Transformer Based Solutions to Power Quality Problems

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Abstract

In this paper we propose transformer-based solutions to several power quality problems. Elsewhere we have shown how to solve the acoustical noise emission problems. In this paper we introduce toroidal transformers with reduced inrush currents, transformers with reduced electromagnetic emissions, and other transformers useful to reduce the transfer of harmonics. With the low-inrush transformers we are able of eliminating (or reducing) voltage sags and nuisance service interruptions caused by false operation of breakers and fuses. The low-stray emissions transformers are used for reducing the electromagnetic interference (EMI) caused by stray fields emitted from the transformer. Electromagnetic noise reduction transformers (NRT) are used reduce the harmonic pollution problem.

Because of their construction tape-wound toroidal transformers are more efficient and produce less acoustical and electromagnetic noise than standard E-I transformers. Therefore, properly designed and built toroidal transformers are smaller and/or work cooler. The power density (per volume or weight) is larger. The sole disadvantage could be that standard toroidal transformer designs produce larger inrush currents. We have solved the inrush problem right from the transformer design without resorting to external inrush limiting circuits. Therefore we increase the reliability of the overall system while simultaneously reducing cost. We have also reduced the electromagnetic field emissions even below the already reduced fields emitted by standard toroidal transformers. In addition, we have invented a transformer with a narrow frequency bandwidth to limit the transfer of harmonics from primary to secondary or viceversa.

1. Introduction

In this paper we present transformer-based solutions to several power quality problems. One is a solution to the large inrush currents that a transformer draws from the line at switch-on. Another one is the reduction of electromagnetic field emissions from transformers. And a third one is the reduction of electromagnetic noise. The latter problem is also commonly referred as harmonic pollution, common mode and/or differential mode noise.

Toroidal transformers are more efficient and produce less acoustical noise than standard E-I transformers. They draw less magnetizing current in steady state. Therefore, they are smaller and/or work cooler than transformers made with stacked laminations. The power density per volume or weight is larger and typically less expensive in sizes from 3 kVA to 20 kVA. The main reason for this is that the core of toroidal transformers is wound with a continuous tape of grain oriented silicon steel (GOSS) with no gaps and all grains are oriented in the preferred direction. Paradoxically, this highly efficient use of the steel produces larger inrush currents. The transformer inrush currents may cause voltage sags and nuisance service interruptions caused by false operation of breakers and fuses. In some instances (for example in UPS systems) this false disconnection may be of fatal consequences. To prevent service interruption the protective elements are commonly specified with a much larger than needed rating. This produces that, for safety approvals, every component (including the transformer) connected to primary side is (at the very least) temperature overrated.

In the current state of technology there are a number of solutions, external to the transformer, for the inrush current problem. For example, soft start power electronics, pre-insertion resistors, thermistors, etc. Using special design and manufacturing techniques we are able to substantially reduce the inrush currents that a toroidal transformer draws from the line. By the wise selection of core materials and transformer design/manufacturing processes we can control the magnitude of the inrush currents.

Toroidal transformers emit reduced electromagnetic noise when compared to transformers built with bobbins on staked laminations. The reason for this is their closed geometry. The first winding completely covers the core. Subsequent windings completely cover the internal windings. Therefore the electromagnetic coupling is maximized.

The standard solution to electromagnetic interference (EMI) problems caused by transformer stray fields is to add electromagnetic shielding. Typically a few layers of GOSS are wound around the transformer to prevent the stray fields from escaping the side of the transformer. We believe that the problem needs to be solved at the source. In addition, shielding becomes less effective as the frequency reduces. For example, 50/60 Hz electromagnetic fields are very difficult to stop. We have researched on several design/construction techniques to obtain a toroidal transformer with much more reduced stray field emissions. We have examined design and construction parameters such as: core material and geometry, winding style and sequence, lead work, insulation system, etc.

Harmonic pollution is becoming an increasingly important power quality issue. There are already available a large number of solutions. One can find an ample gamut of passive and active filters. While some of those filters do a good job, they reduce the reliability of the system and could be expensive. The transformer-based solution to the problem of harmonics is to furnish the transformer with filtering power.

2. Low-Inrush Transformers

2.1 Inrush Currents in Transformers

Transformer inrush currents are originated by the high saturation of the iron-core during the switching-in of the transformer. Good physical explanations can be found in many sources; see for example [1] or [2]. The driving force of the inrush currents is the voltage applied to the primary of the transformer. This voltage forces the flux to build up to a maximum theoretical value of double the steady state flux plus remanence. Therefore, the transformer is greatly saturated and draws a large amount of current. Since the current is of short duration there are not adverse effects to the transformers, however, the protective devices for overloads may falsely operate and disconnect the transformer.

The idealized behavior (ignoring resistances) of the inrush currents is governed by Faraday’s Law:

$$v(t) = \frac{d}{dt}\, l\,(t) \tag{1}$$

Where *v(t)* is the instantaneous voltage applied to the transformer primary and λ*(t)* is the instantaneous flux linkage of the winding. Since the voltage is the driving force, the flux builds up according to:

$$l\,(t) = \int_0^t v(t)\, dt \tag{2}$$

When we neglect the leakage flux, the following relationship is true:

$$l\,(t) = N\, f\,(t) \tag{3}$$

Where *f(t)* is the total instantaneous flux in the core and *N* is the number of turns of the winding. Combining (2) and (3) we have

$$f\,(t) = \frac{1}{N}\int_0^t v(t)\ dt \tag{4}$$

If we assume that the voltage is sinusoidal

$$v(t) = Vm\ \ \sin(w\,t + j\ ) \tag{5}$$

equation (4) results in:

$$f\,(t) = \frac{Vm}{Nw}[\cos f - \cos(w\,t + j\ )] + f\,(0) \tag{6}$$

Assuming that the remanence at *t=0* is *f(0)=Fr,* the maximum flux that can be built in the core is when the closing angle is φ=0. Under these conditions the maxim flux will be

$$\Phi\,\mathrm{max} = 2\frac{Vm}{Nw} + \Phi r = 2\,\Phi m + \Phi r \tag{7}$$

See Figure 1 for a graphical description of the inrush current phenomenon. The effect of the remanence is depicted in Figure 2.

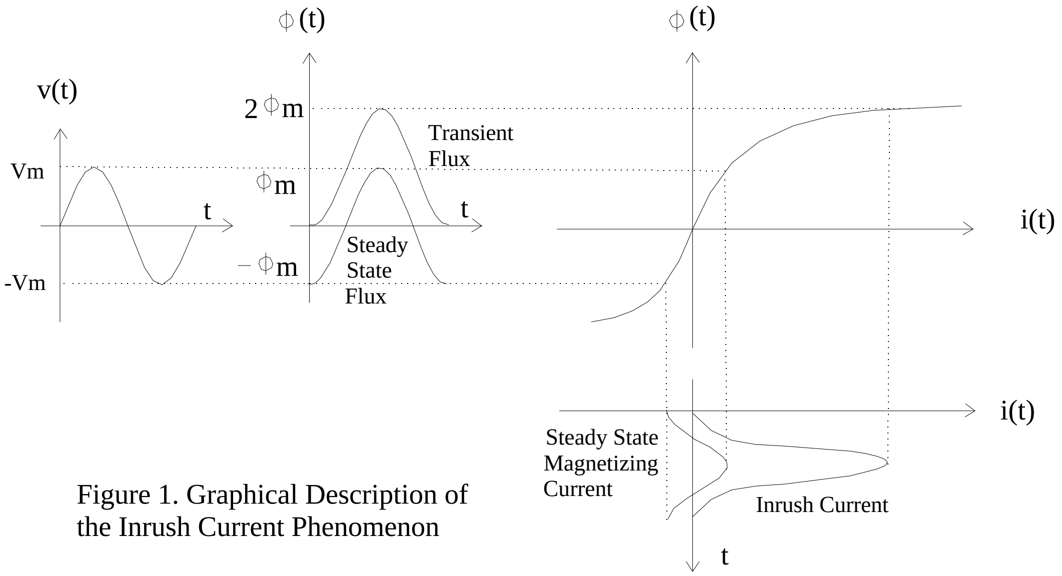


Figure 1. Graphical Description of the Inrush Current Phenomenon

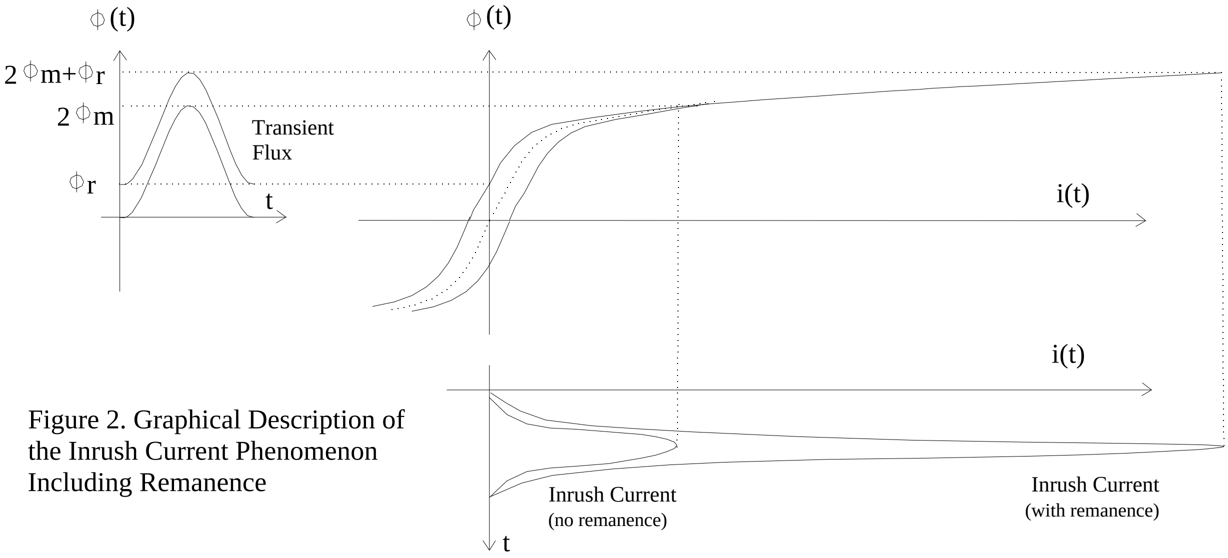


Figure 2. Graphical Description of the Inrush Current Phenomenon Including Remanence

By considering the resistance of the winding we note that not all the voltage goes into building up flux in the core. Some voltage is dropped in the primary resistance and thus there is a reduction on the maximum flux. As a consequence a reduced amount of inrush current is drawn from the line; see Figure 3. Note that the transformer designer cannot increase the primary resistance too much before falling into thermal problems.

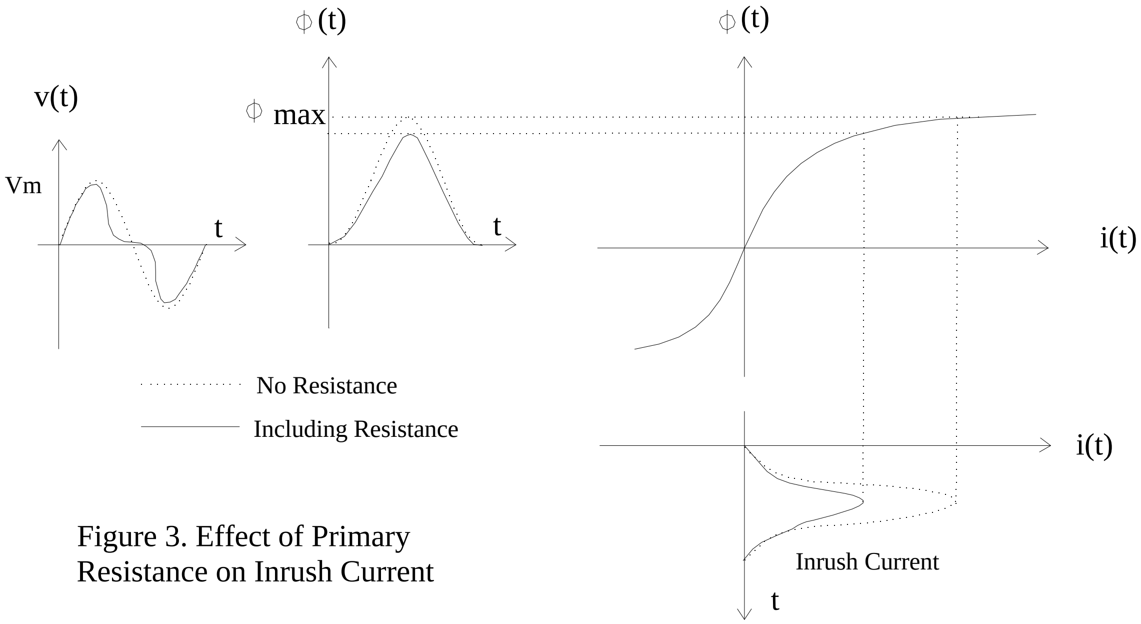


Figure 3. Effect of Primary Resistance on Inrush Current

2.2. Alternatives for Limiting Inrush Currents

There are several (external to the transformer) approaches to the reduction of the inrush currents. The main parameters controlling the magnitude of the currents (once the transformer is built) are the remanence, the switching angle and the resistance of the primary circuit. The following techniques are used to control one of the parameters:

Controlled Resistors. Pre-insertion resistors are used in series with the primary. They are removed form the circuit after the connection. Those resistors can be controlled by temperature (thermistors), time, they can have negative resistance, two stage switching, etc. The disadvantage is the addition of series components that reduce the overall reliability. In addition, not all solutions are effective under all operating conditions, for example a thermistor will not be effective against a service interruption of a few cycles because it does not have time to cool down.

Controlled Switches. The exact time (or angle) for switching-in the transformer is controlled by adding series electronic components [3]. This solution has the same disadvantages as the previous technique.

Reducing the Remanence. There are two techniques in the literature to eliminate the remnant flux. (1) By connecting a capacitor in parallel with the transformer. This technique takes advantage of the disconnecting transient to eliminate (or reduce) the remanence [4,5].

2.3 Transformer-Based Solutions to Inrush Currents

We have solved the inrush current problem by the use of special core materials and design/construction techniques. Our solution does not require of external components, however, the transformers can be bulky and more expensive.

Currently virtually all power transformers are built with high permeability GOSS cores. An unwanted feature of using high permeability core materials is that the inrush currents are largely increased. This is even more problematic when the transformers are toroidal shaped made of tape wound GOSS. To solve the inrush problems, transformer manufacturers resort to gaps in the core. Gapping is an expensive production methodology and is difficult to control and test. In addition, gapped transformers become acoustically noisy.

With our proprietary technology (gapless) we can produce toroidal transformers that have reduced inrush currents without resorting to gaps or external components. The magnitude of the inrush currents has become another specification to meet rather than a problem.

3. Stray Fields in Transformers

We should make a very clear distinction between *leakage* field (or flux) and *stray* field (or flux). The leakage is formed by the flux that links one winding and does not link the other winding. It can be measured as a voltage drop at the transformer terminals. The leakage flux does not necessarily escape the transformer. Stray fields necessarily escape the transformer. The stray flux can link one or two of the windings. Stray flux can exist in the air without adding to the leakage inductance. The stray flux is not measured as a voltage drop at the terminals. It can be measured with a coil in the neighborhood of the transformer. A portion of the leakage flux can also be stray flux when it escapes the transformer boundaries.

Stray fields emitted from a transformer (or any other electrical device) can cause serious operating problems to the surrounding electronic components. EMI/EMC issues are becoming increasingly important. Our experience shows that sound amplifiers are very sensitive to stray fields.

3.1 Production of Stray Fields

There are two sources of stray fields in the neighborhood of toroidal transformers: (1) Current in windings according (Ampere's Law), and; (2) Core released due to the imperfection of the material: boundaries, misoriented grains, inclusions, and stacking effects [6].

The fields produced by current in windings are very much dependent on winding geometry and strategy: interleaving, number of layers, size of conductor, crossovers. In general, a uniformly distributed winding produces less stray fields. Core emissions due to imperfections are dependent on core geometry, for example, flat and tall geometries behave differently.

In [7] there is a comparison between the losses and stray fields caused by different winding strategies. The effects of the position of the turns in the same layer are analyzed, for example sector winding, interleaving, winding overlapping, separation between turns and distance from primary to secondary. The effect of the number of layers and gaps is also shown. The comparisons are made using the resistance and leakage inductance as measurement.

3.2. Alternatives for Reducing the Effects of Stray Fields

The standard solution to the problem of stray fields is the addition of shielding. This solution is effective although frequently is not economical. The rules of shielding are governed in a simplified way by the penetration depth defined as:

$$d = \sqrt{\frac{2}{wms}} \tag{8}$$

where:

δ = Penetration depth
ω = Angular frequency (= $2\,\pi f$)
f = Frequency (the smallest frequency to be shielded)
μ = Permeability of the shielding material
σ = Conductivity of the shielding material

The penetration depth works very much as a time constant. The percentage of stray field reduction introduced by a shield is given by:

$$\%\text{Reduction} = 100\left(1 - e^{-\frac{d}{d}}\right) \qquad (9)$$

Where d is the thickness of the shield. As a rule of thumb when $d = 4d$ we have better than 95% shielding. When $d = 5d$ we have better than 99% shielding

2.3 Transformer-Based Solution to Stray Fields

We propose to solve (or reduce) the problem right at the source. We have new transformer design techniques to reduce the amount of stray fields emitted. We have made a substantial number of experiments varying the following transformer design parameters: (1) The permeability of the core; (2) The design flux density; (3) The coupling between primary and secondary winding; (4) The coupling between the windings and the core; (5) The sequence of winding; and (6) The lead terminations.

We can now design transformers with reduced stray field emissions. We have been able to further reduce the amount of stray fields emitted by a toroidal transformer by a factor of 2 to 5 when compared to the standard practice. The following design parameters play important roles in reducing the stray fields:

a) The design flux density.
b) The permeability of the material.
c) The core geometry (flat, tall, squared cross sectional area, etc.)
d) Winding sequence.
e) Winding style (precision, random, casual, bank, sector, etc.)
f) Single, bifilar, or multi-filar windings.
g) Use shielding core bands.

4. Electromagnetic Noise – Harmonic Distortion

4.1 Sources and Effects

Harmonic distortion is a deviation of the voltage (or current) from the ideal sinusoidal wave. The sources of harmonics are mainly power supplies based on electronic elements (rectifiers, SCR, etc.). These are virtually all the power supplies used in most modern industry, office, and house hold equipment (computers, fax machines, speed drives, etc.). There is a great number of book and papers on harmonic distortion; see for example [8-10]. The negative effects of harmonics include overheating of transformers and motors, malfunction operation of electronic components, high currents in the neutral, problems with computing and communication equipment, etc.

4.2 Electromagnetic Noise (or Harmonic) Reduction

There are several ways to eliminate (or reduce) the transfer of harmonics (or electromagnetic noise). The first one devised was the use of tuned passive filters. They consist of an inductor in series with a capacitor. The circuit is connected in shunt with the load. The capacitance and inductance are computed in such a way that the selected harmonic is shorted to ground. This happens at the frequency of resonance:

$$fr = \frac{1}{2p}\frac{1}{\sqrt{LC}} \tag{10}$$

This filtering system work well for a few low-order large-magnitude harmonics. For higher order harmonics and smaller magnitude low pass filers (passive) are preferred. They consist of one or more sets of series inductors with shunt capacitors. As the frequency increases the impedance of the series inductance increases blocking the circulation of high frequency currents. Simultaneously, as the frequency increases, the shunt impedance of the capacitors reduces, shorting the high frequency currents to ground. These solutions have the disadvantage that the reliability of the overall system reduces due to the addition of components.

There are also a number of possibilities for active filtering. Since the main source for distortion is power electronic elements, also power electronics can be used to clean the line. Complex electronic systems (with feedback and amplification) are already available to perfectly clean the line. However, they are expensive and also reduce the reliability of the system.

4.3 Transformer-Based Solution to Harmonics Problem: NBT

NBT (Narrow Bandwidth Transformer) is an isolation transformer technology that reduces the distortion commonly present in the mains. This newly invented technology has been patented [11]. NBT is an electromagnetic noise reduction transformer (NRT) with a very narrow passing frequency band. Narrow Bandwidth Transformers damp distortions in the mains due to harmonics and spikes. It is very effective for damping high and very high frequency signals. NBT technology is compatible with all transformer design technologies (E-I, tape wound, etc) including toroidal.

NBT work based on the combination of the phase cancellation principle and the increase of the internal series inductance. Phase cancellation is obtained by connecting a bifilar winding in contraposition through a capacitor. By adjusting the series inductance and the capacitor we can control the passing bandwidth of the transformer.

Figure 4 gives the essentials of the new Narrow Bandwidth Transformers (NBT) filter technique. The secondary winding (or the primary winding) is extended with an extra winding (the fp winding), with equal number of turns, connected in reverse phase to the existing secondary winding through a capacitor C_{fp}. At low frequencies, the impedance of the capacitor C_{fp} is high, the capacitor acts as an open switch, only one secondary winding functions and thus the 50/60 Hz is free to cross the transformer. At higher frequencies (above 1 kHz), the capacitor begins to act as a closed switch. Both secondary windings are now at 180 degrees phase difference. Therefore the voltage induced in the two windings cancel one another and no transfer of high frequency signals occurs. The transformer acts as an effective low pass filter with adjustable bandwidth.

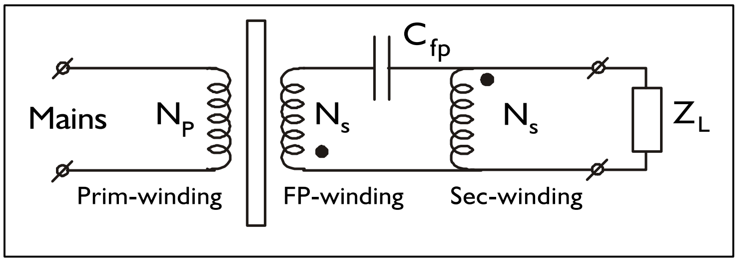


Figure 4. Principle of NBT filtering

5. Comparative Results

5.1 Inrush Currents

We have performed a large number of inrush current tests. Special lab equipment is required to perform reliable inrush current experiments. One needs a strong power source, a controlled switch, and proper instrumentation. Large currents may easily produce substantial voltage dips in the power source. We have built an 86 kVA transformer to serve as the power source for inrush current tests on transformers up to 10 kVA. We have an inrush switch box that allows energizing a transformer at the moment when the voltage is crossing the zero value. We also have the required instrumentation to perform accurate measurements. It is important to note that it is easy to make inaccurate measurements when the proper equipment is not available.

Figure 5, shows the case when a weak power source is used to test a 7.5-kVA standard toroidal transformer. The peak inrush current is about 650 Apk. The same transformer measured more than 900 A pk with the 86 kVA power source. In Figure 6 we show the results when a similar transformer is designed for low-inrush. This transformer was subjected to a more severe test is the double-pulse test. This test is when a negative (or positive) voltage semi-cycle is suppressed. This condition yields the maximum possible inrush current, since the first semi-cycle takes the transformer to the maximum remanence and the second semi-cycle builds the flux in the same direction to produce the maximum possible saturation. The test is important because some UPS units could operate under those circumstances. The maximum inrush current for the low-inrush design is only 380 A pk even when the load current has been added. Table 1 shows comparative examples of standard versus low-inrush designs.

Power [VA]	Standard Design [A pk]	Low-Inrush Design [A pk]
500	360	5.5
1000	520	7.0
1500	600	8.0
2000	700	10.0
3000	900	13.5
5000	1000	We can design the transformer to draw inrush currents that can be coordinated with the protection device.
7500	1100	
16000	1500+	
20000	1600+	

Table 1. Inrush current comparison for standard versus low-inrush designs

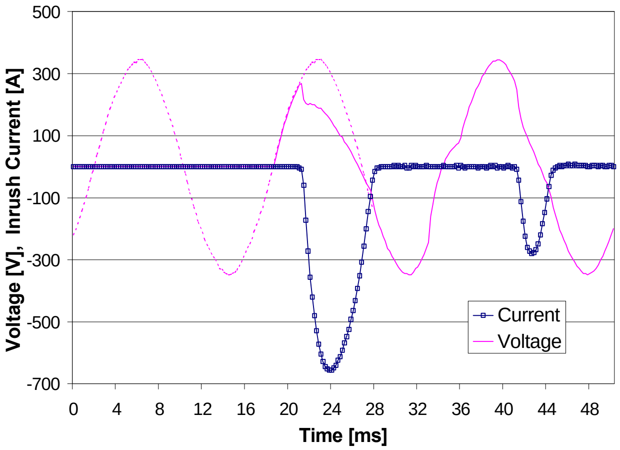


Figure 5. Inrush current test on a 7.5 kVA transformer with a weak power source

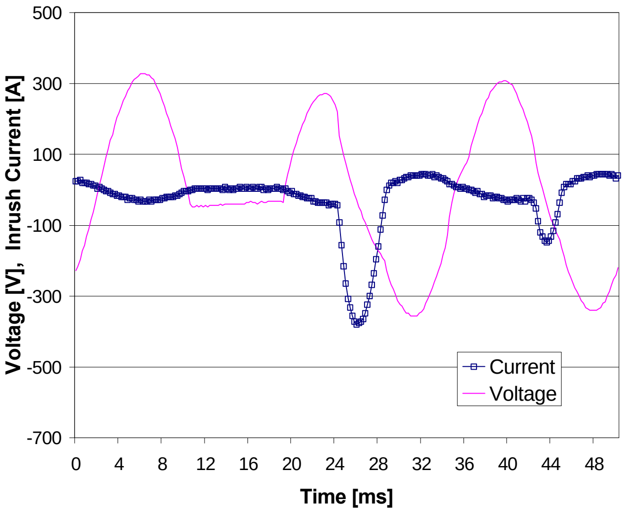
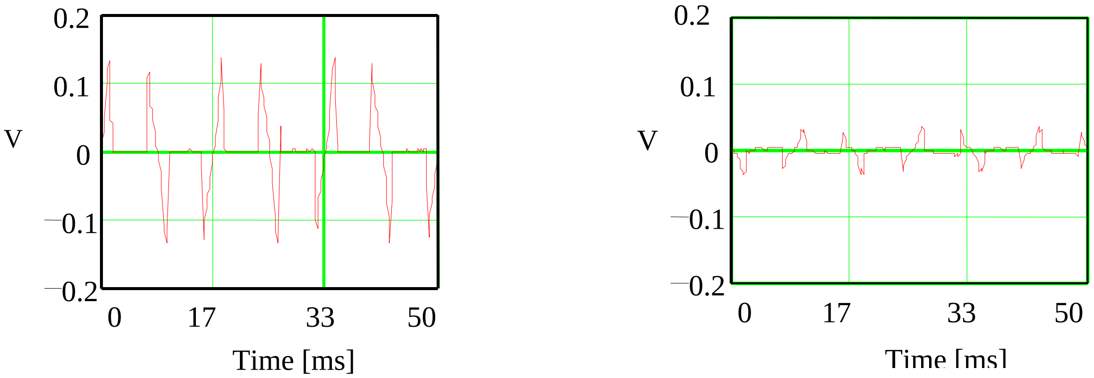


Figure 6. Double-pulse test on a 7.5 kVA low inrush design with a large power source

5.2. Stray Fields

We have measured the stray fields on a large number of transformers and under varied conditions. Figure 7 presents a graphical comparison of the stray fields measured with an inductive probe when a small transformer is supplying a bridge rectifier. The probe measures the stray field emitted by the transformer from the top. The pick-up is at and inch from the transformer surface. The peak value of the induced voltage for the standard design is 138 mV while for the low-stray transformer design the peak value is only 38 mV. For this case have reduced the stray fields by 72.5%.



(a)

(b)

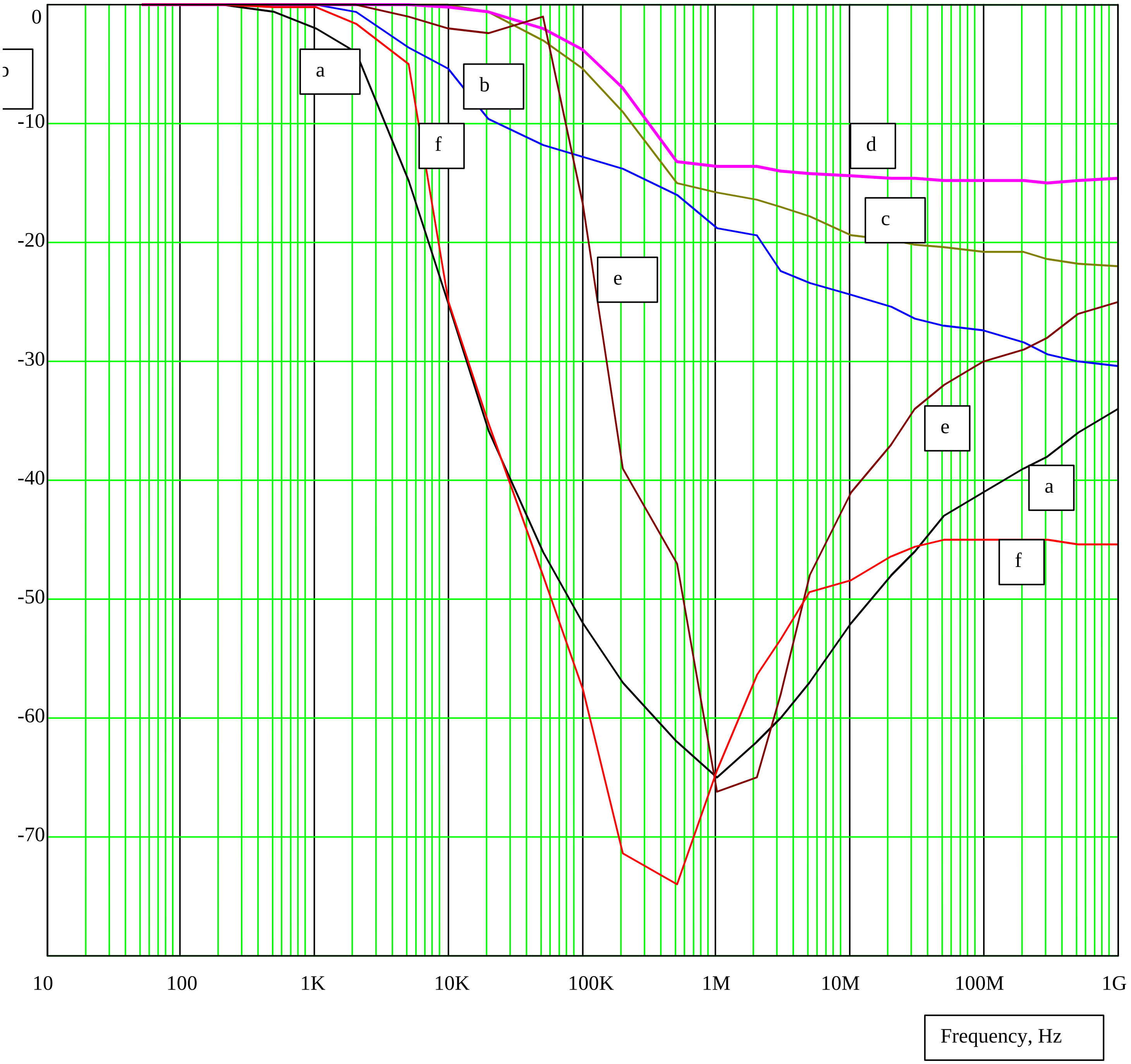
Figure 7. Comparison on the stray fields emitted by a small transformer
(a) Standard design; (b) Low-stray field design

5.3. Narrow Bandwidth Transformers (NBT)

Figure 8 shows the normalized frequency transfer measurements on four different power transformers from primary to secondary. In this measurement the primary input voltage, delivered by a separate oscillator, is kept at a constant level. Measurement 1 is a standard toroidal transformer. It is clearly visible that up to 200 kHz there is almost no decrease in secondary output voltage as function of the frequency.

In measurement 2 a special toroidal transformer is used with increased leakage inductance between the primary and secondary winding. Up to 50 kHz this leakage inductance creates a first-order low pass filter. Above 50 kHz the capacitive coupling between primary and secondary windings takes over, resulting in a slight increase of the transfer function up to 200 kHz. Measurements 3 and 4 were performed on two different NBT with enlarged leakage inductance. They clearly show the large reduction in transfer from the primary to the loaded secondary winding. The leakage inductance and the fp-capacitor were given values such that the corner frequency of the low pass filter is at 1 kHz.

Frequency Response Comparison for NBT design against standard, balanced power, and standard with commercial filter



a) NBT, center-tap, with load across one winding
b) Balanced power with Screen
c) Standard part with screen
d) Standard part no screen
e) Standard part using commercial Filter
f) NBT, secondary in series connection

Conclusions

In this paper we have presented transformer-based solutions to common power quality problems. We have shown that transformers can be built with a specified inrush current. Therefore the inrush current issue has become another transformer specification rather than a problem. We have also shown transformers with much reduced electromagnetic emissions. The techniques presented in the paper will help in the reduction of EMC/EMI problems. Additionally, we have shown the working principle of a new transformer technology for harmonic filtering. These Narrow Bandwidth Transformers (NBT) use the phase-cancellation principle and the increase of the leakage inductance to furnish a transformer with substantial filtering power. The transformer becomes in fact a low pass filter. The frequency at which the filtering starts is a design parameter and can be set to any desirable value.

6. Acknowledgements

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