Power Transformer Attenuates Harmonics

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A novel line-frequency transformer design shapes the transformer's leakage inductance, internal capacitance and resistance to create a low-pass filter that suppresses noise generated by nonlinear loads and RF interference.

The mains of the world were constructed as a giant copper causeway to transport electricity from the generating station to our homes and factories. Today's problems on the mains were unknown a few years ago, when power grids were expanding all over the continent. No provision existed to carry frequencies that are thousands of times higher than the fundamental power bandwidth.

A new form of pollution envelops us from within our walls and is interfering with the operation of our appliances and our lives. Uncontrolled harmonics can diminish the life span of equipment and accelerate failures; can cause excessive heat in many appliances, leading to shock and fire hazard; and can increase power consumption and reduce system efficiency. Most insidiously, these harmonics can propagate through the power grid and infect everyone in the neighborhood.

A common approach to cleaning the mains is through the use of an LCR filter network. However, an innovative alternative addresses the causes of line distortion and offers a simple transformer-based solution to clean up the mains. This approach doesn't rely on separate inductors, capacitors and resistors, but instead defines the filter based on the transformer's inherent internal characteristics of leakage inductance, internal capacitance and resistance.

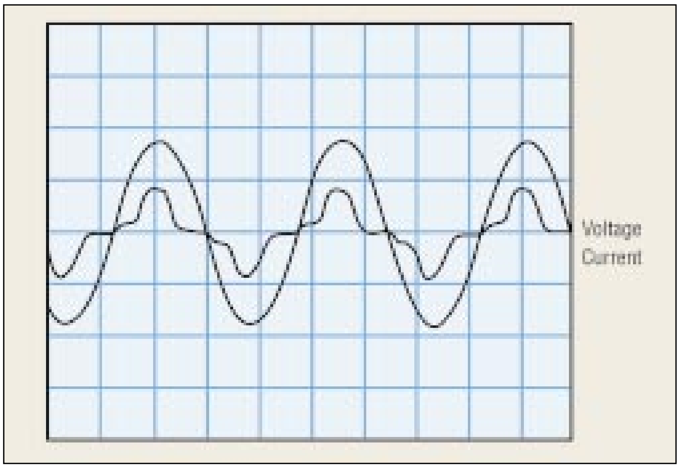

Fig. 1. *Voltage and current waveform for nonlinear load. The voltage waveform is sinusoidal, but current waveform is not.*

Sources of Harmonics

Harmonics are currents and voltages at frequencies that are integer multiples of the fundamental power frequency. As a result, power lines contain pure undistorted 50-Hz or 60-Hz sine wave voltages as well as other signals. The sine wave is distorted and consequently harmonics of the 50-Hz or 60-Hz fundamental are found. At higher frequencies, switching transients appear from rectifiers, motor drives and other sources. In addition, at frequencies above 50 kHz, strong HF signals from radio, TV and computers are superimposed on the line and appear across the primary winding of a transformer.

These extra signals, called noise or distortion, appear in two ways on the power lines. At frequencies above 1 MHz, noise is mostly common mode, which refers to both line and neutral containing an equal amount of amplitude and phase distortion. For frequencies below 1 MHz, the major component of the noise is typically differential mode, where the noise on line and neutral sides is equal in amplitude and opposite in phase. Differential-mode noise generates a real noise voltage difference between line and neutral.

If all these harmonics and noise on the line are detrimental and dangerous, why isn't there some sort of control over the power quality leaving the generation station? As a matter of fact, there is. The power leaving the plant and fed into the power grids is clean, green and sinusoidal

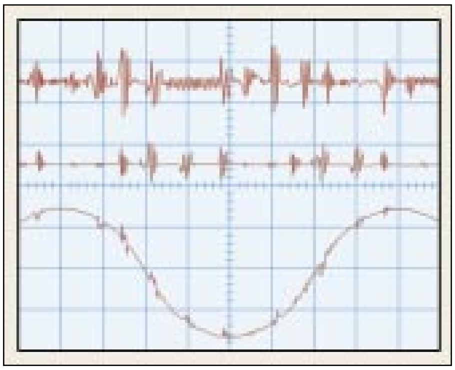

Fig. 2. *Waveforms showing harmonics typical in switching devices.*

in nature. It is rare that the lowly state of power found downstream is related to the source generator. We must look elsewhere for the source, not to the generation of power.

The harmonics generated downstream can find their way back onto the utility lines and affect all power users on the system, and ultimately adversely affect the operation of utility and distribution power transformers all down the line. All loads in common with the transformer secondary share the effects of the harmonics—so it's a community issue.

Most harmonics originate from the generation of harmonic currents caused by nonlinear load signatures. A nonlinear load is characteristic in products such as computers, printers, lighting and motor controllers, and much of today's solid-state equipment. With the advent of power semiconductors and the use of switching power supplies, the problem has become more severe in the last few decades. Most of these products didn't exist 30 years ago, thus the trouble is recent and a direct result of technological innovation.

A nonlinear load draws current in a non-sinusoidal manner, despite the fact the voltage may be perfectly sinusoidal (Fig. 1). Nonlinear loads draw current during a portion of the incoming voltage waveform, not continuously as with a light bulb. Current is drawn in bursts or planned abrupt pulses, as required by the product. The result is distorted current wave shapes, the harmonic content of which can flow back and contaminate other parts of the power supply (Fig. 2).

Harmonics and the resulting harmonic distortion are a constant repetitive occurrence within a product. Sometimes transients on the line are confused with harmonics, but they are not the same. Transients typically are not related to normal operating conditions and are a random occurrence with no repeatable time signature or frequency.

Electronics Demand Clean Power

Although the root cause of the harmonic problem is the same in different settings, the magnitude of the problem is scalable and shows up at many levels. On an industrial commercial scale, it's not uncommon for a building or plant engineer to face nonlinear loads in excess of 25%.

Most installations can manage 10% to 15%. However, seemingly unaccountable though symptomatically predictable things begin to occur when the total harmonic distortion (THD) levels rise above this range. Local distribution transformers can become inductively overheated for no apparent reason and suffer minute levels of daily deterioration. Their usable life is shortened and early failure will result.

Problematic harmonics for commercial and industrial sites are the always dreaded third, fifth, seventh, eleventh and a few other assorted odd numbers. Within the affected site, other harmonic-induced problems will be experienced, such as electronic equipment shutting down as a result of voltage distortion, nuisance fuse interruptions, motor failures due to overcurrent caused by undervoltage, and various other destructive, mysterious equipment anomalies. Thus, it can be seen that on an industrial, commercial or residential scale the affects of harmonics are becoming a severe but hidden catalyst resulting in equipment failure, expensive downtime and low-efficiency power utilization.

On a smaller desktop scale, the problems of an uncontrolled harmonic-rich environment manifest themselves in other ways. Our focus will be on desktop and household scale. Electronic equipment is sensitive to noise entering through the power line. This unwanted noise may affect the product in many ways, including performance degradation and malfunctions. The problematic harmonics for computers and equipment are higher in frequency than those that plague power systems. When dealing above 100 kHz or so, we would refer to them in terms of frequency rather than harmonic number, so the terminology would speak of a 5-MHz component and not the Nth harmonic.

Processing speeds are increasing at a fast rate. The clock frequencies and ultrahigh-speed operation of today's electronics would seem like science fiction to engineers a few decades ago. But because of the high clock rates associated with modern microprocessors and the high switching frequencies associated with switching power supplies, PCs and other equipment are guilty of generating and kicking back massive amounts of distortion into the line.

Ironically, the same equipment that generates this distortion demands clean power to operate. Modern electronic equipment depends on a low-distortion voltage supply to operate to spec, and there is high sensitivity to fluctuations and transients. In addition, large pulsating currents can cause flat topping of the voltage waveform. Noise can be introduced into susceptible cables or other components from high-frequency circulating currents, causing havoc with microprocessors and other sensitive components.

Common Solutions to Attenuate Noise

Effective noise rejection filters should

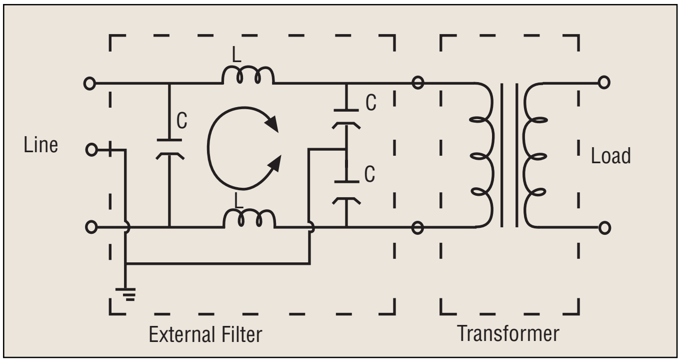

Fig. 3. *An external LC filter connected to the primary of the transformer. Series inductors must carry full primary current, and C following increases leakage current to ground.*

pass the 50-Hz or 60-Hz fundamental and remove all higher frequencies. However, the line source impedance, combined with the impedance of the actual load, is low (ranging from 1 Ω to 100 Ω at 50 Hz or 60 Hz). Therefore, for optimum attenuation, the impedance of the filter should be low as well. In reality, however, this would require impracticably large and expensive capacitors and inductors.

A more practical approach is to start filtering noise at frequencies above 1 kHz, where most of the unwanted noise is found and where such interference causes malfunction of electronic equipment. The filter should be of the low-pass type with second- or higher-order slopes. The internal capacitance and inductance inside the transformer are the tools to create the desired filter. A common solution is the installation of an off-the-shelf line filter, which is available in a variety of configurations from various companies (Fig. 3).

Sometimes, line filters are packaged in the same box with other primary circuit modules, such as an input selector switch (dials 100 Vac, 120 Vac, 220 Vac or 240 Vac positions), or an IEC connector for power cord or fuse housing assembly. These devices offer good filtering and attenuation and have proven successful in many products. Upfront line filters usually are specified for reasons such as compliance to CE or other legislated standards for radiated emissions, or in products where noise entering through the primary circuit is detrimental to the operation of the product.

External line filters are installed in series with the primary circuit, as shown in Fig. 3, and thus must carry the full primary current (load current passing through the inductors L). Therefore, there may be some power or performance limitation imposed by current handling capability of the series inductor as it must grow in size, weight and thermal dissipation to accommodate higher power devices. In addition, the high-pass shunt capacitors from line and neutral to ground increase system leakage current to ground. This becomes a significant factor where low levels of leakage current are demanded, such as in medical applications in patient care devices.

Another common solution is the use of K transformers.

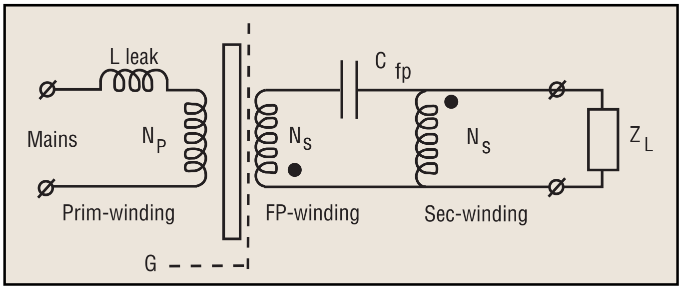

Fig. 4. *NBT with the external capacitor and control winding used where extreme extended high-frequency attention is required.*

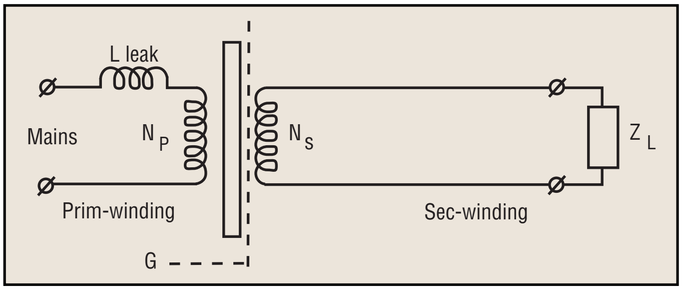

Fig. 5. *NBT circuit with standard construction. Attenuation is similar to external filter (Fig. 3). No series inductors or ground capacitors are required.*

Basically, a K transformer is a transformer built with any excessive temperature rise calculated strictly on I^2R losses. IEEE provides a formula to calculate THD and then derive a K number. At that point, it's simple for the transformer designer to understand the nature of the thermal issues as a result of harmonics and design accordingly. Use of multistranding will assist with heating from skin effect.

On installations where attenuation of high frequencies are not demanded but deemed as performance enhancements, such as in audio systems, a common noise reduction system on the market is balanced power. Balanced power uses no external components to achieve filtering, and makes clever use of offsetting characteristics of a precision designed and wound power transformer. Effective noise cancellation is achieved through phase cancellation of precisely offsetting wave shapes, realized by balancing secondary halves on a power transformer resistively, capacitively and inductively so that they cross cancel. The center tap is tied to the system ground, which is used for the discharge path.

One intrinsic concern in a balanced power configuration is the creation of a local elevated system ground at 60 V (center tap of 120-V winding), which necessitates electrical isolation from all standard 0-V ground points. Compliance to electrical codes may require ground fault detectors as a means of circuit interrupt in the eventuality the grounds collide.

The Transformer as a Filter

The three basic elements of a power line filter include L, C and R. A power transformer contains all three of these elements in the form of leakage inductance, internal capacitance and resistance. Therefore, we endeavored to determine a method to use the transformer's resident L, C and R as a filter and eliminate the requirement for external components. Following a two-year research project, Plitron Manufacturing Inc. developed a system called NBT, which stands for Narrow Bandwidth Technology.

Leakage inductance between the primary and secondary windings in all transformers already functions as a first-order low-pass filter. Its corner frequency is high—20 kHz for EI-transformers and 200 kHz for toroidal transformers (due to the toroid's inherently low leakage inductance).

Previously, leakage inductance and interwinding capacitance were viewed as a byproduct of the design of line-frequency transformers, a function of spacings and dielectrictics. NBT exploits these characteristics to attenuate all unwanted frequencies. Plitron has developed the means to accurately calculate specifications and to construct transformers to meet specified corner frequencies. NBT reduces line distortion within isolation or power transformers.

NBT transformers restrict electromagnetic energy to a very narrow passing frequency band. This technology allows the transformer to dampen distortion on the line due to harmonics and spikes. It is effective for attenuating high- and very high-frequency signals, whether originating on the line or generated by asymmetrical loads.

NBT can be adapted to most transformer-based power applications.

An NBT transformer performs as a low-pass filter with a selected corner frequency. The system is based on two principles that involve an increase of the internal series inductance and the phase cancellation principle.

We can use these two systems either combined (Fig. 4) or individually (Fig. 5). The value for leakage inductance L_{leak} is calculated through the following equation:

$$N\Phi_{Leak} = L_{leak}\, i$$

where N is the number of turns, Φ_{Leak} is the leakage flux and i is the current. Because leakage inductance is function of leakage flux, L_{leak} can be controlled by the design method. An effective filter can be achieved through controlled leakage inductance. This typically offers good attenuation to 10 MHz.

To extend the attenuation bandwidth into the gigahertz range, phase cancellation is obtained by connecting a bifilar-wound control winding in contraposition through a capacitor, C_{fp}, as shown in Fig. 4. The optimum value of C_{fp} is computed through P-Spice modeling, using Butterworth tuning:

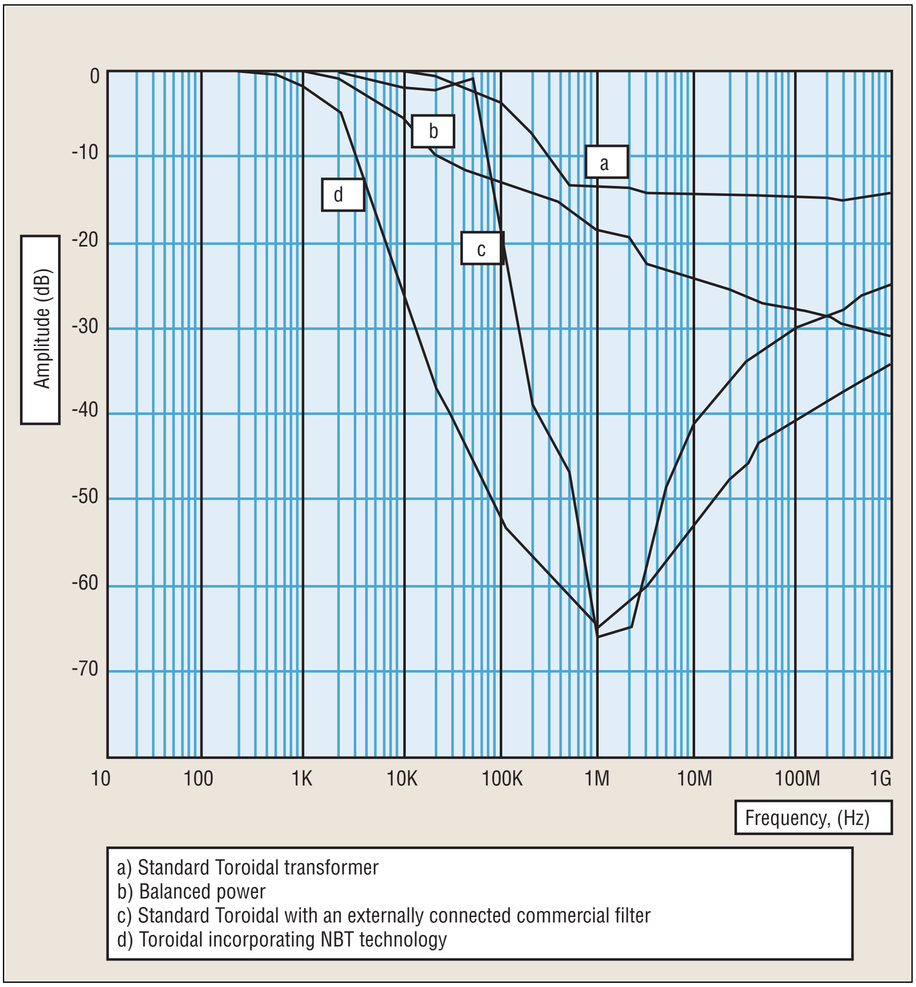

Fig. 6. *Frequency response for a standard toroid power transformer (a), balanced power transformer design (b), a standard toroid with a commercial filter (c) and an NBT design (d).*

$$C_{fp} = K (L_{leak} P^2) / (V_p^2 V_s^2)$$

where K is a constant, P is power, and V_p and V_s are primary and secondary voltages. At low frequencies, the capacitor acts as an open switch, allowing the power frequency (50 Hz or 60 Hz) to freely cross the transformer.

At high frequencies, the capacitor behaves as a closed switch. Therefore, the magnetic flux of the two windings cancels one another and full deletion of high-frequency signals occurs. By adjusting the series inductance and the capacitor, the passing bandwidth of the transformer can be controlled.

NBT resolves both differential and common-mode noise with the help of increased series inductance, phase cancellation principal and a reduction in primary to secondary capacitance. Typically, high-frequency filters are applied to remove the noise before the line voltage enters the power transformer that supplies the electronic equipment. However, with NBT the power transformer becomes an effective noise rejection filter and the external components to remove the high-frequencies are no longer required.

The elimination of primary-side filter components not only reduces parts count and cost, but also expedites safety agency and approvals certifications. In addition, reduced leakage current results from eliminating line-to-ground components.

How NBT Works

The two techniques of NBT—increasing internal series inductance and phase cancellation—satisfy different attenuation requirements. Simply adding leakage inductance has the affect of inserting a series inductor and removing any current handling limitations. The increased leakage inductance L_{leak} is the prime factor in the performance of the NBT design. The combination of the leakage inductance with the transformed capacitance from secondary to primary (C) and the primary dc-resistance (R) acts as a second-order low-pass filter. The corner frequency of the filter is determined by the combination of the L, C and R elements along with the load impedance Z_L.

To increase the usable frequency range, a capacitor can be added across a special control transformer winding. As depicted in Fig. 4, the secondary winding is extended with an extra winding (control winding), which has an equal number of turns to the existing secondary winding but is connected in reverse phase through a capacitor (C_{fp}).

At low frequencies, the impedance of the control capacitor is high, the capacitor acts as an open switch, only one secondary winding functions, and the 50 Hz or 60 Hz is free to cross the transformer. At higher frequencies (above 1 MHz), the control capacitor begins to act as a closed switch. Both secondary windings now generate magnetic flux in the transformer core; however, with 180 degrees phase difference. Therefore, the magnetic flux of the two windings cancels one another and full cancellation of high-frequency signals occurs. Then, there is no magnetic transfer of energy through the core to the secondary.

An advantage of this approach is the large impedance of L at high frequencies. Noise from the line will not be reflected at the input terminals of the transformer, but absorbed in L. At high frequencies, the NBT transformer will deliver no load to the power lines.

When the control winding is used to deliver energy to an extra secondary load, more efficient use of copper is made (Fig. 4). When the loads are equal, the total effective current through connection (2) becomes zero (phase cancellation). When connecting (2) to ground, a clean ground reference is created without high-frequency noise.

To verify the performance of the NBT transformer, frequency response tests were carried out, with the results shown in Fig. 6. The primary of the transformers is fed by an oscillator and the voltages of the primaries, and the loaded secondaries are measured at frequencies ranging from 50 Hz to 1GHz. The ratio of the secondary to primary voltage, in decibels, versus frequency is plotted for each transformer. Four different toroidal transformer constructions were compared:

- Standard toroidal transformer
- Balanced power (biflar-center tapped secondary connected to ground)
- Standard toroid with external filter
- Toroidal transformer incorporating NBT.

The standard toroid (a) has a high corner frequency of about 50 kHz and a low attenuation rate. Balanced power (b) has better performance with a reasonably low corner frequency of about 3 kHz and an attenuation of about -15 dB around 100 kHz and -30 dB close to 1GHz. The standard toroid with an external commercial filter (c) performs much better in the range of 50 kHz to 40 MHz in comparison with the balanced power, but has poor corner frequency of about 60 kHz. NBT (d) outperforms the other designs in terms of both corner frequency and attenuation. It has a low corner frequency of approximately 1 kHz, which can be design-adjusted to any reasonable value, with attenuation in excess of 60 dB around 1 MHz and 35 dB at 1GHz.

Applications

The applications of NBT in power supply transformers are various. A good example is audio applications, where it is important that differential high-frequency noise not enter the sensitive audio equipment. A second application is found in general power-supply transformers in any electronic equipment where differential noise filtering is mandatory. The choice for an NBT-transformer is then based on the balance of costs for an NBT transformer compared to a standard power transformer with an external differential-mode filter.

In IT applications with uninterrupted data transport over long distances, the advantages of clean power lines are obvious. In medical applications—especially safety-critical patient connected devices—NBT transformers with electrostatic shields provide clean power with low leakage currents. In large power applications, NBT can remove the higher harmonics with cutoff frequencies starting from 800 Hz. **PETech**

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