current will flow in all three windings. There is one winding around the center leg of each transformer, in other words, one winding around the center leg of each phase. As saturation of the core results in a current spike in the tertiary windings as well as for the primary windings, the series connected tertiary windings will see a current spike every time the core for each phase gets saturated. Which is three times per period, since it is a 3-phase system. This also gives rise to smaller third harmonic in the primary winding.

The sixth harmonic that was mentioned earlier will later be discussed more deeply. When the transformer core goes into deep saturation, each phase will give rise to a second harmonic [11]. Meaning phase A will have a spike at 0° and 180°, phase B at 120° and 300°, phase C at 270° and 60°. Which when connected in series, will result in a sixth harmonic.

4.2.2 Three-legged transformer

The same laboratory tests were performed on the three-legged transformer, in order to see how this transformer responded to GIC.

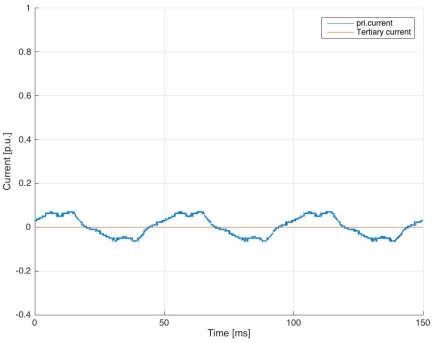


Figure 4.6: Primary and tertiary current without GIC and compensation

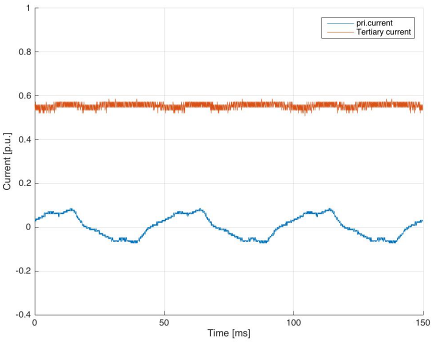


Figure 4.7: Primary and tertiary current with 3.5A GIC, without compensation.

Comparison of Figures 4.6 and 4.7 shows that the three-legged transformer is hardly affected by GIC. This is a great contrast to the single phase transformers, 4.3 and 4.4.

4.2.3 Five-legged transformer

Finally, the tests were performed on the five legged transformer, see Figure 4.8 and Figure 4.9. The GIC had a huge impact on this transformer, as the outer legs of the transformer provide a low reluctance path for the flux created by the GIC. There is also a very visible third harmonic in the primary current, both with and without GIC.

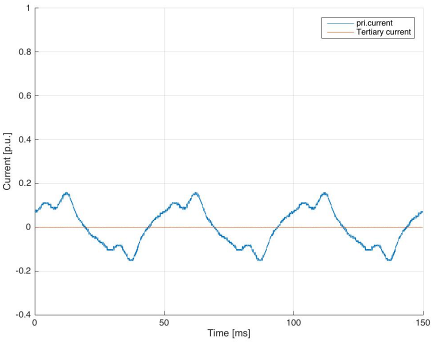


Figure 4.8: Primary and tertiary current without GIC and compensation

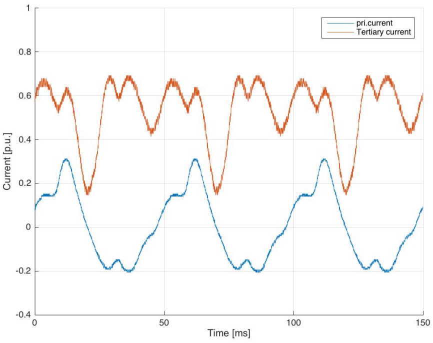


Figure 4.9: Primary and tertiary current with 3.5A GIC, without compensation.

4.2.4 Harmonics in transformers without GIC

As Figures 4.6 and 4.8 show, the primary current is not only a 50 Hz fundamental. When doing a FFT on these currents, Figures 4.10 and 4.11 show that there is a third, fifth and seventh harmonic in the case without GIC. As there is no load on the transformers and no faults or disturbances during the tests, these harmonics are assumed to be a result of transformer design not being fully symmetric as desired. The results of the single phase transformers are a lot better, see Figures 4.3, 4.6 and 4.8. Due to this fact, the experiments, and thus also the simulations, will focus on the single phase transformers.

This is also the transformer type used in the simulations made by Boteler and Bradley [8] which allows comparison with their results.

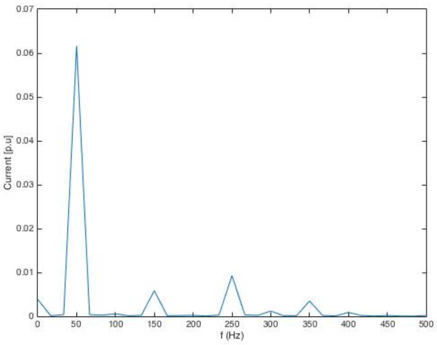


Figure 4.10: FFT, Three legged transformer

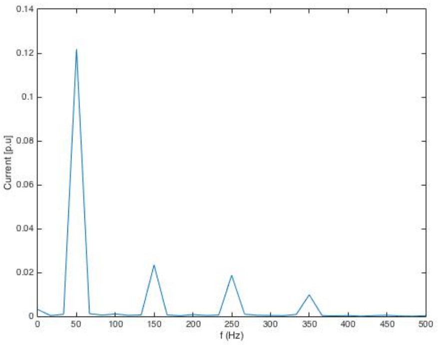


Figure 4.11: FFT, Five legged transformer

4.3 GIC mitigation in transformers

This part will compare the GIC mitigation that will be produced by different number of turns on the compensation windings.

The GIC is running through the secondary windings in parallel. The normally delta connected tertiary windings are opened and one end is connected to the neutral point of the secondary winding and the other end to ground, changing the purpose of these tertiary windings from zero sequence current compensation to GIC compensation, see this reconfiguration in Figure 4.12 This results in three times as large DC in every compensation winding compared to every secondary winding. Hence, tertiary windings with one third of the voltage of the secondary windings will lead to perfect flux compensation of the GIC. This is assuming that the GIC is led through the tertiary winding in the opposite direction of the secondary winding. If the tertiary winding has less than a third of the voltage of the winding which the GIC is led through, the GIC will only be reduced and not completely eliminated. If the tertiary winding has more than a third of the voltage of the winding which the GIC is led through, it will overcompensate. This leads to a saturation at the opposite side.

In this section under-compensation, perfect-compensation and over-compensation will be studied on the three different transformer types.

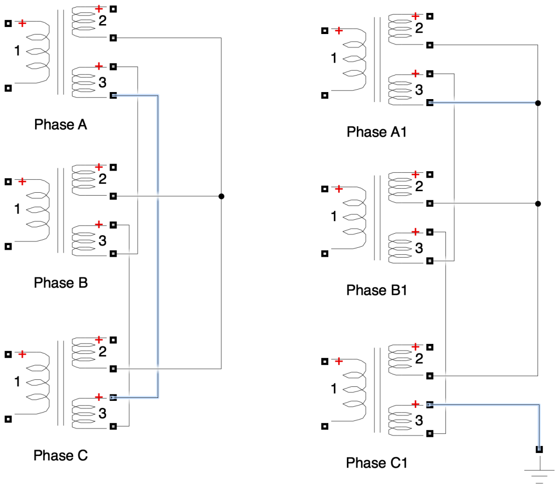


Figure 4.12: Reconnection from delta to compensation winding

4.3.1 Single phase transformers with compensation winding

To achieve perfect compensation the compensation winding would have to have one third of the voltage of the winding that is exposed to the GIC.

$$\frac{3 * 42V}{127V} = \frac{126V}{127V} \approx 1$$

This was examined in the lab, and the result was just as expected, perfect compensation, see Figure 4.13.

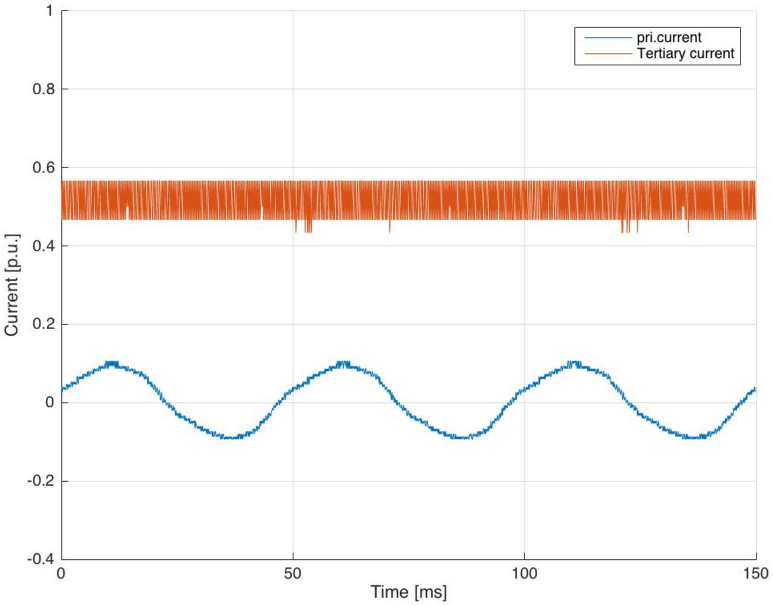


Figure 4.13: Primary and tertiary currents in a single phase transformer with perfect compensation

A slight under compensation was tested, where the GIC was led in through the secondary side of the transformer, which was marked as $127V$. The tertiary winding used as a compensation winding was marked as $31V$. As the GIC is led in series through the compensation windings, and in parallel through the secondary winding, the compensation ratio will be:

$$\frac{3 * 31V}{127V} = \frac{93V}{127V} \approx \frac{3}{4}$$

Hence, three quarters of the GIC impact is compensated. Meaning the impact of $4A$ GIC when compensated, will have the same affect as $1A$ uncompensated, see Figure 4.14

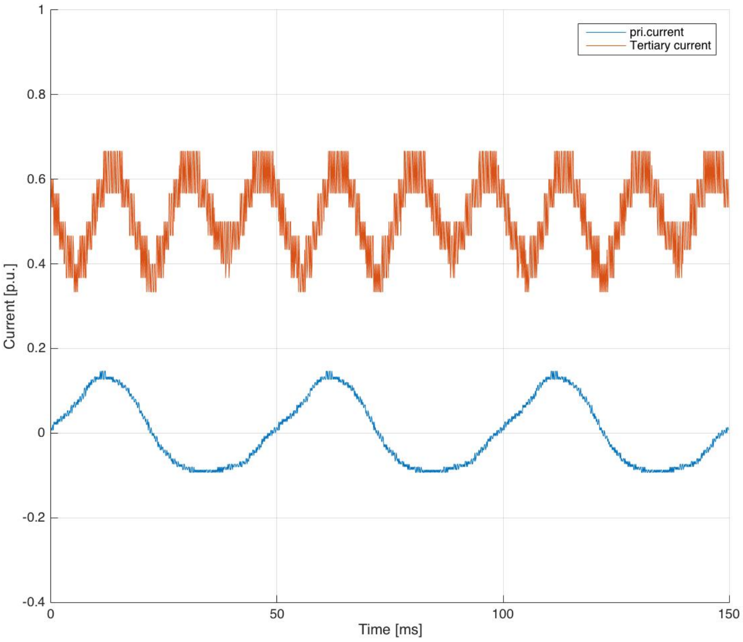


Figure 4.14: Primary and tertiary currents in a single phase transformer with three fourths mitigation

Finally a test was conducted with over compensation. The DC offset was led through the secondary 127 volt winding as before, but instead of using a $31V$ compensation winding, a $73V$ compensation winding was used. This results in a compensation of

$$\frac{3 * 73V}{127V} = \frac{219V}{127V} \approx \frac{7}{4}$$

This over compensation is very visible on the primary current, as it now peaks on the negative side, instead of the positive, see Figure 4.15.

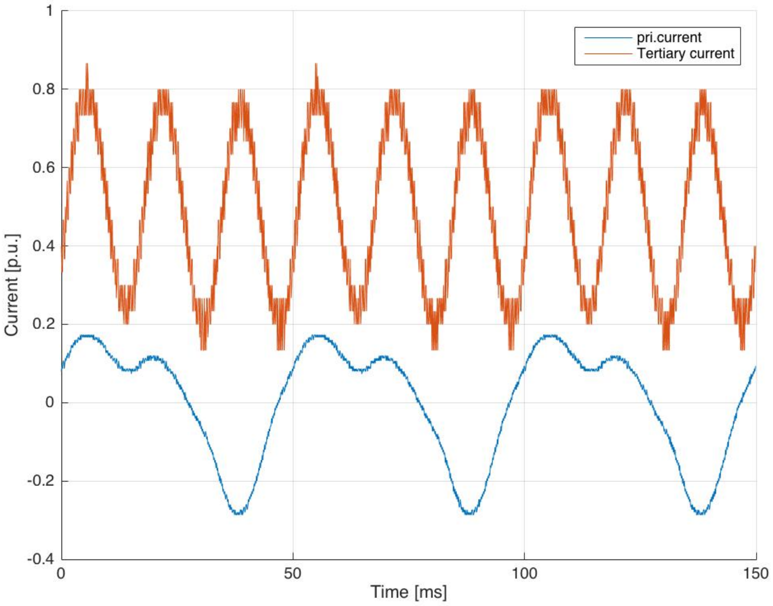


Figure 4.15: Primary and tertiary currents in a single phase transformer with seven fourths compensation

4.3.2 Three-legged 3-phase transformer with compensation winding

The same tests as for the single phase transformers were carried out for the three legged 3-phase transformer. As the DC offset had nearly no impact on the transformer when uncompensated, no difference in the result was expected when a compensation was implemented, as there is not really a disturbance to compensate for.

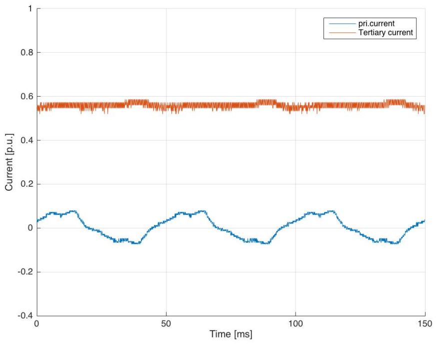


Figure 4.16: Primary and tertiary currents in a three-legged 3-phase transformer with three fourths compensation

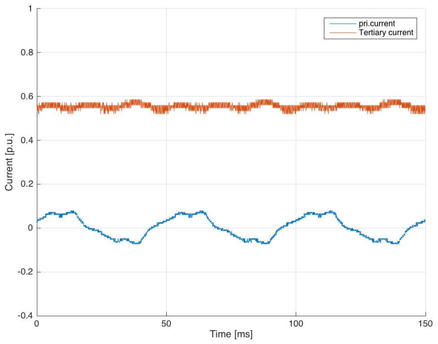


Figure 4.17: Primary and tertiary currents in a three-legged 3-phase transformer with seven fourths compensation

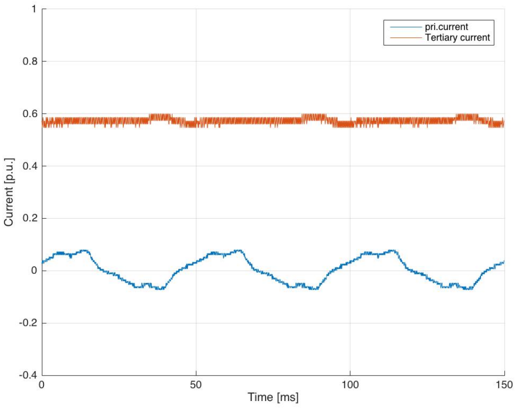


Figure 4.18: Primary and tertiary currents in a three-legged 3-phase transformer with perfect compensation

As expected, there is no visible difference between the different compensations, as the GIC has no visible effect on this transformer.

4.3.3 Five-legged transformer with compensation winding

Finally the same laboratory tests were carried out for the five legged transformer. Just as for the single phase transformer, the compensation windings had a great positive impact on the primary current. However there is a rather big third harmonic in the primary current, which is not due to the DC offset, as it is also visible for the measurement without both DC offset and load.

The perfect compensated transformer has the same primary current as when with no DC offset, see Figure 4.19 and Figure 4.30. The wave form of a partially compensated transformer is almost equally good as for a perfectly compensated transformer, see Figures 4.19 and 4.20 This shows that a partial compensation is a great improvement compared to the uncompensated transformer.

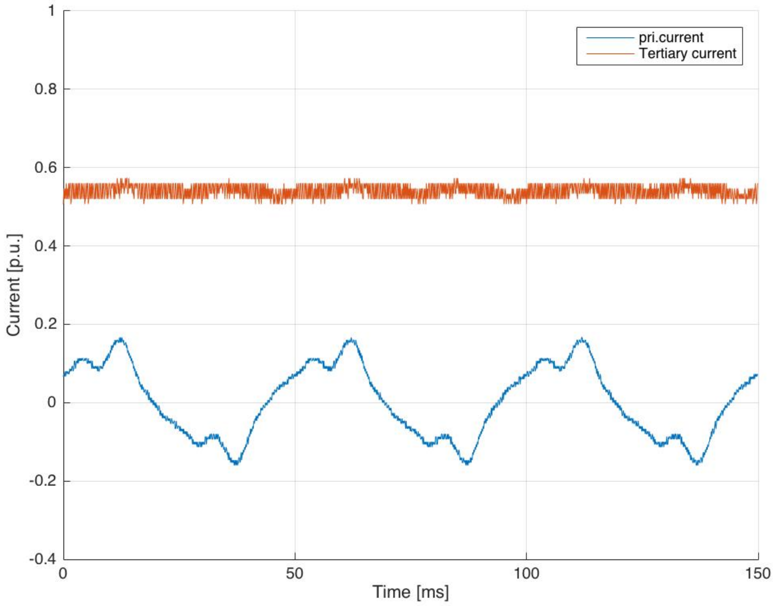


Figure 4.19: Primary and tertiary currents in a five-legged 3-phase transformer with perfect compensation

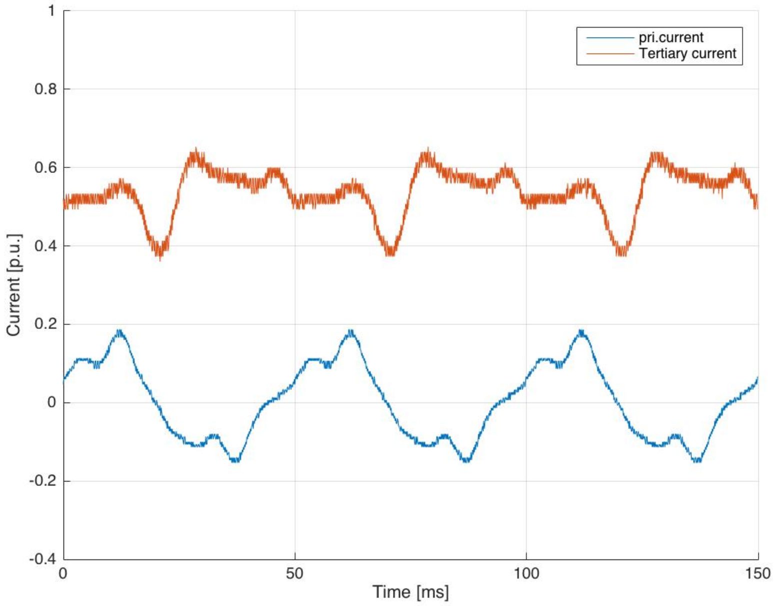


Figure 4.20: Primary and tertiary currents in a five-legged 3-phase transformer with three fourths compensation

As Figure 4.20 shows, this is a great improvement from the uncompensated trans-

former. However, the third harmonic is still very visible.
The final Figure 4.21 concerning mitigation of GIC, the over compensation was executed on the five legged transformer. The result was as expected, negative current spikes on the primary current and a very visible third harmonic.

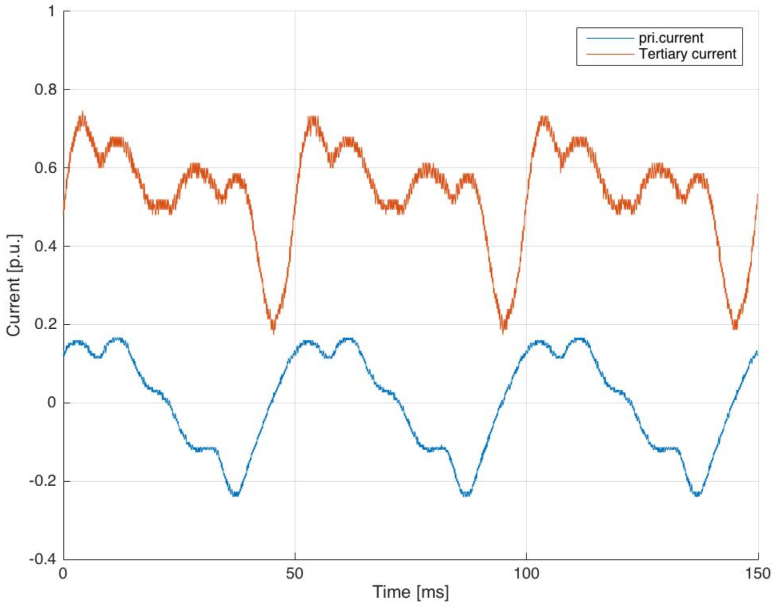


Figure 4.21: Primary and tertiary currents in a five-legged 3-phase transformer with seven fourths compensation

4.4 Comparison

In order to more easily compare of the mitigating effect that different number of turns on the compensation winding provides, plots with the same GIC and different configurations of compensation windings are compared more closely in this section. We chose not to compare with the plots where the compensation winding was overcompensating, as this is not likely to happen in reality.

4.4.1 Single phase transformer

There is a very visible third harmonic in the tertiary current, which is most likely a result of the core saturation that occurs once every cycle for each phase. As visible in the Figures 4.22, 4.23, 4.24, 4.25, the amplitude of the harmonic decreases as the GIC induced flux is compensated and no saturation occurs, leaving no third harmonic when the GIC is perfectly compensated. As seen in Figure 4.5 there is a clear second harmonic in the primary windings, apart from the obvious fundamental frequency. This is a result of deep saturation, which also can be seen from the slight sixth harmonic in the compensation windings.

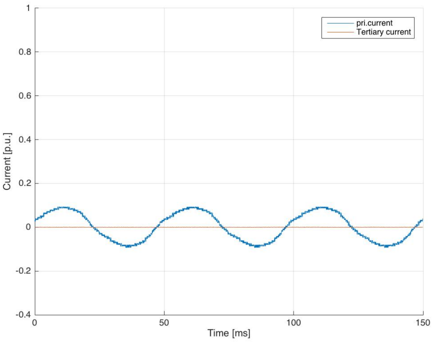


Figure 4.22: Primary and tertiary currents in a single phase transformer without GIC and compensation

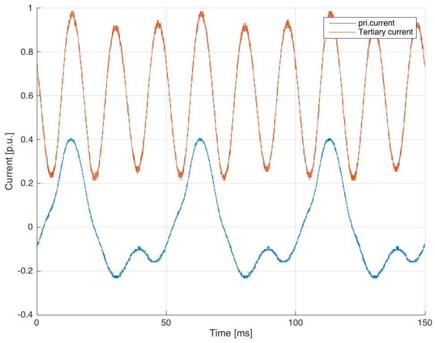


Figure 4.23: Primary and tertiary currents in a single phase transformer with 3.5A GIC, without compensation

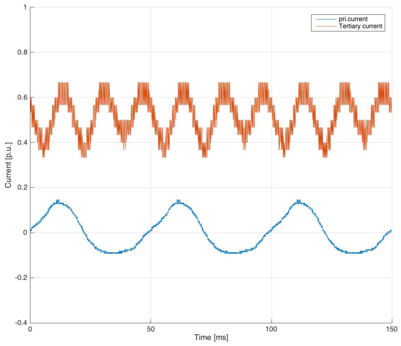


Figure 4.24: Primary and tertiary currents in a single phase transformer with 3.5A GIC and three fourths mitigation

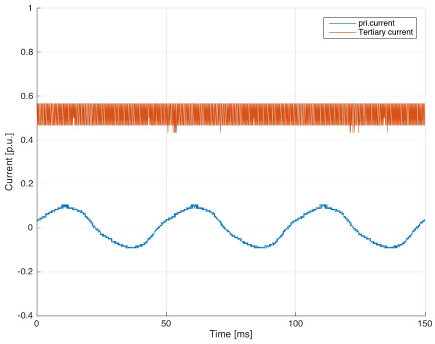


Figure 4.25: Primary and tertiary currents in a single phase transformer with 3.5A GIC and perfect mitigation

4.4.2 Three legged 3-phase transformer

The three legged 3-phase transformer shows no visible change of the primary currents when the GIC is applied in the tertiary windings, see Figures 4.26, 4.27, 4.28, 4.29. This is due to the fact that it is very hard for a DC offset to drive a three legged 3-phase transformer into saturation, as there is no available leg for the extra flux to return through. This design makes the three legged transformer superior to the other transformers, when it comes to handling GIC. However the primary current in the plots is not a nice sinusoidal current. This has nothing to do with the fact that we were using a three legged 3-phase transformer. But rather that the transformer is designed in a way that it slightly saturates when operating at nominal voltage.

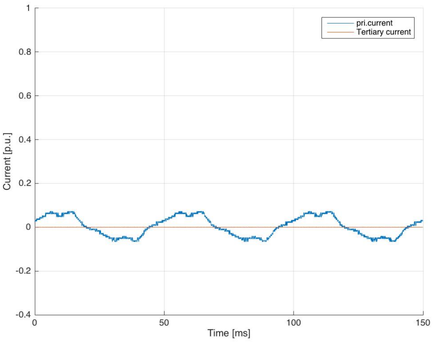


Figure 4.26: Primary and tertiary currents in a three legged 3-phase transformer without GIC and compensation

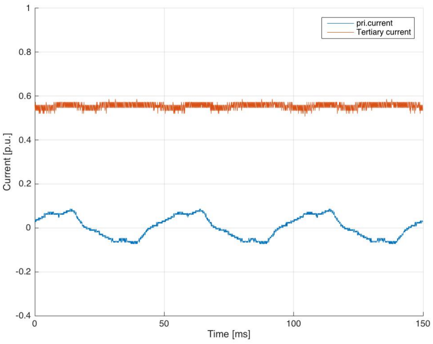


Figure 4.27: Primary and tertiary currents in a three legged 3-phase transformer, with 3.5A GIC and without compensation

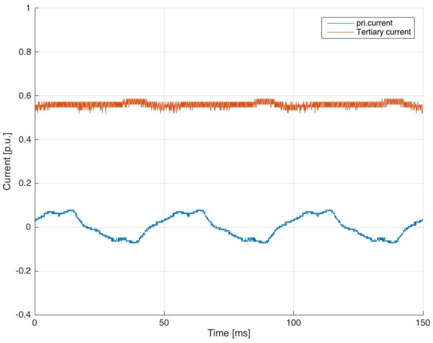


Figure 4.28: Primary and tertiary currents in a three legged 3-phase transformer, with 3.5A GIC and three fourths mitigation

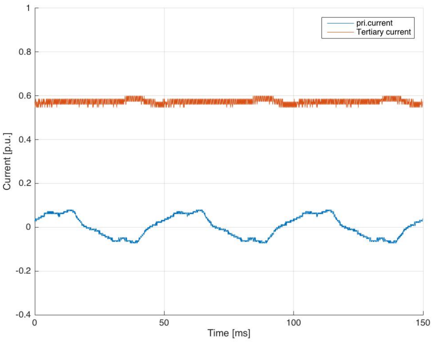


Figure 4.29: Primary and tertiary currents in a three legged 3-phase transformer, with 3.5A GIC and perfect mitigation

4.4.3 Five legged 3-phase transformer

Finally, the five legged transformer showed the same problem with the primary current at nominal voltage and no DC offset as the three legged did. However, the difference between these two transformers is that the five legged transformer handles the DC offset a lot worse than the three legged, as there are two outer legs where the flux induced by the GIC can return. Compared to the three single phase transformer, the negative effects of the GIC are similar, as there are paths for the DC induced flux to return in both cases. But as the Figures 4.22, 4.23, 4.24, 4.25 compared to 4.30, 4.31, 4.32, 4.33 shows, the single phase transformer had a lot less trouble with harmonics, this is most likely due to the fact that the single phase transformer are better designed than the five legged transformer. As in the case where a five legged transformer is well designed, it does not go into saturation at nominal voltage and no load.

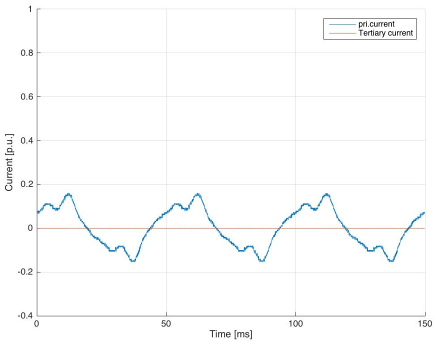


Figure 4.30: Primary and tertiary currents in a five legged 3-phase transformer without GIC and compensation

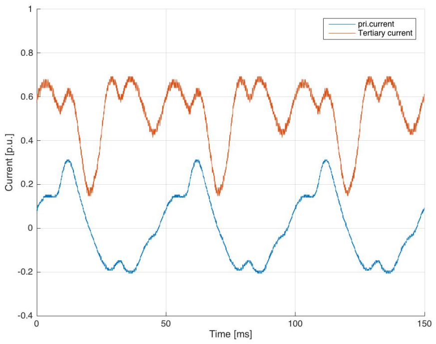


Figure 4.31: Primary and tertiary currents in a five legged 3-phase transformer, with 3.5A GIC and without compensation

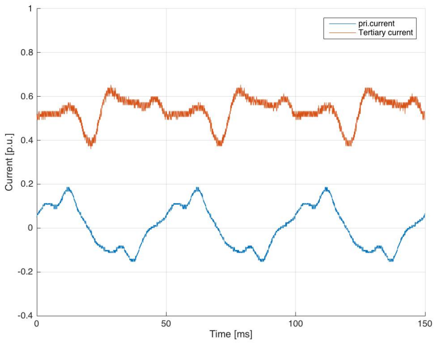


Figure 4.32: Primary and tertiary currents in a five legged 3-phase transformer, with 3.5A GIC and three fourths mitigation

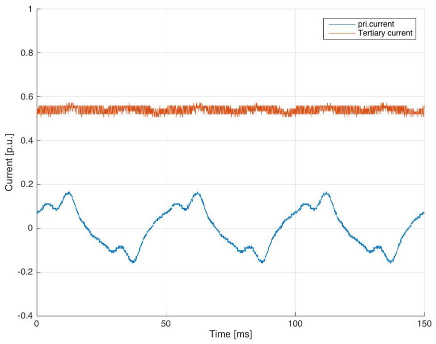


Figure 4.33: Primary and tertiary currents in a five legged 3-phase transformer, with 3.5A GIC and perfect mitigation

Chapter 5

Experiments - transients

5.1 GIC step response

A GIC step response was performed with a bank of three single-phase transformers. The purpose of the test was to compare it with Boteler and Bradleys simulations [8] of the same type of input. Boteler and Bradley [8] introduce the effective inductance, which is the inductance value averaged over one cycle. In the case where the core is unsaturated through the whole period, the effective inductance is very large resulting in a very high time constant for the GIC. When the core enters periodical saturation, the effective inductance is reduced. The large quote of the period that is saturated, the lower the effective inductance became allowing the flow of GIC to drastically increase, due to core saturation. As the GIC voltage step was made in [8] simulations, there is no significant increase of current until the transformer core started to partially periodically saturate. As the time constant for the GIC was very large before the core starts to saturate, almost 2 seconds from the time of the step before the GIC grown large enough to drive the core into saturation, see Figure 5.2. This results in a drop of effective inductance and a lowered time constant for the GIC, see Figures 5.2 and 5.3. The GIC is almost perfectly stationary up to the time where the effective inductance drops, this is due to the high inductance of $3500H$ of the transformers in the simulations.
As the simulations made by Boteler and Bradley only were performed for single phase transformers, the experiments were only performed on single phase transformers as well, as test without comparison is pointless.

Since the laboratory 2kVA single phase transformers has a lot lower inductance, it will be impossible to achieve the same step response as in the simulations. However, looking for similar behavior is not impossible and will strengthen the conclusions made by Boteler and Bradley [8]. See Figures 5.1, 5.2, 5.3.

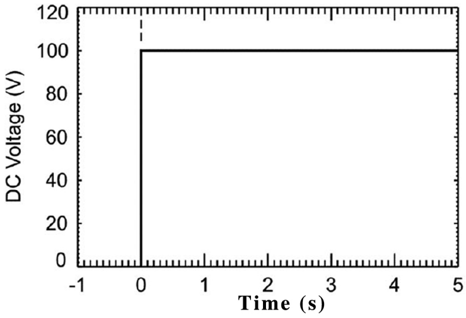


Figure 5.1: Voltage step

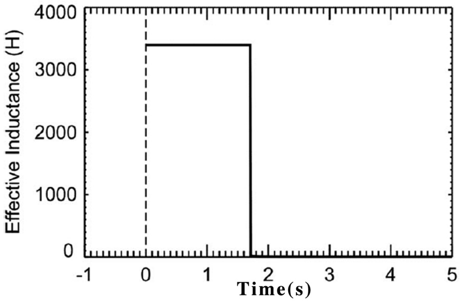


Figure 5.2: Inductance drop

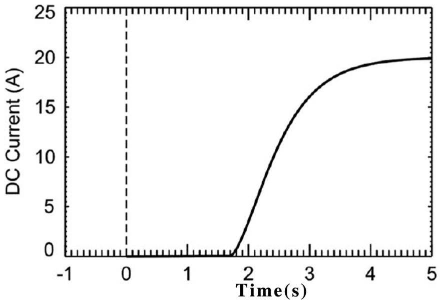


Figure 5.3: DC step

5.1.1 Without GIC mitigation windings

Experiments were first performed without any type of GIC mitigation windings, which is the same set up as in the simulations in [8]. The experiments were performed with $50V$,$100V$,$150V$ and $200V$ AC phase to ground voltage, where it is expected that higher AC voltage will earlier saturate the core. This resulted in a lower effective inductance for higher AC voltages. The DC offset is visible in Figure 5.4.

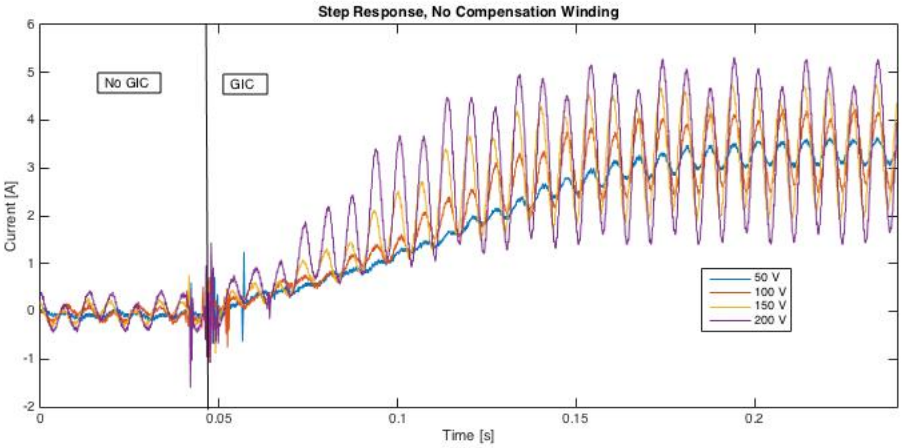


Figure 5.4: Step response

It is quite hard to discern the form of the curves from this plot, and as the interesting part of this experiment is the behaviour of the step response as the inductance of the transformer is reduced, a low pass filter was applied to the data. This gave the result, shown in Figure 5.6. In order to not introduce phase shift in the low pass filtered curve, the filtration was made in both directions. Meaning first one filtration that starts at time zero and ends at the end time, then a filtration that starts at the end time and ends at time zero. This method is only possible since the filtration is not made in real time, as this type of filtration is non causal. The result of the filtration can be seen in Figure 5.5.

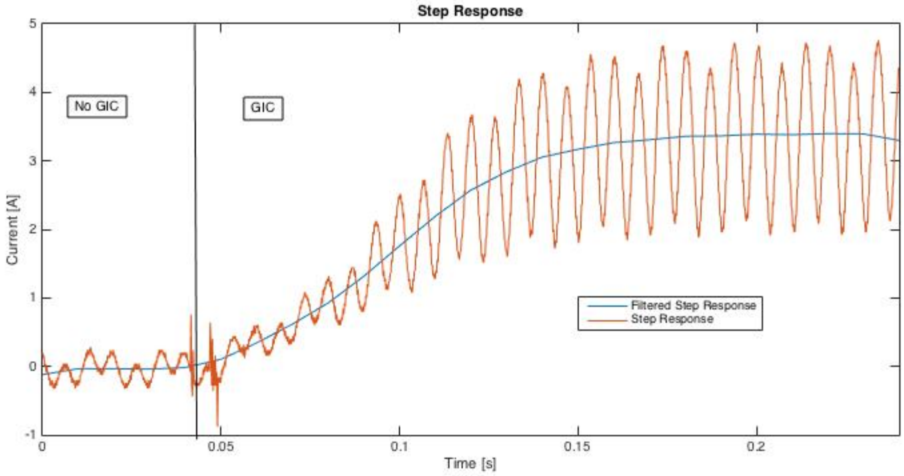


Figure 5.5: Step Response 150 V, filter and no filter

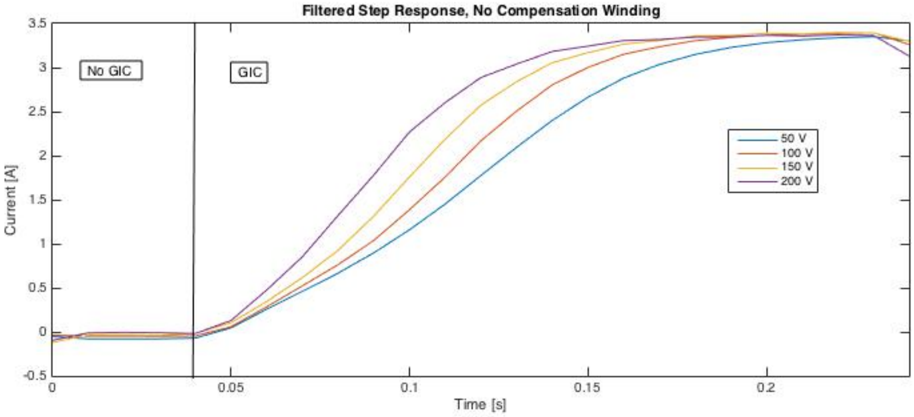


Figure 5.6: Step response with low pass filtration

As Figure 5.6 shows, the current does not have the highest derivative at the time of the voltage step, but slightly later, when the inductance of the transformer has been lowered, due to saturation.

The stationary DC current is on the same level as the GIC we provide the system with. This is expected since there is no other way for the GIC to travel than through the tertiary windings.

The fast variations in Figure 5.4 appear to be a third harmonic. In order to confirm this, an FFT was made. As Figure 5.7 shows, the largest spike was at $150Hz$, which is the frequency of third harmonic. The first harmonic of the system can also be seen at $50Hz$. At $0Hz$, the amplitude is really large, but not of interest, this is due to the steady state value of the step, which can easily be seen without FFT in Figure 5.4.

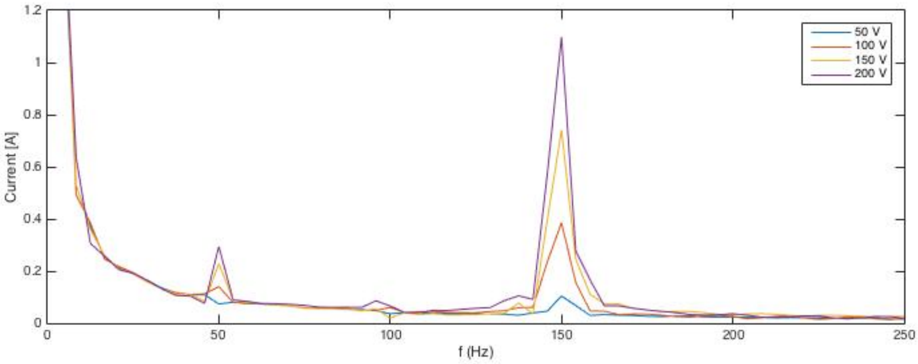


Figure 5.7: FFT of step response

5.1.2 With GIC mitigation windings

Following, the laboratory studies were performed with the compensation windings. $31V$ at the compensation windings and $127V$ at the secondary windings, where the GIC is led into the system. As the compensation windings are of the opposite direction around the core compared the secondary windings, the GIC would most likely see less inductance when not saturated, leading to a smaller inductance difference when the core reaches saturation. As the experiments were performed this anticipation was confirmed.

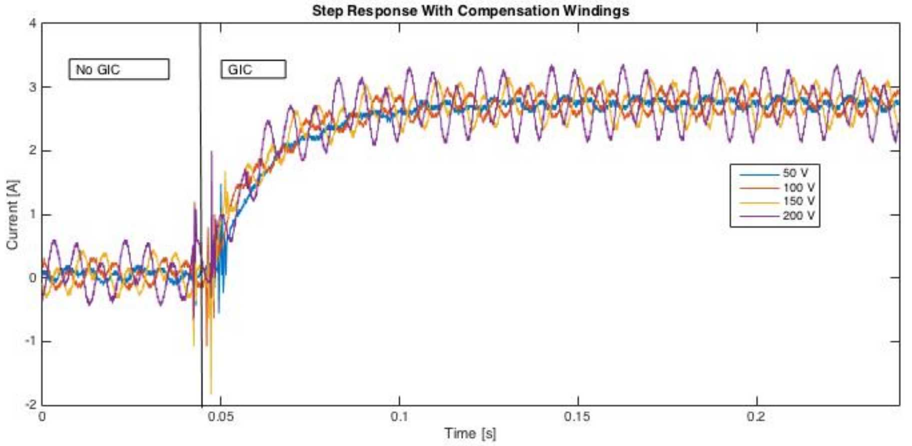


Figure 5.8: Step response with mitigation windings

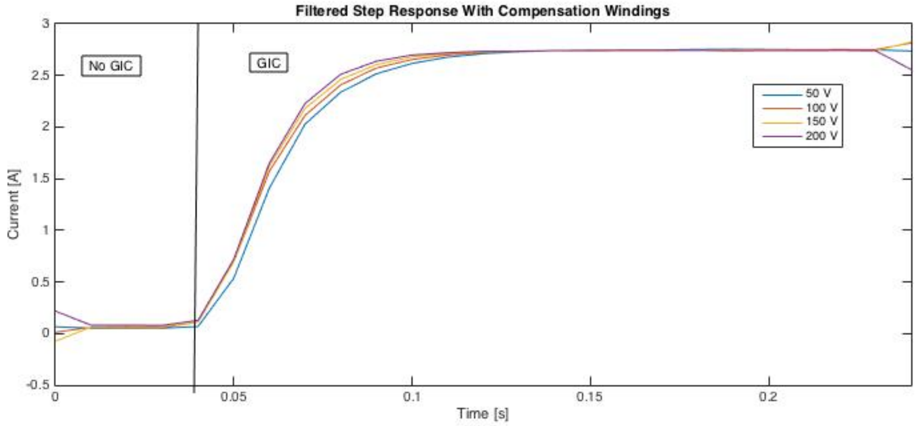


Figure 5.9: Step response with mitigation windings and low pass filtration

When comparing Figure 5.8 and Figure 5.9 with Figure 5.6 it is very clear that the inductance is higher early on in Figure 5.6. This make it a lot easier to see the phenomena that was discussed by Boteler and Bradley [8].

5.1.3 With reversed GIC mitigation windings

In order to make the impact of the inductance on the GIC even more clear, the compensation windings were connected so the current rotated in the same direction around the core in both the compensation and secondary winding. This increases the inductance of the transformer seen by the GIC and the core will saturate at even lower levels of GIC. This allowed us to see the impact of the core saturation on the GIC even more clearly, see Figure 5.11. Note that the time scale is larger, due to the long step response.

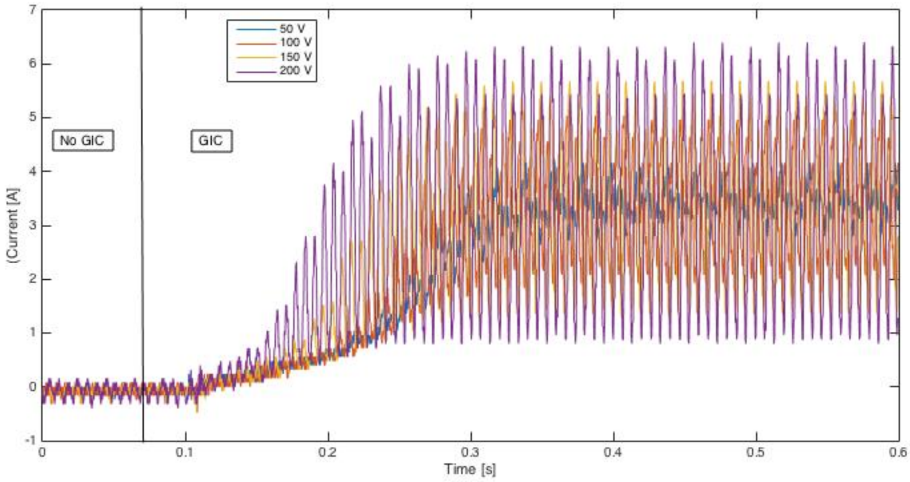


Figure 5.10: Step response with mitigation windings

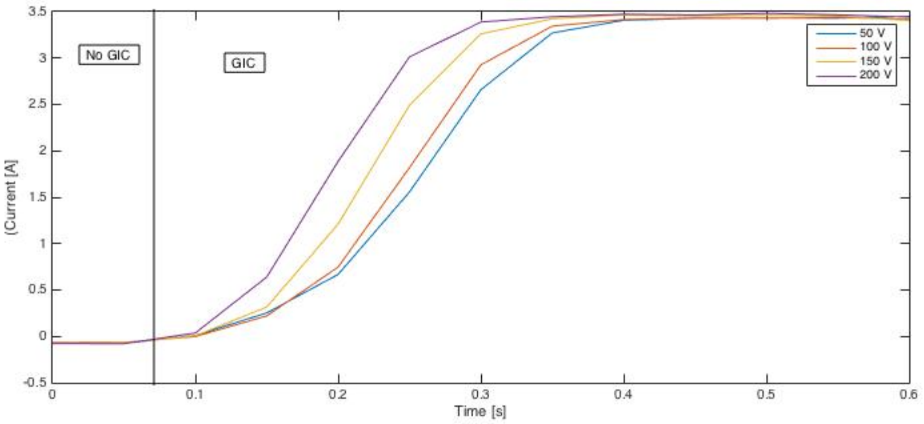


Figure 5.11: Step response with mitigation windings and low pass filtration

5.1.4 Summary

As seen in section 4.6, the larger inductance, seen from the GIC point of view, the longer it takes before the GIC reaches its steady state value. However, when the inductance is larger, the amplitude of the magnetic flux will also be larger. As discussed earlier in this chapter, the time constant for the step increases in proportion with the inductance seen from the GIC, as well as the magnetic flux which also increases proportionally to the inductance. This results in that the rate of the saturation will increase equally fast no matter what inductance that is seen from the GIC. However, it will increase for a longer period of time with a large inductance, resulting in the core reaching deeper saturation for higher inductance.

As there is a lot of third harmonic, it is a bit hard to see what is actually happening and all trust has to be put on the filtered signal. In order to see what really is happening without using a filter, the same test will be performed again, but with only one phase connected. This is not commonly used in reality, but was used by Boteler and Bradley [8] and will help get a better look into the current step of the single phase transformer.

5.2 One phase GIC step response

In order to remove the disturbance of the third harmonic when investigating the step response, two phases were disconnected and the experiments of section 4.5 where executed for only one phase instead of three phases. This laboratory study will mostly be comparable with the simulations in [8], as they only used one phase in their simulations. However, the experiments of section 6.4 is more applicable on a real case scenario, as the majority of power transformers are working with three phases.

5.2.1 Without GIC mitigation winding

Just as anticipated, there was no third harmonic. However, the measurements still had to be filtered, as the fundamental was large at the point of saturation. Which makes it hard to distinguish the DC current step.

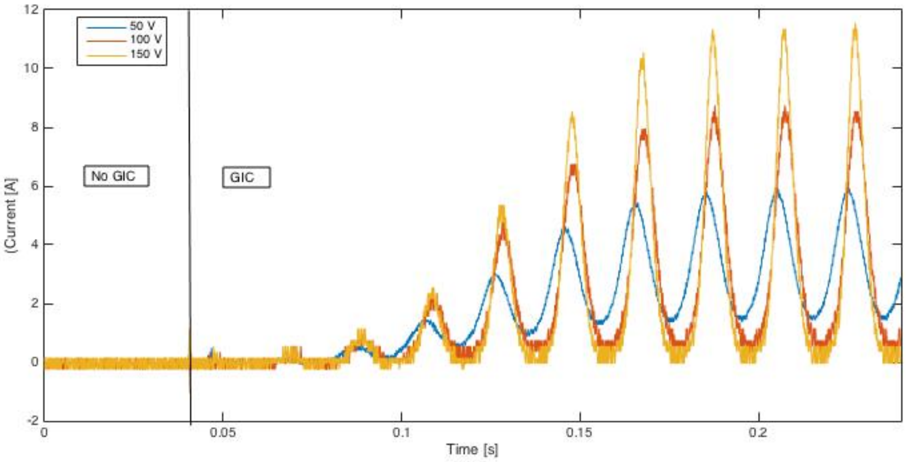


Figure 5.12: Step response without mitigation windings, one phase only

When filtered, the same behaviour of the time constant accrues as in section 4.6, which was anticipated. However, there is no difference in the amplitude of the rate of change in the GIC when different AC voltages is applied on the primary side. The reason why there is no difference in the rate of current change, as a function of the primary AC voltage, has further been studied in section 4.8.

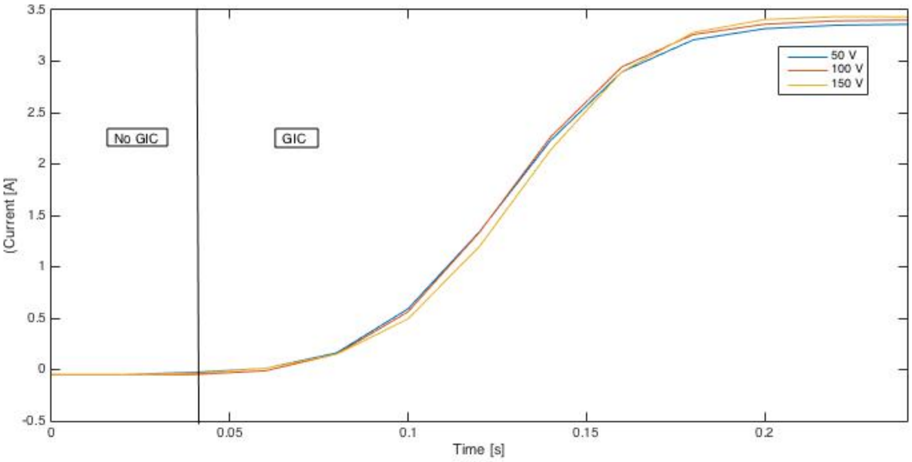


Figure 5.13: Step response without mitigation windings and low pass filtration, one phase only

5.2.2 With GIC mitigation winding

When the compensation windings are implemented the inductance seen from the GIC was anticipated to be lowered, resulting in a shorter time constant for the current step response of the GIC. However, the time constant was not visibly lowered in this case where only one phase was connected. When comparing Figure 5.11 with Figure 5.9, it is very clear to see that the compensation windings has a larger impact in reducing the inductance seen from the GIC in a 3-phase system. The reason for this is still unclear and need future studies.

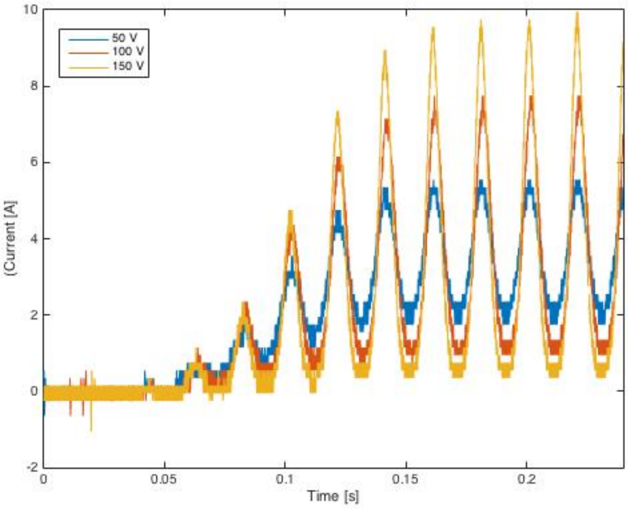


Figure 5.14: Step response with mitigation windings, one phase only

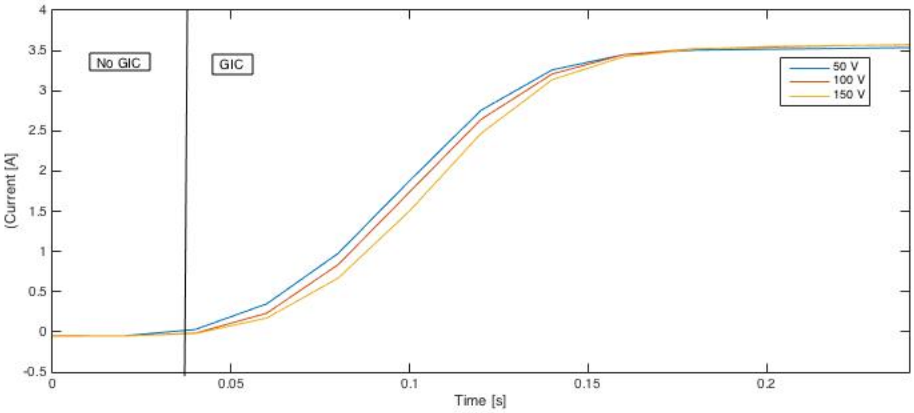


Figure 5.15: Step response with mitigation windings and low pass filtration, one phase only

5.2.3 With reversed GIC mitigation winding

Finally, as the reversed compensation windings are implemented the inductance seen from the GIC was anticipated to be increased, resulting in a longer time constant for the current step response of the GIC. However, as in the previous case, the time constant was not visibly lowered. When comparing Figure 5.15 with Figure 5.17, it is very clear that the reversed compensation windings have a larger impact in increasing the inductance seen from the GIC in a 3-phase system. Just as in the previous section the reason for this behaviour is still unclear and will need future work.

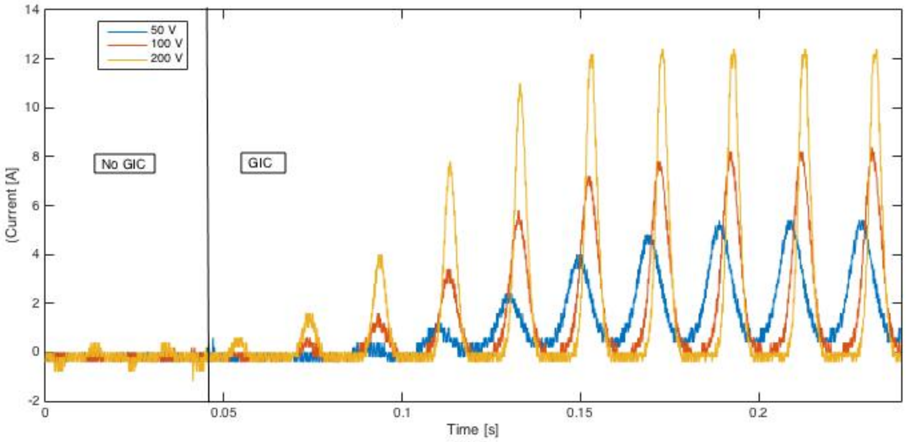


Figure 5.16: Step response with reversed mitigation windings, one phase only

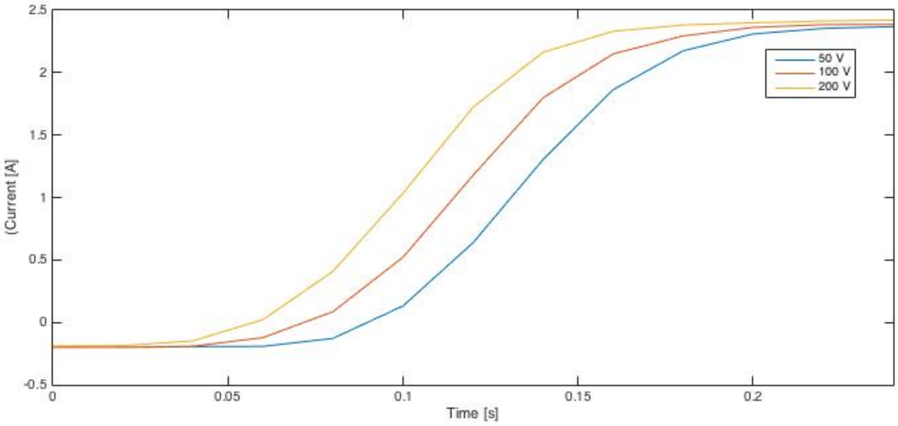


Figure 5.17: Step response with reversed mitigation windings and low pass filtration, one phase only

5.3 3-phase GIC step response with delta connected tertiary windings

As there were no difference in the growth of DC current when supplying the primary side with different voltages in section 4.7, a final scenario was tested in the laboratory. This was done in order to find out why the rate of change in the DC current was not higher with a higher primary side AC voltage. The case with delta connected tertiary windings was discussed by Boteler and Bradley, [8]. Where they discussed that transformers with delta connected tertiary windings will reach its saturation later than transformers without this delta connection. Due to the fact that the tertiary windings will counteract the flux that is induced by the DC offset according to *Lenz's law*.

$$\varepsilon = -\frac{\delta\Phi}{\delta t}$$

Another nice aspect of the tertiary windings, when delta connected, is that it compensates for the third harmonic. Low pass filtration of the GIC should therefore not be necessary.

5.3.1 No delta windings

In order to really understand what happened with the current step response when the tertiary windings are delta connected, there was first some measurements taken without the tertiary windings. The actual measurements of the experiments can be seen in Figure 5.18 and the low pass filtered measurements seen in 5.19. Just as in section 4.6, it is very clear to see that the growth of the DC offset is larger when the input voltage on the primary side of the transformer is larger. This is, as explained in 4.6, due to the fact that the effective inductance is lower when the input voltage is higher, as the time of saturation is longer with a higher input AC voltage at the primary side. The larger rate of change is due to a short time constant, which is a direct result of the lower effective inductance.

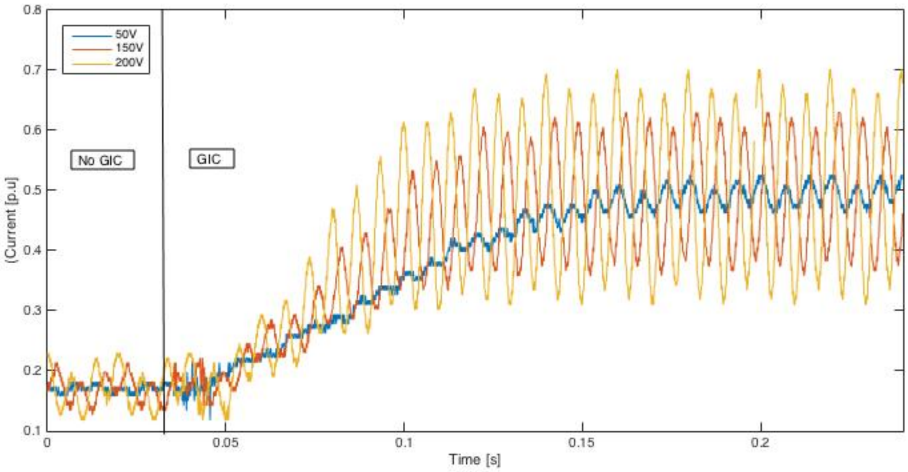


Figure 5.18: Step response without delta windings

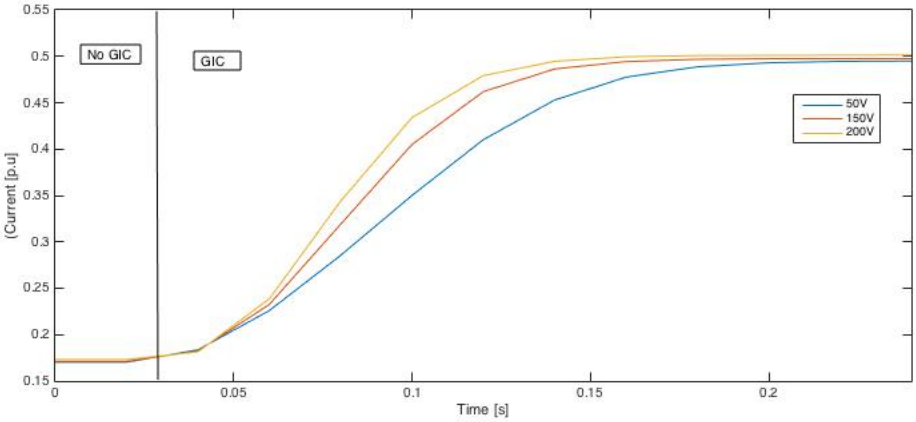


Figure 5.19: Low pass filtered step response without delta windings

5.3.2 31 Volt delta windings

As the tertiary windings were delta connected, the expected result was to see a slower saturation of the core, as the tertiary windings would counteract the flux induced by the DC offset in the secondary windings. However, when studying the results of the current step response a different conclusion can be drawn. As seen in Figure 5.20, the current step is a lot faster for the DC offset through the secondary winding, when a delta connected tertiary winding is present. This is due to the fact that the counteraction to the DC flux that is performed by the tertiary windings made the inductance of the secondary windings appear smaller seen from the DC offset. So what really happened is that for the transformer without tertiary windings, the current step is a lot slower in the secondary windings, as the magnetic inertia of the flux made the current step slow. While in the case where the tertiary windings are connected, the flux is counteracted by the opposite flux of the tertiary windings. The counteraction of the flux implies that it would take a longer time for the core to reach saturation, while the faster current step in the secondary windings imply that the core would reach its saturation faster. The conclusions that could be drawn from Figure 5.20 is that the core will be completely saturated when the current in the tertiary windings has reached its steady state of $0A$ again. A conclusion based on this theory would result in an approximately equally fast saturation of the core with and without delta connected tertiary windings. However, as there are some assumptions made in this theory, the voltage over a separate winding surrounding the core will be measured, to get a more trustworthy measurement of the flux, in order to verify this theory.

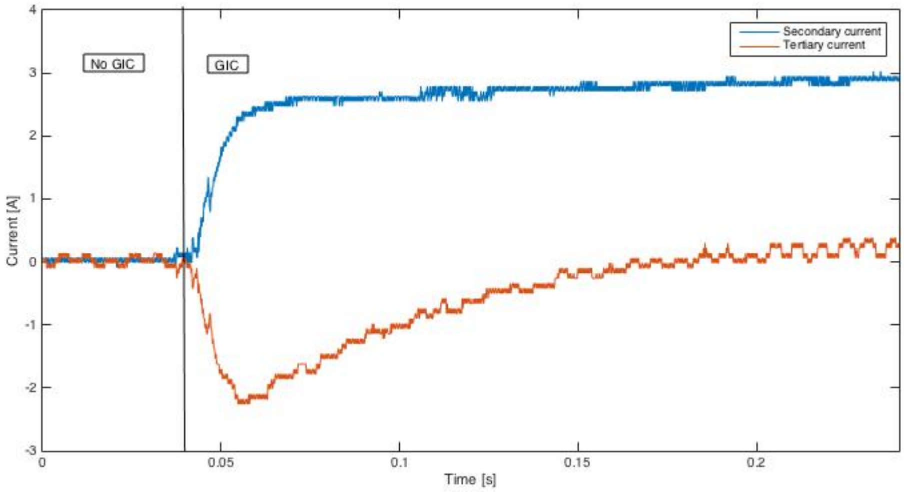


Figure 5.20: Step response for $31V$ delta windings and $50V$ AC at primary side

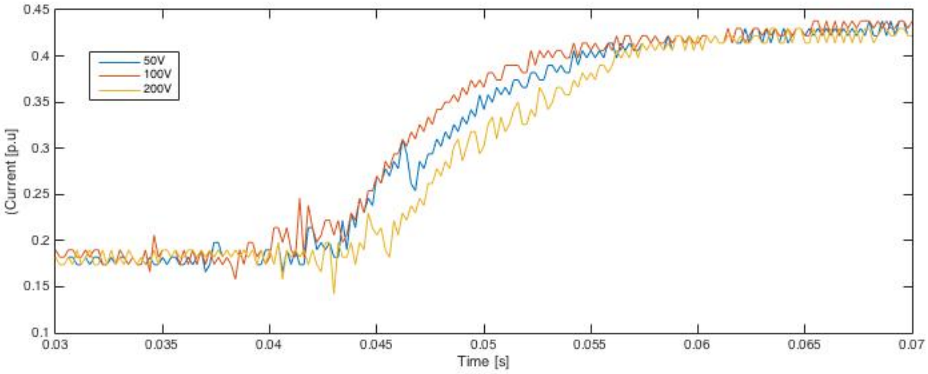


Figure 5.21: Step response with $31V$ delta windings

5.3.3 Flux measurements over unconnected winding

As Figure 5.23 shows, which is a low pass filtered version of the very noisy Figure 5.22, the voltage of the separate unconnected winding is larger for the transformer without the delta connected tertiary windings. As the voltage of these connected windings is a function linear to the derivative of the core flux, the transformer without the delta connected tertiary windings do reach its point of saturation faster, compared to the transformer with delta connected tertiary windings.

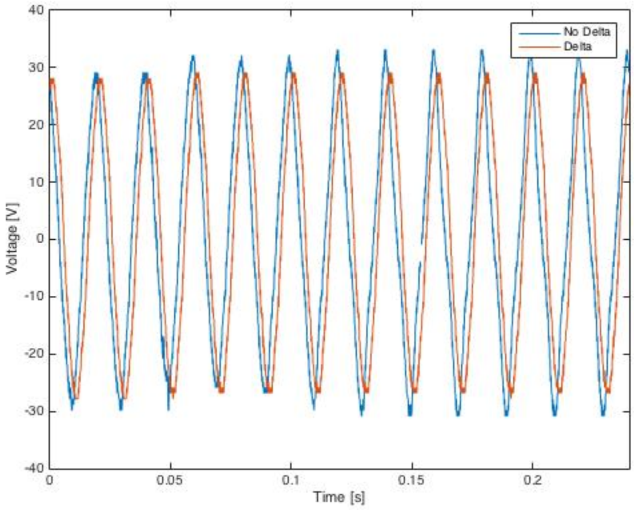


Figure 5.22: Voltage measured over separate winding in order to estimate flux

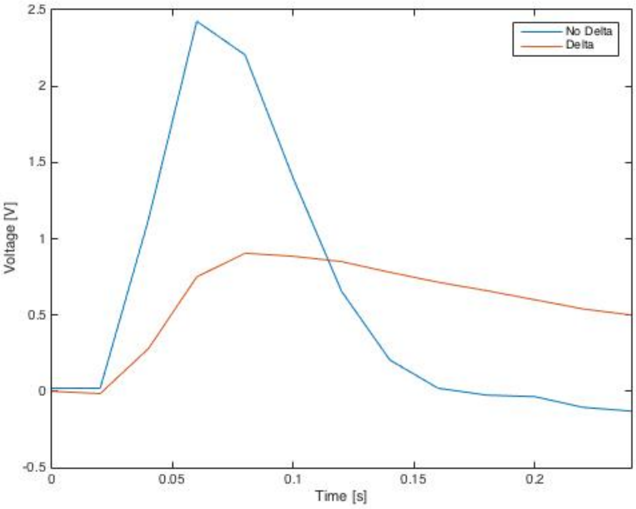


Figure 5.23: Filtered Voltage measurements over separate winding

Chapter 6

Experiment results

This chapter will discuss the results of the experiments in chapter 4, focusing on why the results became what they are and what the underlying reasons for the results are.

6.1 GIC impact on system

The impact that GIC can have on a power system, mainly through saturation of transformer cores. The half cycle saturation in the experiments gave rise to current spikes during the saturated time. It also gave rise to third and sixth harmonics as each leg of the core got saturated once per cycle. For a three-phase transformer this gives a third harmonic in the neutral. The sixth harmonic that is visible when driving the core into deep saturation is due to the fact that partial periodic saturation causes second harmonics [11]. As the saturation occur three times per cycle, this phenomenon causes a sixth harmonic which is most visible in the compensation windings, as they are connected in series with one winding around each leg of the transformer.

6.1.1 Single phase transformers

As shown in section 4.3, the single phase transformers are very vulnerable to GIC. This is due to the fact that the flux have a closed magnetic circuit to flow in, as the DC flux enters the core in the middle leg and is able to flow back in the outer legs. As the magnetic circuit always is closed for this type of transformer, the flux could correspond to the AC and DC voltages and currents that the core was exposed to, until the core reaches saturation. As the DC offset was increased, the core gradually reached saturation at the parts of the AC cycle where the flux from the AC source plus the flux from the DC source was greater than the maximum amount of flux that could be led through the core. As the flux from the AC source is alternating, this saturation only occurs when the direction of the flux from the AC- and DC source have the same direction and great enough amplitude.

6.1.2 Three-legged transformer

Compared to the single phase transformers, the three legged 3-phase transformer does not have a closed magnetic path for DC flux. The GIC enters all three phases at the same time and in the same direction, resulting in flux in the same direction in every leg. In other words, there is no leg where the flux can return, hence the magnetic circuit is not closed. As the magnetic circuit appears as an opened circuit for the DC flux, the

GIC has virtually no impact on the three legged transformer, see Figure 4.6 and 4.7. This is in contrast to the single phase- or five legged transformer, where the magnetic circuit is closed for DC flux. Worth mentioning is that the magnetic circuit appears as closed for AC flux, as the three phases are 120 degrees apart, resulting in an addition of the flux at the top and bottom of the transformer that is always zero in a balanced system. This is like three-phase currents that sum to zero at the neutral point.

6.1.3 Five-legged transformer

Just as the single phase transformer, the five legged transformer has two legs at the sides where the flux can return. This results in a closed magnetic circuit for the DC flux. Naturally this means that the five legged transformer also is vulnerable to GIC, as it saturates the core easily, just as for the single phase transformers. The result from the laboratory studies do look rather different when comparing the single phase transformers and the five legged transformer. This is due to the fact the the five legged transformer is slightly saturated already without any DC offset, probably due to different design of the transformer. This can be seen in Figure 4.8.

6.2 GIC mitigation

The tertiary winding was introduced in order to mitigate the negative impact of the GIC. As mentioned earlier this tertiary windings is already present in wye-wye transformers, where its function is to mitigate zero sequence currents. In order to do this, the tertiary windings from the three phases are simply just connected to each other in a delta configuration. In order to use these windings to mitigate the negative impact of the GIC, the delta connection has to be opened. One end was connected to the neutral point of the main windings. The other end was connected to ground. This connection allowed the GIC to flow from the main winding, which usually is the winding on the high voltage side of the transformer. Then continue to flow through the aeries connected compensation windings. As the tertiary windings are in series and the high voltage windings are in parallel, seen from the GIC, one third of the voltage in the tertiary windings compared to the high voltage windings would completely eliminate the flux induced by the GIC. This is not the ordinary voltage the tertiary windings in wye-wye transformers have, but the laboratory studies were made on a series of different voltages on the tertiary winding, which came to the conclusion that the amount of DC flux reduction in the core is proportionally related to the voltage of the tertiary windings. Complete DC flux elimination was accomplished when the tertiary winding had one third of the voltage of the high voltage winding. To more easily grasp this reasoning, the amount of flux induced in the core is dependent on the amount of current in the GIC times the number of turns it does around the core. The GIC first went in one direction around the core in the high voltage windings, then in the other direction around the core in the tertiary windings. As the tertiary windings are series connected between the neutral point of the high voltage windings and ground, the total current around each core is:

$$GIC * (\frac{n_{hv}}{3} - n_t)$$

Where GIC is the total amount of DC in all three phases, n_{hv} the numbed of turns of the high voltage windings and n_t the number of turns of the tertiary windings. As easily seen from this formula, if n_t is larger than one third of n_{hv}, the result will be negative. In reality, this corresponds to saturating the core in the other half cycle, as the core would react as if there was a GIC acting in the opposite direction.

6.2.1 Single phase transformers

Just as expected, the mitigation method with the tertiary winding proved to work very well for the single phase transformers. A partial compensation delayed and mitigated the effects of the GIC and a full compensation, meaning:

$$n_t = \frac{n_{hv}}{3}$$

resulted in no difference in the currents of the primary windings, compared to the scenario completely without GIC. Running a DC current of $1A$ through an uncompensated transformer, gave the same AC currents, in other words, the same saturation of the core, as running a $4A$ current through the transformer, when it had a compensation winding n_t that was three fourths of $n_{hv}/3$. Which further proves the statement of a linear relation between GIC flux mitigation and number of turns on the tertiary windings. Further on, an overcompensating winding was connected, which led to saturation at the other half cycle, just as expected. If the tertiary windings n_t is equal to two thirds of the high voltage windings, the compensation is exactly double of what it should be.

$$n_{hv} * n_t = \frac{2n_{hv}}{3}$$

Resulting in an equally large saturation as for no compensation, but in the other half cycle.

6.2.2 Three-legged transformer

The laboratory results of the three legged transformer with compensation windings had more or less no difference from the results without the compensation windings. This was due to the fact that the three legged transformer did not suffer any consequences from a DC offset at this amplitude, as the DC flux circuit of the transformer could be viewed as opened. In other words, the reason that the compensation had no affect on the three legged transformer was not that the compensation did not work, but rather that there was no negative affects to compensate for.

6.2.3 Five-legged transformer

As expected the compensation windings for the five legged transformer showed the same result as for the single phase transformer. However, as mentioned in section 5.1, the point of where the transformers reaches their point of saturation varies between the different transformers, resulting in not so similar looking plots. But the purpose of the laboratory study was to find how the tertiary windings affected the different transformers, and the effects of the tertiary windings was close to identical for the single phase transformers and the five legged transformer. This means very obvious reduction of the primary side current spikes as the compensation windings are connected. Full flux compensation when the compensation windings had the optimal number of turns and current spikes at the opposite side of the period when the compensation windings had too many turns around the core.

6.3 Summary of steady state

To summarize section 4.1-4.2 is that the five legged 3-phase transformer and the single phase transformers suffer negative effects as a result of GIC. These negative effects are due to saturation of the transformers core. However, the saturation can be mitigated or eliminated by leading the GIC through the transformers tertiary windings. The three legged 3-phase transformer does not get any positive effects by using the tertiary windings for GIC mitigation. The reason for this is not that the tertiary windings did not work for the three legged transformer, but simply that the three legged transformer did not reach a saturated state as a result of GIC in the laboratory study. It is a lot harder to saturate this type of transformer with a DC, as there is no outer legs for the induced DC flux to return through.

6.4 Step response without compensation windings

When comparing the four different step responses that were made for the single phase transformers in section 4.6, a couple of conclusions could be made. Firstly, it was clear that a transformer exposed to a higher AC voltage would reach its saturation point earlier, compared to the same transformer with lower AC voltage. As the saturation point was reached earlier, the current step response took a shorter time to reach its steady state value, due to the earlier drop of inductance. Conclusions that can be made from this, is that a transformer with a higher AC voltage will not only be more saturated when the GIC reaches its steady state, but the GIC will also reach its steady state quicker.

Compared to the simulations of power transformers in [8], the rise time in the experiments are much shorter. This is due to the big difference in inductance. Apart from the different time scale, a rather similar response is obtained by the experiments and simulations. The results from the simulation had almost no increase in current as a result of the voltage step before the core was saturated, this is due to the extreme inductance of $3500H$, while the laboratory results showed a clear increase of current beginning already at the time of the voltage step. The rate of rise of the current increased drastically at the point of saturation. This increase of current growth in the laboratory result can be compared to the increase of current at the time of saturation in the simulations. The only great difference between the laboratory result and the result of the simulations is that the time constant in the simulations are larger and that the current increases very slowly until the core gets saturated. These differences are due to the large differences of inductance but also resistance in the real 2kVA transformer and the transformer of the simulations. While it is difficult to have 2kVA transformer with the same specifications as the real transformer, this can be simulated, which is done in Chapter 7.

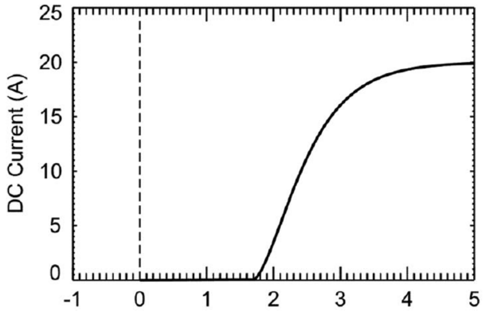


Figure 6.1: Current response from simulations

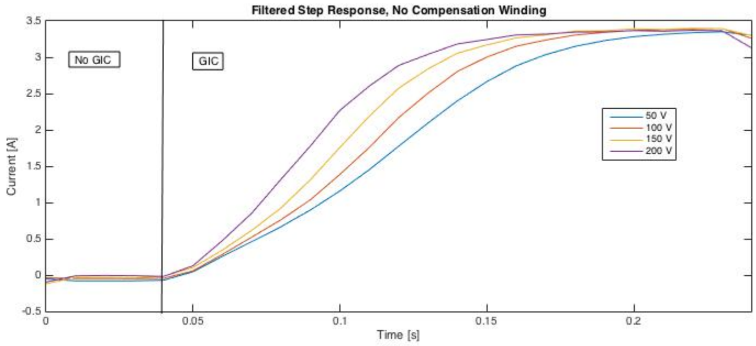


Figure 6.2: Current response from laboratory study

6.5 Step response with compensation windings

When the compensation windings were used in order to mitigate the negative effects of the GIC, the current step response got faster. This is, as earlier mentioned, due to the fact that the inductance seen from the DC source is lowered when the compensation windings are implemented. With perfect GIC compensation, the zero sequence inductance goes to zero. So the positive effects of using the compensation windings to mitigate the negative effects of the GIC is that the core gets less saturated when the GIC reached its steady state. However, a negative side effect of this compensation is that the GIC will reach its steady state faster. When comparing the time constants of the current step response with and without compensation windings, the time constant is approximately 4 time higher for the transformer without GIC compensation. Which also can be seen in the formula:

$$\tau = \frac{L}{R}$$

As L for the uncompensated transformer is 4 times bigger, seen from the DC source compared to the compensated transformer. There is however a small increase of resistance in the compensated transformer, as the current also has to travel through the compensation windings. This can be seen when comparing Figure 5.6 and 5.11, as the steady state value of the current is slightly smaller for the compensated transformer, compared to the uncompensated.

What really is interesting is whether or not the saturation of the core increases faster for the compensated or uncompensated transformer. The answer to this is that the saturation increases at a similar rate. This is due to the fact that the GIC increased 4 times faster in the three fourths compensated transformer. Meaning that the three fourths compensated transformer got the same level of saturation as the uncompensated transformer when it was exposed to a four times bigger current.

Seen from the core perspective, this means that the saturation will increase at a similar rate no matter how much the GIC is compensated for. However, the increase will stop earlier if there is more compensation. Assuming the rise time for an uncompensated transformer is α, the rise time for a compensated transformer will be

$$\alpha * (1 - \beta)$$

where β is the amount of compensation, with 1 being a 100%.

This formula is also applicable for negative compensation, as subsection 4.6.3 showed. Meaning a negative compensation will increase the time constant of the current step, but would also increase the saturation in proportion to the increase of the time constant. Obviously, negative compensation is not a good thing for the transformer when it comes to handling GIC. But this helped in order to further compare to the results of the simulations in [8], as the negative compensation increased the inductance of the transformer seen from the GIC. Hence, it made the current step response time constant even higher, which allowed for even more accurate comparisons to [8].

6.6 Step response with delta connected tertiary windings

The delta connected tertiary windings does not have a mitigating effect on the stationary value of the DC flux, but it results in a slower flux step response, even though the current step in the secondary windings got faster. The reason why the flux step response was slower with the delta tertiary windings present, is that they counteract the DC flux induced by the GIC in the secondary windings according to Lenz law. This counteraction results in a lower induction in the secondary windings, seen from the GIC, which is the reason for the quick current step response. This counteraction induces a current in the tertiary windings, that fades out over time. When the current in the tertiary windings are back to its steady state of $0A$, there is no more counteraction on the DC flux.

6.7 Summary of step response

The summation of section 5.4-5.6 is that the current step response increases faster for a compensated transformer, as the inductance of the transformer seen from the DC offset is lower, than for an uncompensated transformer. However, it also reaches its steady state faster, which is approximately the same DC current as for the uncompensated transformer, with a little difference as a result of the resistance in the compensation windings. The DC flux in the core increases at the same rate no matter the compensation, leaving us with a lower steady state DC flux for a current step that lasts for a shorter period of time. This means a lower steady state DC flux for a transformer with a compensation closer to 100 %, which is the purpose of the compensation windings. Tertiary winding connected as a closed delta also have a positive effect on the flux step response. The most important part of lowering the steady state flux is not compensated by the delta connected tertiary windings. But the time constant of the DC flux step response is risen, as a result of Lenz law acting through the tertiary windings.

Chapter 7

Simulations

7.1 Model

The simulations were performed in Matlab and Simulink. Figure 7.1 illustrates the Simulink model that was most commonly used. The same model, with different transformer parameters was used for simulations of both the small and large transformers.

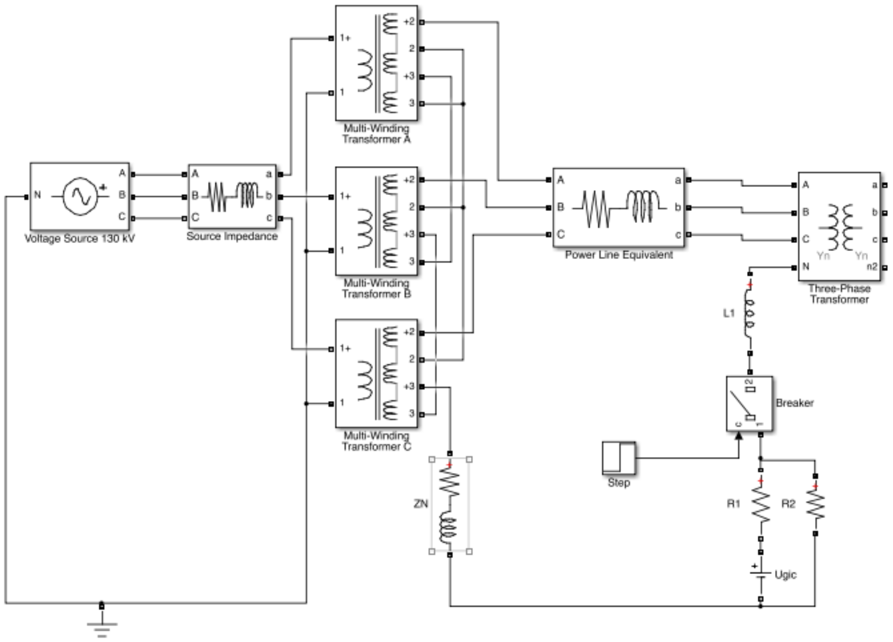


Figure 7.1: Simulink model of the wye-wye connected single phase 800VA transformers with DC-offset

7.2 Simulations

In order to apply the results of the laboratory exercises on a large transformer, a Simulink model of a 2.4kVA transformer was made and later reconfigured to 400MVA.

7.2.1 2kVA

The parameters were set identically to the measured parameters of the real setup. Some slight changes in the grid inductance have been made since we did not know the true impedance of the grid. There were some differences between the simulations and the reality that could not be neglected. The procedure for the simulations were the exact same as for the laboratory study.

Single phase transformers without GIC

In order to see the effects of the GIC on the 2.4kVA transformer in the simulation, the simulations were first conducted without GIC. The supply grid was connected to the primary side of the transformers and the GIC was led into the system through the secondary windings, just as in the experiments. The resulting primary and tertiary currents of the system without GIC can be seen in Figure 7.2.

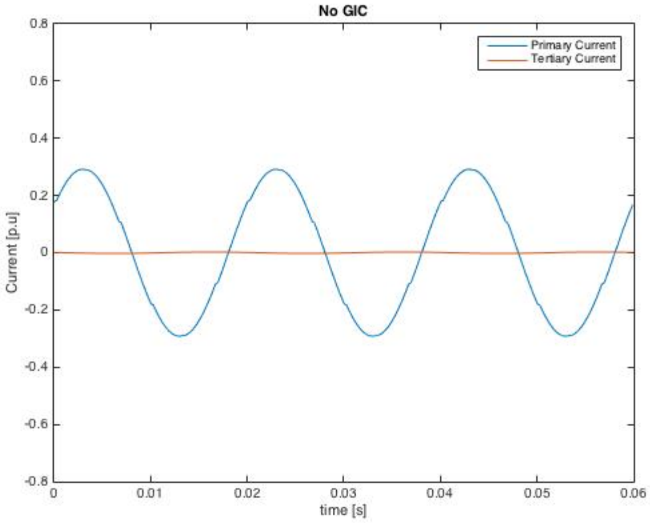


Figure 7.2: Simulations of 2.4kVA transformers, without compensation and GIC

Single phase transformers

As the GIC was added to the system, a clear saturation could be seen in Figure 7.3 in the primary current, when it had the same direction as the GIC, just as in the laboratory study. This figure can be compared with Figure 4.23. The two figures are similar, apart from the fact that the third harmonic is bigger in the neutral point on the secondary side in the results from the experiments and the third harmonic is slightly larger in the primary windings in the results from the simulations. Finally, the current spikes in the simulations were a bit larger, which is most likely due to the fact that there are some additional resistances and inductances in the experiments or that the drop of inductance due to saturation is larger in the simulations. This results in a shorter time constant for the spikes in the simulations, which results in larger spikes. These matters will be further discussed in Chapter 8, where simulations and experiments will be compared more in depth.

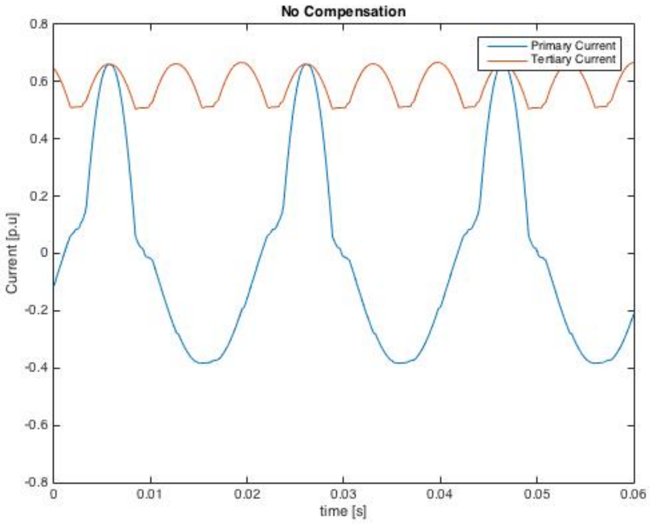


Figure 7.3: Simulations of 2.4kVA transformers, without compensation windings.

FFT of the single phase transformers waveform

In order to better understand the waveforms of Figure 7.3, an FFT was made in Matlab and is presented in Figure 7.4. The most interesting part of this spectrum is the third harmonic of the primary windings, which is a lot larger in the simulations, when compared to the experiments. As 7.5 shows, the amplitude of the third harmonic is identical for the primary and tertiary current.

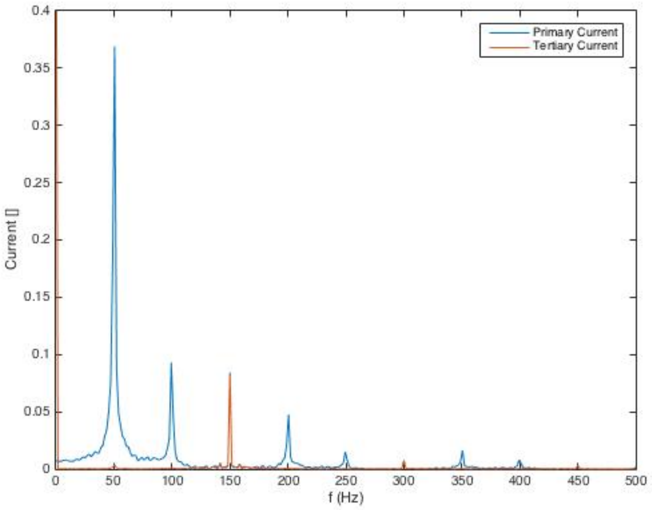


Figure 7.4: FFT of 2.4kVA transformers

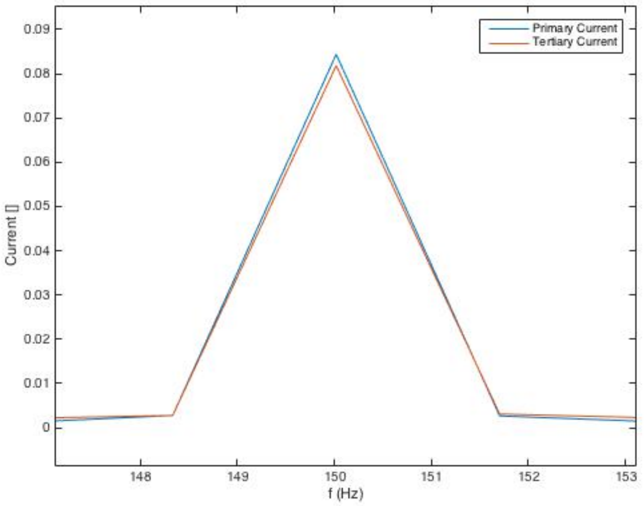


Figure 7.5: FFT of 2.4kVA transformers, at $150Hz$

Single phase transformers with perfect compensation

With perfect compensation, meaning the voltages of the compensation windings were one third of the voltages of the secondary windings, the currents in the primary windings were similar to the primary currents from the case with no GIC. This was expected, as perfect compensation should eliminate the negative effects from the GIC. Meaning, seen from the primary windings, there is no difference in the two cases of no GIC and GIC with perfect compensation windings. As Figure 7.6 shows, this is the case in the simulations. This was also the case for the experiments.

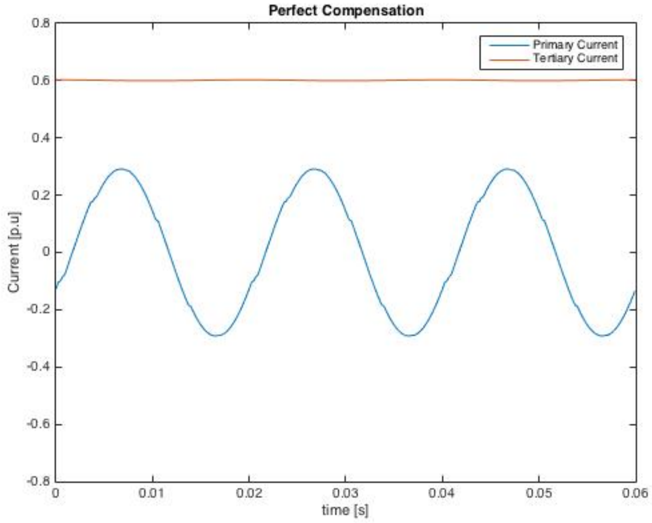


Figure 7.6: Simulations of 2.4kVA transformers, with perfect compensation windings.

Single phase transformers with three fourths compensation

When the compensation windings were connected in the simulations, see Figure 7.1, the amplitude of the current spikes were reduced a lot in the primary windings, compared to the uncompensated transformer, which was anticipated. The current spikes are somewhat more distinct in Figure 7.7 from the simulations, when comparing to the corresponding Figure 4.24 from the experiments. One reason why the current spikes were more distinct in the simulations is due to the fact that the relation between inductance and resistance is lower in the simulations for the whole GIC path when the core saturated, compared to the laboratory study, as previously mentioned. Also, the amplitude of the third harmonic is larger in the laboratory study for the compensated transformer, just as for the uncompensated transformer. These matters will be further discussed in this chapter and Chapter 8.

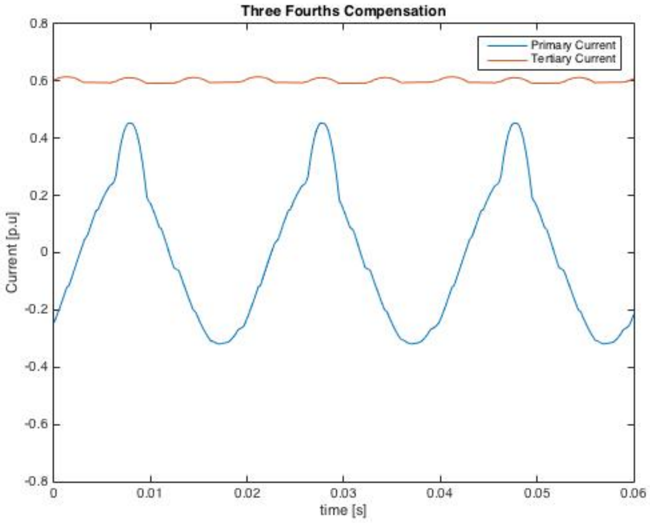


Figure 7.7: Simulations of 2.4kVA transformers, with three fourths compensation windings.

Single phase transformers with over compensation

Finally, the case where the voltages of the tertiary windings is larger than one third of the voltages of the secondary windings. As Figure 7.8 shows, over compensation results in current spikes in the opposite direction of the GIC. As earlier explained, this is due to the fact that seen from the transformer core, there is a larger current flowing in the compensation windings than in the secondary windings. This results in DC flux in the opposite direction, hence negative current spikes. When comparing Figure 7.8 with Figure 4.15, it is clear to see that they show the same tendency of negative current spikes. The spikes were however a bit larger for the simulations and the third harmonic of the tertiary current is a bit larger in the experiments. This is the same phenomena that can be seen in the other cases as well.

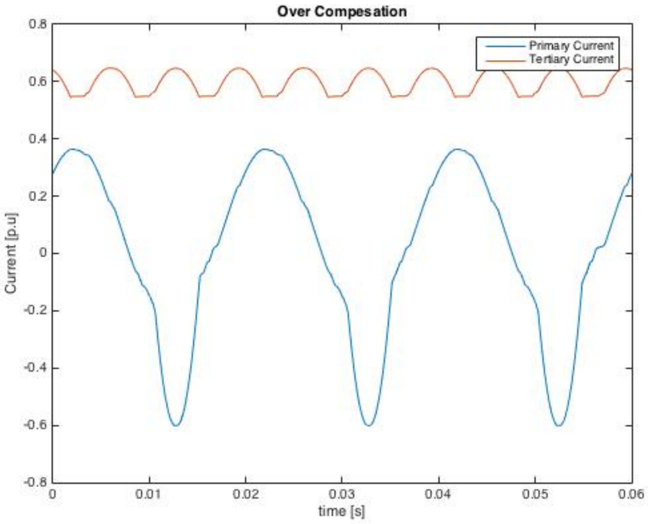


Figure 7.8: Simulations of 2.4kVA transformers, with over compensation windings

7.2.2 Lower inductance on supply grid

As mentioned in subsection 6.2.1, the third harmonic almost completely disappeared in the compensation windings when the inductance of the supply grid was drastically lowered, see Figure 7.9. The current spikes in the primary windings are not as drastic as expected when the inductance of the transformer is reduced as a result of the saturation of the core, when the supply grid is inductive.

When the inductance of the primary windings are heavily reduced the current spikes of the primary windings is not increased enough to match this inductance reduction, due to the fact that the grid inductance is not reduced. Due to this, there is less current transferred to the secondary and compensation windings than expected, seen from the transformer. This results in a change of current in other windings surrounding the same leg. As the tertiary windings are in series, this change of current will appear as a third harmonic, due to the fact that there is three phases in the transformer.

However, when the inductance of the supply grid is very low compared to the inductance of the saturated transformer, the current spikes of the primary windings will be matching the inductance in the transformer, hence no third harmonic in the compensation windings. This can be seen very clearly when comparing Figures 7.3 and 7.9. The current spikes of the primary windings are clearly more distinct with a lower grid inductance and there is virtually no third harmonic.

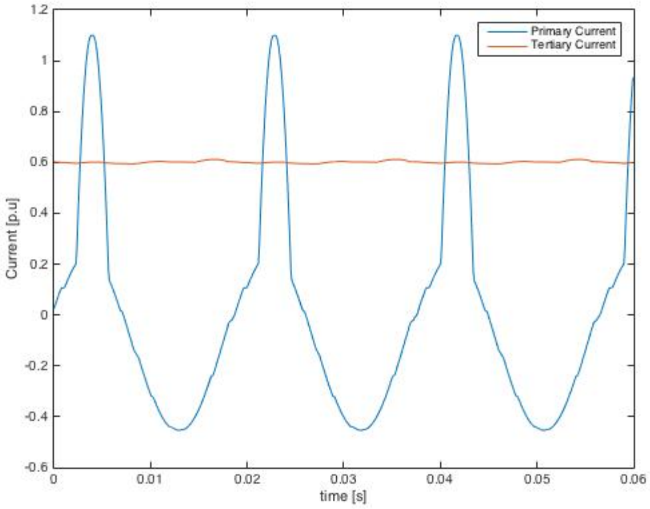


Figure 7.9: Simulations of 2.4kVA transformers with lowered inductance in feeding grid

7.2.3 Transient behaviour

The transient behavior in the simulations was implemented in the exact same way as in the laboratory study. The over all time constant was about the same for the laboratory studies, meaning a rise time of about $100 - 150ms$. However, as seen when comparing the different curves of Figure 7.10, the time constant did not get affected by the primary AC voltage, which it should have, as the duration of saturation increases with a larger primary AC voltage. Hence, supposedly lower effective inductance for the GIC. There is also no time delay from the time of the step to maximum saturation. This is clearly seen in Figure 7.10, as the rate of change of the GIC is at its largest at the time of the step. This indicates that the effective inductance does not depend on the actual GIC that is flowing, but on the estimated steady state value of the GIC, which is most likely due to a design flaw in the simulations.

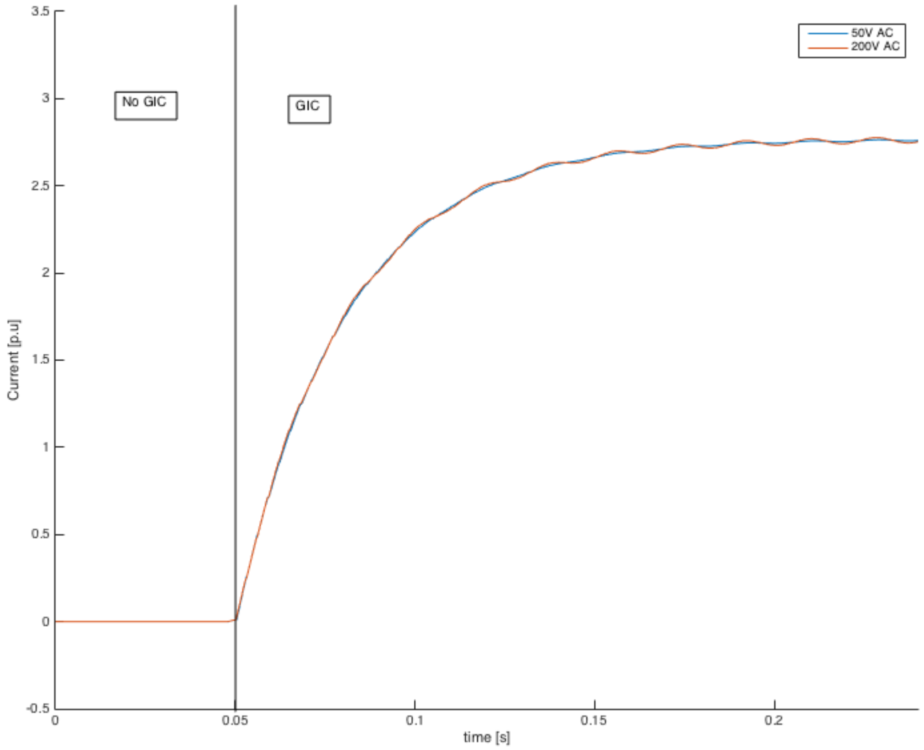


Figure 7.10: GIC step response for an uncompensated transformer

The amount of compensation had a large impact on the current step time in the experiments. This was expected, as the inductance seen from the GIC gets lower with better compensated transformer. However, this result was not reached in the simulations, where the amount of compensation made no difference to the current step time. This is very clear when comparing the current steps for the differently compensated transformers in Figure 7.11. The primary AC voltage is set to 200V for all different compensations in Figure 7.11 .

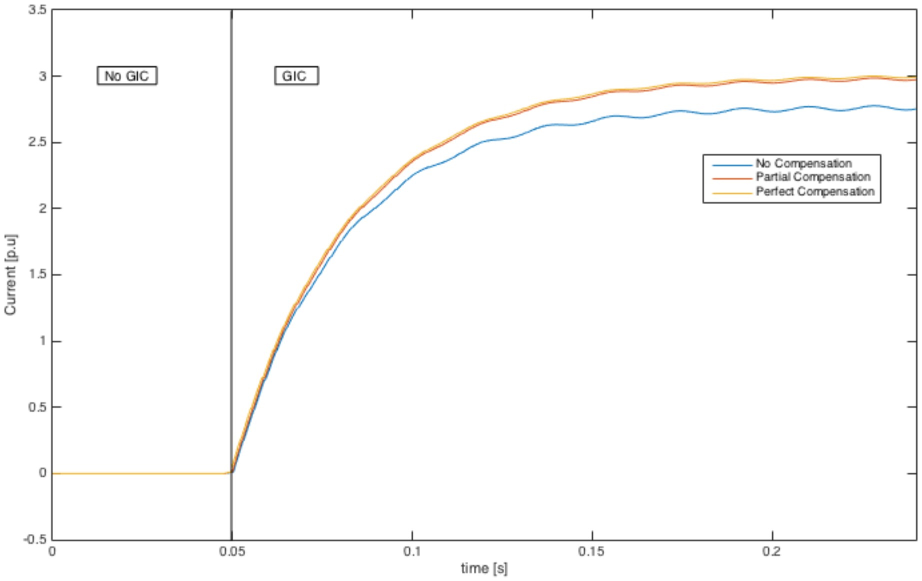


Figure 7.11: Current step response for partial, perfect and no compensation

7.2.4 400MVA 130/400kV

In this section the GIC is led into the high voltage side of the transformer, where the ratio between the primary and secondary voltage is not the same as in the laboratory study. In Appendix A, there is a middle step between this 400MVA 130/400kV and the 2.4kVA transformer, in the form of a 400MVA 400/230kV, which has the same voltage ratio between the secondary and primary side as the 2.4kVA transformer. The reason why the simulations of the 2.4kVA transformers have been made, was to be able to compare the results of the simulations with the laboratory results of the same transformer. The reason this comparison is important, is that we can assume that the simulations of the 400MVA transformer are corresponding to a real 400MVA transformer in the same way as the experiments and simulations of the 2.4kVA transformer corresponded to each other.

Single phase transformers without GIC

Just as for the 2.4kVA transformer, a test with neither GIC, load nor compensation was conducted, in order to have a reference point to compare the following tests with. The p.u primary current of this transformer is slightly smaller than the p.u primary current of the 2.4kVA transformer in the simulations. This indicates a larger impedance in the 400MVA transformer relative to its sizes, than the impedance of the 2.4kVA transformer relative the size of the 2.4kVA transformer. The primary and tertiary currents can be seen in Figure 7.12

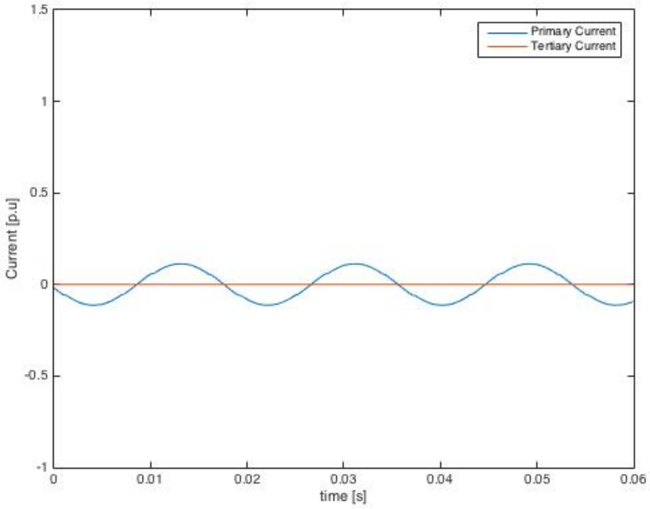


Figure 7.12: Simulations of 400MVA 130/400V transformers, without compensation windings and GIC

Single phase transformers

As the GIC is initiated in the simulations, half cycle saturation caused spikes in the, just as expected. However, when comparing the amplitude of the spikes between the 400MVA and the 2.4kVA transformer, it is very clear that the amplitude of the current spikes are a lot larger for the 400MVA compared to the 2.4kVA transformer. This behaviour was also expected, as the ratio between inductance and resistance is a lot greater for the 400MVA, see Figure 7.13 Meaning it looses a greater part of its impedance when the core saturates, leading to larger current spikes. This indicates that larger transformers are more vulnerable to GIC since the reduced inductance due to core saturation will have a greater negative impact on larger transformers, as the impedance of these large transformers is mostly inductive. An other aspect that made the current spikes for the $400MVA130/400kVA$ transformers larger than the current spikes of the 2.4kVA is that the GIC entered the high voltage side, resulting in a larger production of DC flux in the core. Results for a 400MVA transformer with the same voltage ratio as the 2.4kVA transformer can be found in appendix A.

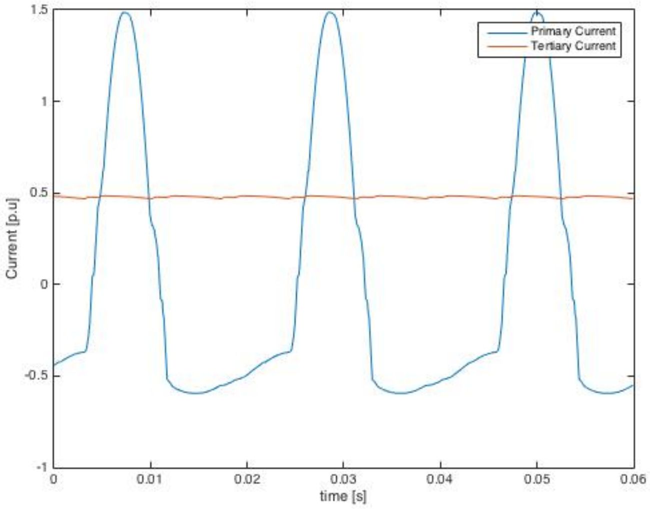


Figure 7.13: Simulations of 400MVA 130/400kV transformers, without compensation windings.

Single phase transformers with perfect compensation

The current in the primary windings for a perfectly compensated transformer that is exposed to GIC is identical to the primary current of a transformer that is not exposed to GIC. This can be seen in Figure 7.14, where the primary current can be compared to the primary current in Figure 7.12, which is the uncompensated 400MVA transformer that is not exposed to GIC. This result corresponds very well to the other results for perfect compensation.

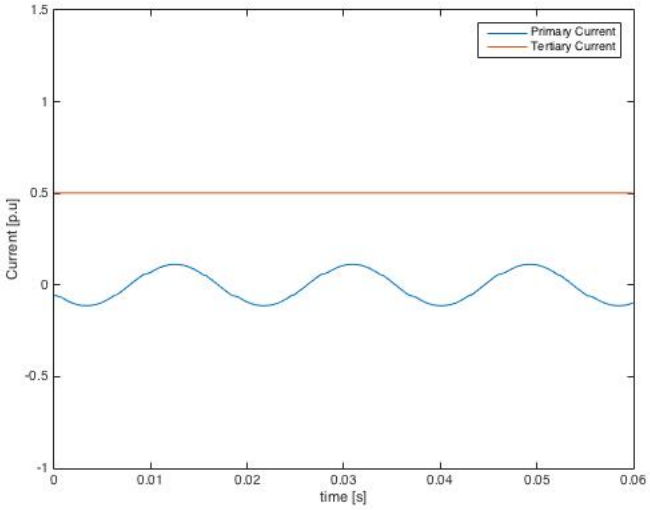


Figure 7.14: Simulations of 400MVA 130/400kV transformers, with perfect compensation windings.

Single phase transformers with three fourths compensation

Just as in previous cases, the amplitude of the current spikes was reduced as the mitigation windings were connected. However, the amplitude of the current spikes were still quite large when compared to the unsaturated part of the waveform for this transformer, even though the GIC impact is mitigated by three fourths. The reduction of the current spikes is great when comparing Figure 7.15 with 7.13. This shows that the mitigation works well. However, the spike is still large compared to the unsaturated part of the waveform due to the fact that the impedance is almost purely inductive for a transformer of this size.

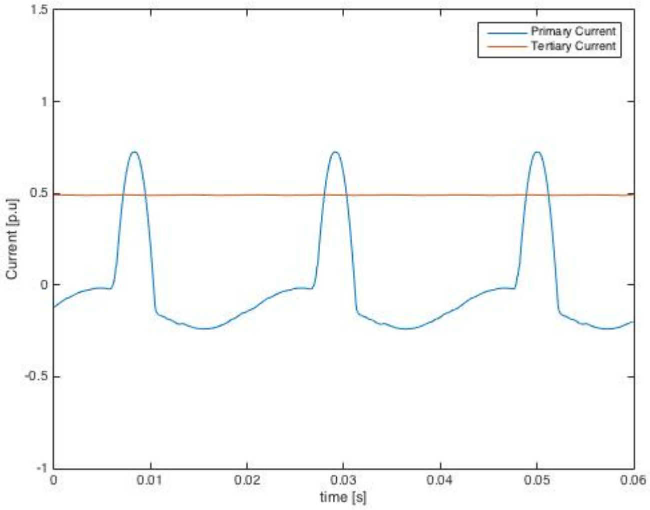


Figure 7.15: Simulations of 400MVA 130/400kV transformers, with three fourths compensation windings.

Single phase transformers with over compensation

Finally, when the compensation windings are over compensating for the GIC, the current spikes of the primary windings were in the opposite direction of the GIC, as in all the other cases before. The only difference with this big transformer is that the amplitude of the spikes is a lot greater compared to the spikes of the 2.4kVA transformer. As mentioned before, this is due to the high inductance and low resistance of the 400MVA transformer.

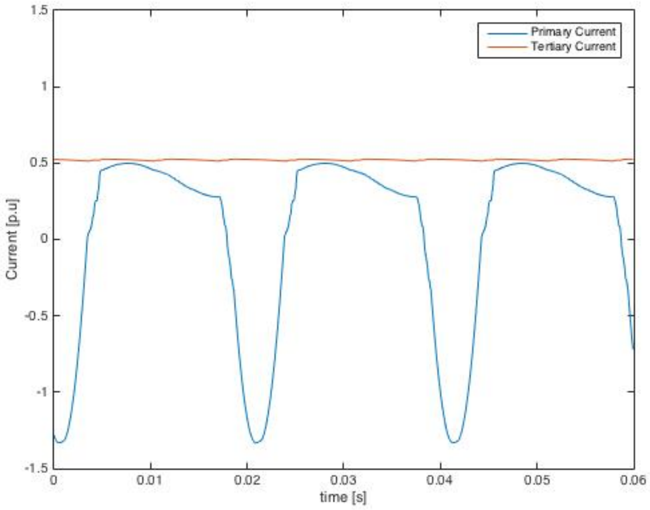


Figure 7.16: Simulations of 400MVA 130/400kV transformers, with over compensation windings

7.2.5 Transient behaviour

The current step response simulations of the 400MVA transformer showed the same results as for the simulations of the 2.4kVA transformer, apart from a lot larger current step time constant. The larger time constant was expected, as the ratio between inductance and resistance is a lot larger for this 400MVA transformer, compared to the small 2.4kVA transformer. The results can be seen in Figure 7.17 and 7.18, which are very similar to the results in Figure 7.10 and 7.11, apart from the different time constant.

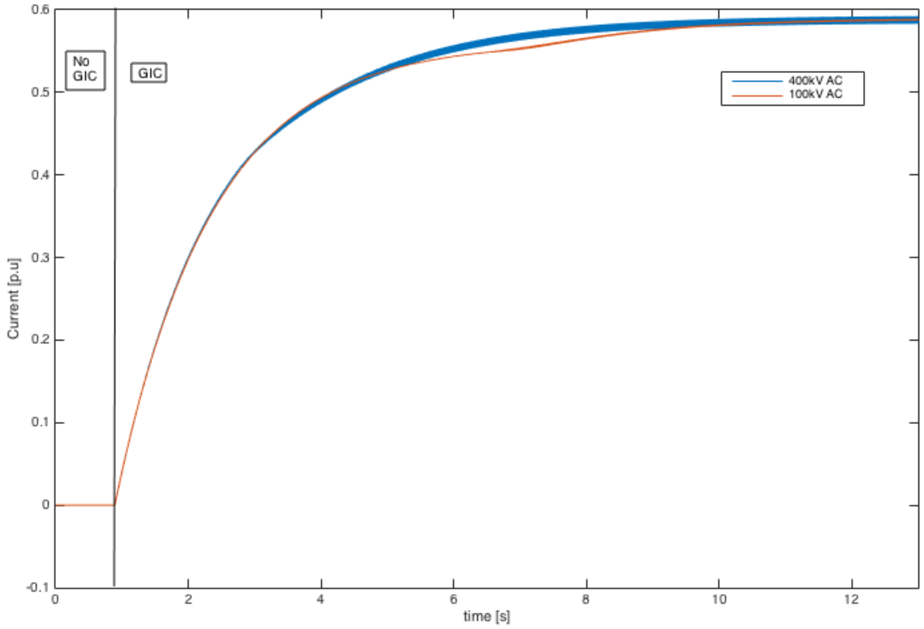


Figure 7.17: Current step response for no compensation

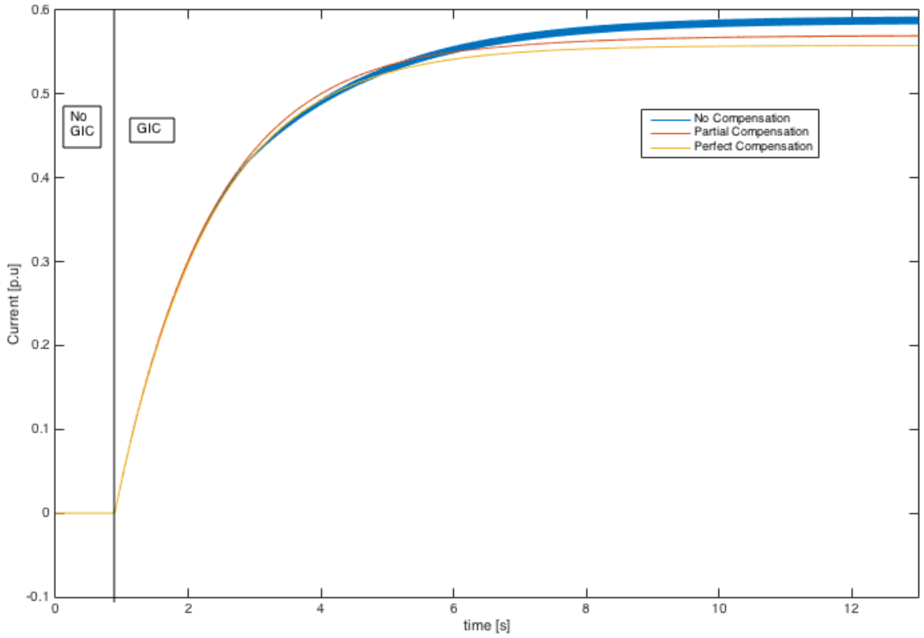


Figure 7.18: Current step response for partial, perfect and no compensation

7.3 Summary

The purpose of this chapter was to compare simulations and laboratory results. This allowed us to see if the simulations were realistic and what aspects may vary in the simulations compared to reality. This was done in order to estimate how a real large power transformer would react to GIC when compensated and not compensated in regard to GIC. As we could see that the simulations and experiments related to each other, it became safer to say that the results of the simulations were realistic and how the behaviour of the large simulated transformer compares to the small one. As chapter 6 shows, the experiments and simulations are quite similar, with some harmonic differences and slightly larger current spikes in the simulations compared to the experiments. The simulations of the large $400MVA$ transformer had much larger current spikes, as most of the impedance is inductive which more or less disappears when the core gets saturated, leaving a high voltage over a very low impedance.

The step response in the simulations had approximately the same time constant as the laboratory results. However, the time constant did not differ due to different amounts of compensation or different AC voltages on the primary side. Fundamentally, different amount of compensation should give different time constants, as the compensation windings changes the inductance that is seen from the GIC. Where more compensation leads to a lower inductance, hence, more compensation should result in a shorter time constant. A higher AC voltage should lead to a shorter time constant as well, since this will lower the effective inductance of the transformer, yet this result did not appear in the results of the simulations. Further more, there was a lot less tendency, in the simulations, for occurrence of a second or sixth harmonic. This was most likely due to the fact that the laboratory transformers had a rather wide and real hysteresis curve, compared to the simulated transformers.

Another phenomena that was noticed in the simulations was that there were almost no third harmonic in the tertiary windings when the inductance of the grid was drastically lowered. This phenomena can not be tested in the laboratory, as the inductance of the voltage providing system can not be removed in reality.

The conclusions that can be drawn from this chapter is that larger transformers suffer a greater consequences from GIC. Since the larger transformers has a higher inductance/resistance ratio, meaning the impedance is more inductive than resistive in larger transformers. However, in this particular case, the large inductance is a problem, as the inductance gets heavily reduced when the core saturates, resulting in huge current spikes for the mainly inductive system.

Chapter 8

Simulation results

The results of the simulations were quite similar to the results of the laboratory study when comparing the 2.4kVA transformers. When scaling up to a 400MVA transformer, the unloaded transformer had a smaller primary current, due to the high inductance of the large transformer.

8.1 Without GIC

Without any GIC or load in the system, the 400MVA transformer has a far lower p.u current on the primary side, due to the very high inductance of the large transformer.

8.2 GIC without mitigation

As the GIC enters the system it is very clear that a transformer with an almost purely inductive impedance suffer large consequences from core saturation, due to the fact that almost all inductance disappears when the core is saturated. Given that the impedance is almost purely inductive for large transformers as 400MVA, they suffer larger current spikes compared to a smaller 2.4kVA transformer, where the impedance is a bit more resistive.

8.3 GIC with perfect mitigation

As perfectly dimensioned compensation windings are introduced to the system no saturation occurs and consequently all the negative effects of the GIC disappears, apart from a slight heating of the secondary and compensation windings. This happens as a current always will produce some heat when flowing through a resistance. An ideal transformer with zero winding resistance would not have this negative effect, but as real transformer which always have a small windings resistance will therefor always produce heat from GIC. However, the extreme heating of the huge current spikes disappear, as there no longer are any current spikes. The heating due to eddy currents and flux flowing through material with high reluctance disappear as well. Harmonics also disappear, as that also was a result of the core saturation.

8.4 GIC with partial mitigation

The partial compensation reduces the induced DC flux in proportion to the extent of the compensation. This results in a certain percentage of the current spike being reduced when introducing DC flux mitigating windings, which is the compensation windings. As the current spikes of the 400MVA transformer is larger than that of the 2.4kVA transformer, the amplitude of the current reduction is larger as well. What is worth mentioning is that this conclusion can be drawn when the core is in the verge of saturation before the GIC enters the system. If the transformer is far from the saturation point, it would require a large DC current in order to reach saturation. This means a partial compensation could be enough to completely drive the transformer out of it saturated region. A short explanatory example of this would be if a transformer required 10A GIC in order to reach the border of saturation and a GIC of 20A entered the system it would go into saturation. However, if compensation windings with only one sixth of the voltage of the entering windings would be introduce, the negative effects of the GIC would disappear. As $\frac{1}{2}$ compensation with 20A GIC would have the same effect on the core as 10A GIC without compensation. Leaving us with no saturation.

8.5 Grid impedance

Results that could be drawn form the simulations but not the laboratory study was the impact the inductance in the supply grid had on the currents in the transformer. The results of these simulations were that the grid inductance had a huge impact on the systems third harmonics. If the grid reactance was removed, there were no third harmonics at all in either the primary, secondary or tertiary windings of the system. As the reactance of the grid was increased, the amplitude of the third harmonics increases as well. Note that the reactance is 3 times larger for the third harmonic compared to the fundamental, as it is frequency dependent.

8.6 Transient behaviour

The transient behaviour for the small transformer were similar to the results acquired from the laboratory studies. However, the time constant of the current step responses did not vary as the AC voltage on the primary side or the amount of compensation was changed. These factors did change the time constant in the laboratory section and were expected to do so in the simulations as well.

The upscaling to a 400MVA transformer provided the same shape of the current step response as for the 2.4kVA, with the difference being a longer time constant for the large transformer.

Chapter 9

Conclusions

This is the chapter where conclusions are made based on the results of this thesis.

9.1 GIC Effects

GIC are a concern for the power industry because GIC in the power system can lead to severe consequences. The most common effects that this study has looked into is heating, harmonics and reactive power demand, which all are a result of transformer core saturation due to GIC.

9.1.1 Experimental conclusions

The laboratory measurements showed that the effect of GIC depends on the type of transformer. The three legged 3-phase transformer suffered almost no consequences due to the GIC. Since the magnetic flux of every phase is directed in the same way for the GIC combined with the fact there are only three legs as well as three phases, there is no path for the flux to return. Given this, the core does not provide a closed magnetic loop for the flux, which forces the flux to flow through surrounding material in order to close the magnetic loop. As the surrounding material has a reluctance that is far greater than the reluctance of the core, the DC flux would need a very high magnetomotive force (MMF) in order to become great enough to saturate the core. As it is very hard to saturate the core with DC flux for a three legged 3-phase transformer, these transformers are almost immune to GIC. When it comes to the five legged 3-phase transformer and the single phase transformer, the GIC had a significant negative impact. This is due to the fact that both of these transformers have outer legs, where the DC flux can flow, in other words, theses transformers provide the DC flux with a closed magnetic circuit. The most visible signs of saturation was current spikes in the magnetization current and harmonics in all currents, which is a direct result of core saturation. As larger GIC was induced to the system, larger current spikes and harmonics followed.

9.1.2 Simulation conclusions

The simulations provided the same conclusions as the laboratory study, with some additional information regarding the third harmonic. In addition to the laboratory results, the simulation showed that when the inductance of the supply grid was drastically lower, the third harmonic due to the GIC disappeared. Lower grid inductance also results in higher current spikes as the total combined inductance seen from the primary current is lower. The reason why the amplitude of the current spike is lowered when the supply grid is inductive is that the total inductance seen from the GIC is larger if the grid has a larger inductance. Which results in a larger time constant, hence a slower step response for the GIC. As the saturation only last for a small part of the period, generally about $2-3ms$, the step does reach a lower point when the time constant is larger. This rise of the time constant is the reason for the larger third harmonic as well, since the current step is not large enough to match the drop of inductance, resulting in reduced currents in the secondary and tertiary side of the transformer.

9.1.3 Summary of GIC effects

Conclusions that can be drawn regarding the effect of GIC on an uncompensated system with the support of simulations and laboratory study is the following. As the GIC produces a DC flux offset in the transformer core, the core may reach saturation when the AC and DC flux have the same direction. This saturation leads to current spikes and eddy currents, which creates hot spots that can severely damage the transformer. It also leads to second harmonics, as well as small sixth harmonics in the tertiary windings. Given that the system providing the primary windings with voltage is inductive, there will also be a third harmonic in all windings. In a non ideal system, which all real systems are, there will always be some inductance in the supply system. The ratio between the inductance of the supply system and the inductance of the primary side of the transformer sets the amplitude of the third harmonic. If the transformer inductance is large and the grid inductance is small, the third harmonic will be small.

9.2 GIC Mitigation

The effects of compensation windings on a transformer that is being exposed to GIC has been studied extensively. When it comes to mitigating the DC flux that is produced in the transformer core by GIC the compensation windings are proven to be very useful. However, as the delta connected tertiary windings are opened in order to make these compensation windings, some attributes of the delta connection are lost. Among those, the ability to compensate for zero sequence currents.

9.2.1 Experimental conclusions

The laboratory studies showed that the amplitude of the current spike and the amplitude of the harmonics are reduced when compensation windings are implemented in the transformers, due to the fact that the compensation windings mitigate the core saturation. If assuming the transformer is on the point of saturation before the GIC enters the system, the amount of mitigation is linear to the size of the compensation windings compared to the size of the windings the GIC enters the transformer through. If the voltage of the compensation windings is one third of the voltage of the windings where the GIC enters the transformer, a perfect DC flux compensation will be performed. The amount of flux mitigated will always be linear in relation to the size of the compensation windings. However, the amount of prevented saturation does not follow this formula, as there is no guarantee that the core is on the verge of saturation without GIC, which it would have to be in order to saturate for every DC current apart from $0A$. When the dc offset is large enough to drive the core into saturation, there is a linear relation between size of the compensation windings and the amount of saturation. Given this information, it is not necessary to have perfect compensation windings in order to completely avoid saturation.

A brief example of this is if a transformer that can handle a DC offset of $10A$ gets exposed to a DC offset of $30A$. Without any compensation, the core would be driven deep into saturation and with perfect compensation the GIC would not drive the core into saturation. However, a partial compensation would have the exact same effect as the perfect compensation, given that the compensation windings have between 2/3 and 4/3 number of turns in relation to the secondary winding. As this would result in the same amount of flux as a GIC between $10A$ and $-10A$.

9.2.2 Simulation conclusions

The simulations provided the same information as the experimental studies, which strengthen the conclusions made in the laboratory. In addition to experimental conclusions, the simulations gave an insight in how GIC effects transformers of different sizes, most importantly large transformers that are used in the power system, eg. 400MVA As the transformer gets larger, the ratio between reactance and resistance $\frac{X}{R}$ gets larger. A larger ratio is usually desirable as it results in less power losses. However in the case of core saturation, the current spikes get larger as this ratio gets larger, due to the fact that a larger part of the transformer impedance disappears at the point of saturation if the transformer is more inductive. Given this, the larger transformer that is used, the more important it is to compensate for GIC, as they are more vulnerable to core saturation.

9.2.3 Summary of GIC mitigation

Conclusions that can be drawn regarding the effect of DC flux mitigation windings on a system with the support of simulations and laboratory study is the following. The amount of mitigation of DC flux in the core is proportionally related to the size of the compensation windings. This implies that partial compensation can be enough to completely prevent the core from saturating, given that the transformer does not operate on the very edge of saturation. In other words, as long as the DC flux is small enough that the total magnitude of the DC flux added to the AC flux never gets larger than the flux needed to saturate the core, the transformer will not suffer negative consequences due to core saturation. Given this information, partial DC flux compensation is in many cases enough to completely prevent the core from saturating. The larger the transformer, the more important the mitigation windings are. As larger transformer usually have a larger inductance to resistance ratio, resulting in larger current spikes if the core would get saturated. However, it is very important to remember that the delta connected tertiary windings loose their ability to compensate for unsymmetrical faults as this re-connection to GIC compensation windings is made. As unsymmetrical faults occur quite often and GIC is a rare problem, it might not be a good idea to do this re-connection without implementing something in order to take care of the zero sequences currents that arise from unsymmetrical faults. This could be solved with either a capacitor that leads the AC in i closed delta and blocks the DC. Or by implementing the GIC compensation windings as a fourth set of windings, allowing us to perfectly compensate for the GIC while still keeping all the positive aspects of the delta connected tertiary windings.

9.3 Transient behaviour

Another important aspect is the transient behaviour of the DC current and flux, where the compensation windings have both positive and negative effects. Aspects that were considered in the transient behaviour is current and flux step response, steady state value and the impact of delta connected tertiary windings compared to compensation windings.

9.3.1 Delta windings

The removal of the delta connected tertiary windings when implementing the compensation windings does have some effects on the transient behaviour. The tertiary windings produce a faster GIC step response, this behaviour disappears when the delta connection is removed, which is good. However, the reason for this fast current step response is that the delta connected windings counteract the DC flux by inducing an opposite current in the delta. This counteraction is great enough to make the flux step response slower compared to the case without a delta connection. As the core saturation has much worse impact on the system, the total outcome of removing the delta windings is negative in this aspect.

9.3.2 Mitigation windings

The compensation windings had a positive impact on the steady state value of the DC flux. However, the time constant of the flux step response is lowered when compensation windings are implemented. This is due to the fact that the inductance seen from the DC offset is lowered as compensation is implemented. Which results in a shorter time constant for the DC current, which reaches the same steady state with or without compensation. The lowered DC inductance resulting in the shorter current step time constant, which is also the reason for the shorter flux step time constant, as the time constant for the flux is the same as for the current, when no delta connections or large loads are present. However, it is not necessary that the actual derivative of the flux step is higher with compensation as the steady state value of the DC flux is lowered. The final results of the laboratory study showed that the flux step derivative does not change when compensation windings are implemented. Meaning the compensation windings have no impact of the rate of DC flux change, but shortens the time of the change, which of course results in a lower steady state flux. In conclusion, the implementation have no effect on the steady state current or rate of change for the DC flux. It does have a negative impact on the rate of change of the current. However, it does have a positive impact on the steady state flux, which is of greater importance than the current step time constant.

9.3.3 Conclusions of transients

When comparing the positive effects of the compensation windings and the delta connected windings for the transient behaviour, it seems to be worth to reconnect the delta windings to compensation windings. As according to the results of this study, the compensation windings provide a greater positive effect than what the delta windings do. The possible solution would be a transformer with both delta and compensation windings, as this implementation would make the DC flux step both slower and lower. It would also keep the transformers ability to compensate for zero sequence currents due to unsymmetrical faults. However, this implementation would come with a great cost, as new transformers with four sets of windings would have to be constructed.

9.4 Harmonics

The most noticeable harmonics in this study are the second and third harmonics. The second harmonic is a result of deep saturation and appears when a transformer is driven into saturation. The third harmonic appears when the core is driven into saturation as well, but it is not a direct result of the saturation. If the supply grid has no inductance there will be no third harmonic when the core saturates. The sixth harmonic in the tertiary windings is a result of a second harmonic in each phase of the tertiary windings due to deep saturation. As the phases are 120 degree apart and in series, these 3-phase shifted second harmonics will appear as a sixth harmonic.

Chapter 10

Future Work

This study has further given rise to the interest of future work regarding the subject of DC flux mitigation with compensation windings.

A FEM model of the flux in the core and its surrounding material would be of great interest. As this could show how the spread of saturation in the core and which corners that saturates first. A FEM model of how the heat spreads would be interesting as well. As this would show where hot spots in the transformer will occur.

Further research of the implementation of a capacitance between the neutral point of the secondary windings and ground would also be of great interest. Focusing on if there are sizes of the capacitance that can lead the AC in a delta while blocking the DC without resulting in resonant ringing.

Studies of the transformer behaviour for lower frequencies could be of great value. Apart from the step response, the system is viewed as resistive for the GIC, as it is DC or very low frequent AC. However, GIC with frequencies high enough to get affected by the systems inductance could be induced. Hence laboratory studies concerning at what frequency the inductive part becomes large enough to not view the system as purely resistive would be interesting.

A study of a transformer with both delta connected tertiary windings and compensation windings implemented would be of great interest. This type of transformer is very likely to be able to handle zero sequences currents while still possessing the ability to compensate for the negative effects of the DC flux that is produced by GIC. Preliminary results from experiments that were made and is presented in this chapter, as it needs a lot of future work. As Figure 10.1 shows, the GIC current step is a lot faster than the case without a delta, see Figure 5.6, as the delta counteracts the flux induced by the GIC and thereby lowers the inductance seen in the transformer from the GIC.

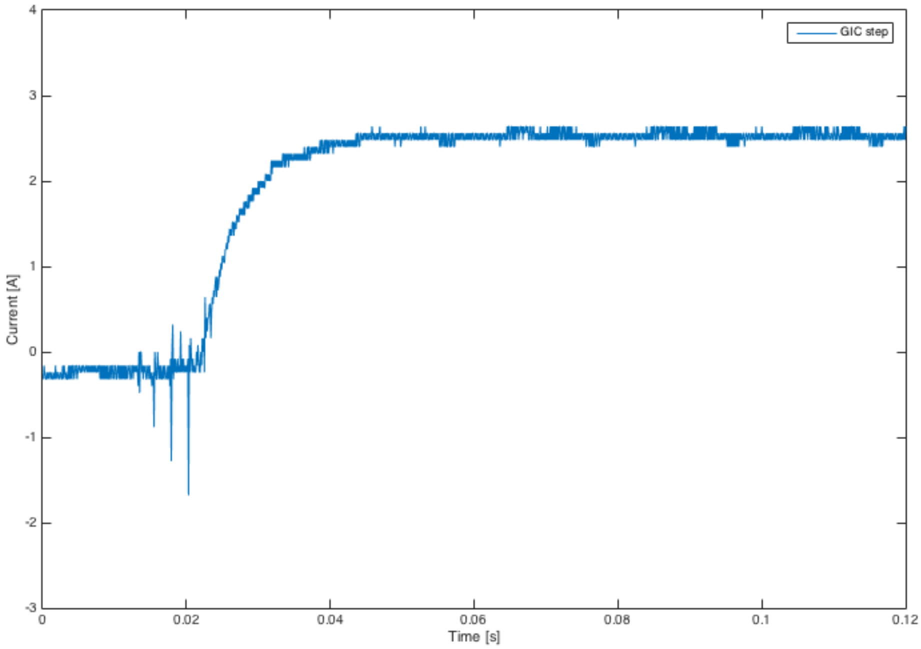


Figure 10.1: GIC step response with both delta connected tertiary and compensation windings implemented

As seen when comparing Figure 10.2, Figure 10.3 and Figure 10.4 the compensation windings have a great impact at reducing the saturation caused by the DC flux produced by the GIC. The compensated figure, Figure 10.3 is quite similar to the case with no GIC, Figure 10.2. While the uncompensated figure, Figure 10.4 has a very ugly looking waveform, due to the saturation.

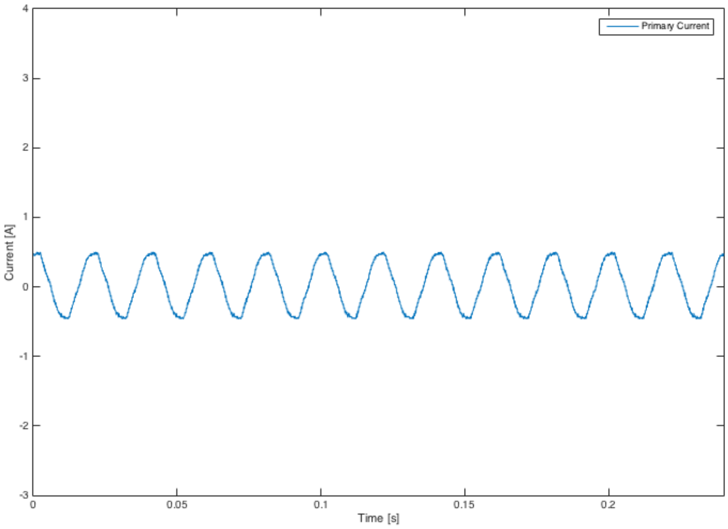


Figure 10.2: Primary Current for no GIC with both delta and compensation windings implemented

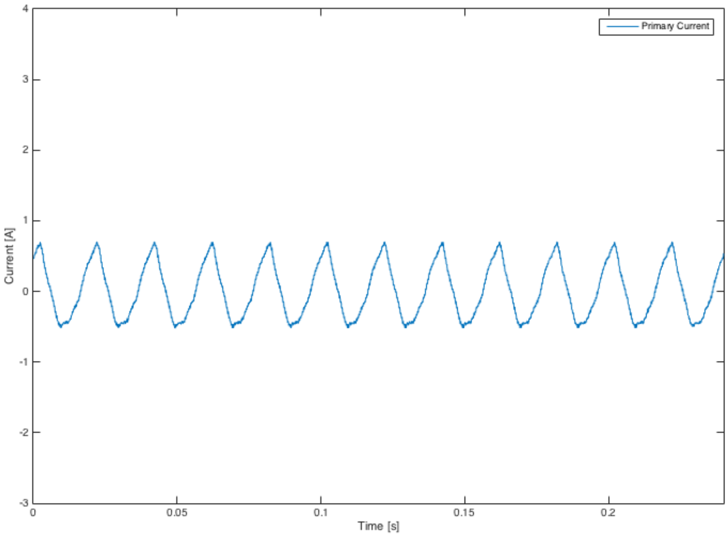


Figure 10.3: Primary Current for GIC with both delta and compensation windings implemented

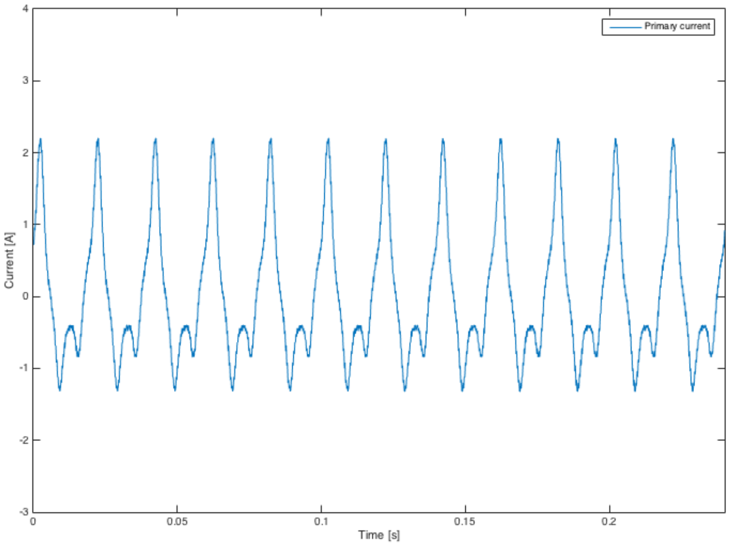


Figure 10.4: Primary Current for GIC with delta but no compensation windings implemented

It would be very interesting to get measurement of the DC flux in the core, especially during the current step. Unfortunately this can not be easily implemented at the current transformer, as there are no windings available to measure the induced voltage over, in order to estimate the flux produced by the GIC.

Appendices

Appendix A

Middle step between 2.4kVA 230/127kV and 400MV 130/400kV transformers

A.0.1 400MVA 400/230kV

In this Appendix the GIC is led into the low voltage side of the transformer, where the ratio between the primary and secondary voltage is the same as in the experiments. The reason why these simulations were made, was to get a middle step between the the 2.4kVA transformers and the 400MVA transformers. The reason why this comparison is important, is that we can assume that the simulations of the 400MVA transformer corresponds to a real 400MVA transformer in the same way as the experiments and simulations of the 2.4kVA transformer corresponded to each other. As we do not have a 400MVA transformer to test in the laboratory, the results of the simulations are of great importance.

Single phase transformers without GIC

Just as for the 2.4kVA and the 400MVA transformer, a test without GIC, load or compensation was conducted, in order to have a reference point to compare the following tests with. The p.u primary current of this transformer is smaller, than the p.u primary current of the 2.4kVA transformer in the simulations, which is rather expected, as the inductance of a large transformer is greater. However, compared to the 400MVA 130/400kV transformer, the unloaded primary current is larger for this transformer. This indicates a larger impedance in the 400MVA 130/400 transformer, relative this transformer. The primary and tertiary currents can be seen in Figure A.1

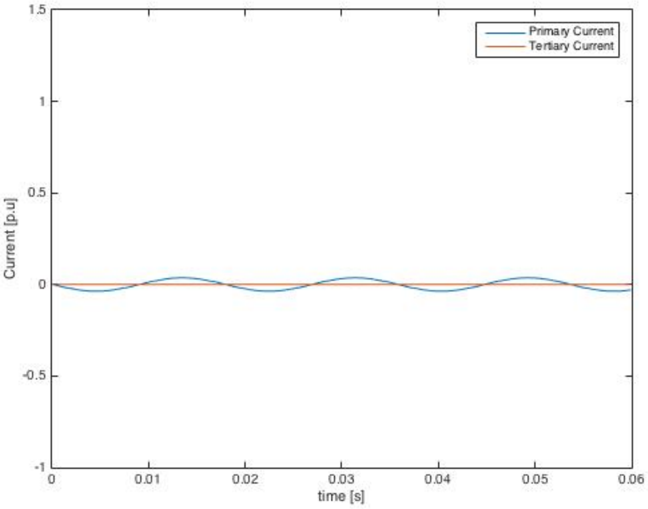


Figure A.1: Simulations of 400MVA 400/230V transformers, without compensation windings and GIC

Single phase transformers

As the GIC is introduced to the simulations, the primary winding got current spikes, just as expected. When comparing the amplitude of the spikes between this transformer and the 2.4kVA transformer, it is very clear that the amplitude of the current spikes are a lot larger for the 400MVA compared to the size of the sinusoidal current, however the maximum amplitude of the current spike in p.u are quite similar for the two cases. This behaviour was expected, as the ratio between inductance and resistance is a lot greater for the 400MVA, see Figure A.2. Hence it looses a greater part of its impedance when the core saturates, leading to larger difference in current between the saturated and unsaturated areas. However, when the comparisons are made between this transformer and the 400MVA 130/400kV transformer, it is clear that the 400MVA 130/400kV transformer suffers greater negative impact due to the GIC. This is due to the fact that the GIC enters the high voltage side of the 400MVA 130/400kV transformer, meaning the GIC will make a larger number of turns around the core, resulting in a deeper saturation than for the 400MVA 400/230kV transformer.

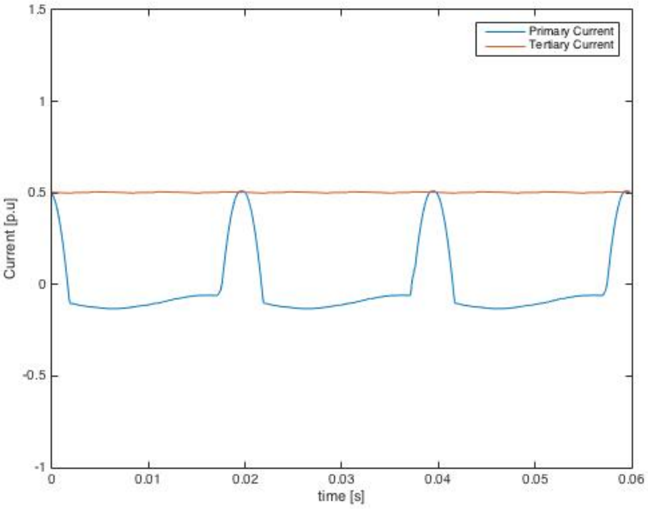


Figure A.2: Simulations of 400MVA 400/230kV transformers, without compensation windings.

Single phase transformers with perfect compensation

Just as expected, after studying the previous results of perfect compensation, the current in the primary windings for a perfectly compensated transformer that is exposed to GIC is identical to the current of a transformer that is not exposed to GIC. This can be seen in Figure A.3, where the primary current can be compared to the primary current in Figure A.1, which is the uncompensated 400MVA transformer that is not exposed to GIC.

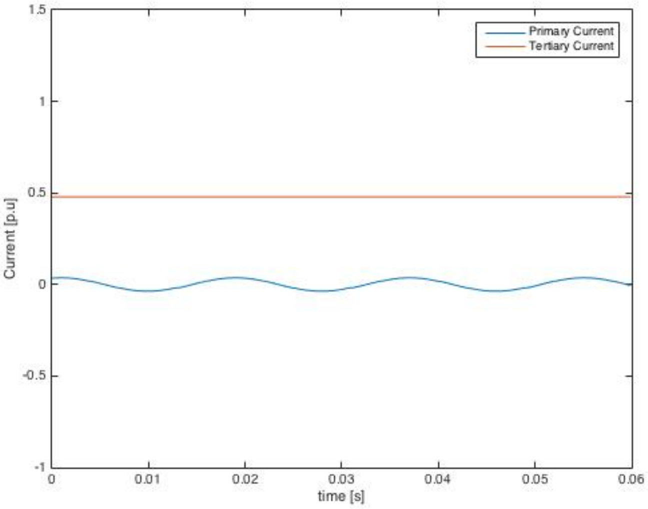


Figure A.3: Simulations of 400MVA 400/230kV transformers, with perfect compensation windings.

Single phase transformers with three fourths compensation

Just as in previous cases, the amplitude of the power spikes was reduced as the mitigation windings were connected. However, the amplitude of the current spikes were still rather large compared to the unsaturated area for this transformer, even though the GIC impact is mitigated by three fourths. The reduction of the current spikes is great when comparing figure A.4 with A.2, which shows that the mitigation works well. However, the spikes are still large compared to the unsaturated wave form due to the fact that the impedance is almost purely inductive for a transformer of this size.

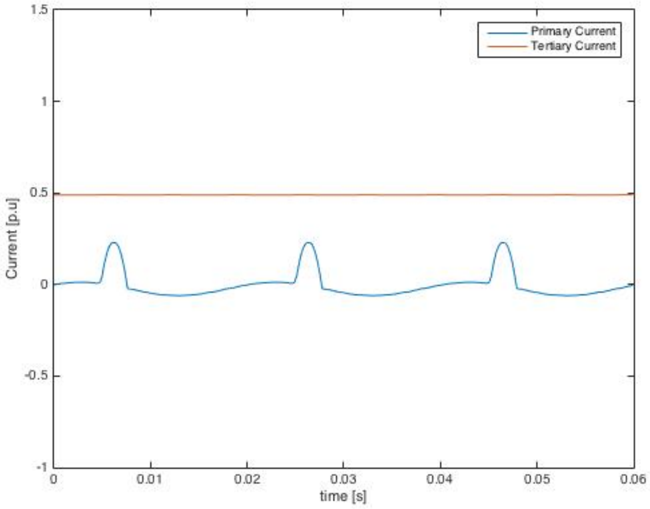


Figure A.4: Simulations of 400MVA 400/230kV transformers, with three fourths compensation windings.

Single phase transformers with over compensation

Finally, when the tertiary windings are over compensating for the GIC, the current spikes of the primary windings were in the opposite direction of the GIC, as in all the other cases before. The only difference with this big transformer is that the amplitude of the spikes is a lot greater compared to the sinusoidal magnitude. As mentioned before, this is due to the high inductance and low resistance of the 400MVA transformer.

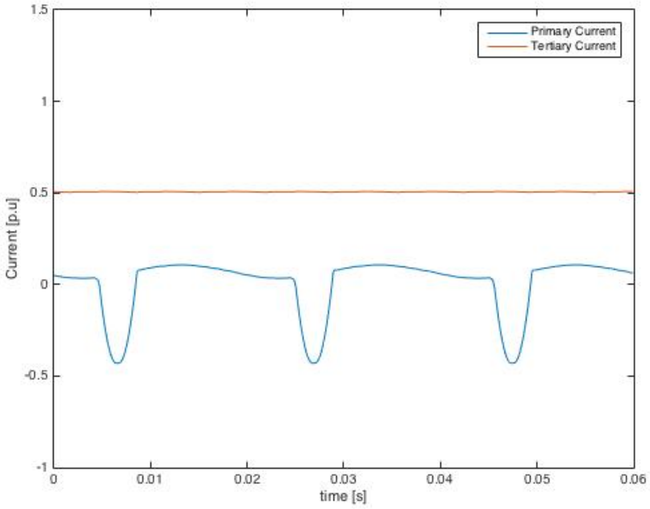


Figure A.5: Simulations of 400MVA 400/230kV transformers, with over compensation windings

Appendix B

List of material

Table B.1: Equipment

#	Item
3	Single phase trafo, 800VA
1	Three legged trafo, 2.4kVA
1	Five legged trafo, 2.4kVA
1	Synchronous generator, 200kVA
1	Variac
2	ASEA Three phase trafo, 2kVA
2	12V car battery
1	circuit board
7	Multimeter
2	Fluke AC current probe
2	Kyoritsu AC/DC clamp adapter
1	Tektronix differential probe
1	Esselte-studium differential probe
1	ASEA-education load capacitor
1	Tramo-ETV load inductor
2	Terco load resistance
1	Powerbox-6303DS

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