Resonant Power Conversion through a Saturable Reactor

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Abstract. The resonant converter control is usually implemented by electronic circuits that regulate the parameters of the necessarily produced energy pulses of circulating in the resonant circuit. In the same time the power circuit is characterized by fixed (or uncontrollably varying) parameters. In this article a research is described that shows a long time ago forgotten techniques: the magnetic amplifier that controls the power circuit parameters and as a result, changes the resonant frequency depending on the needs of control. The inductance that is made to vary its value in a controllable, continuous and linear mode would be a perfect (non-dissipative) regulator for the power converter. This can be achieved through a DC magnetization applied as a control command to the magnetic core. By varying this magnetization current and hence the magnetic parameters of the core, the inductance L is possible to be adjusted to a desired value. This operation is similar to the principle of the (long ago) well known "magnetic amplifier" or the "saturable core reactor" as it is often called. The magnetic amplifier usually has an AC source in series with the load and with its primary while in the secondary the DC control signal is applied. The application of a regulated inductance device in the Wireless Power Transfer (WPT) will guarantee a simple way to adjust the frequency of the transmitter and/or the receiver to achieve the required impedance adaptation and efficient energy transfer.

Keywords: Magnetic amplifier, mag amp, saturable reactor, wireless power transfer.

1 Introduction

The resonant converter control technique is more developed now compared to some decades ago, but still it is very complex and costly to implement. In search for new simple and reliable methods of control, this work is aimed to demonstrate the possible use of the magnetic amplifier principles in the control of the (power) resonant circuit.

The inductance that is capable to vary its value in a continuous and linear mode would be a perfect (non-dissipative) regulator for the power converter, especially if the switching frequency will be kept constant. This can be achieved through a DC current applied as a control. By varying the current and hence the magnetic flux, the value of the resonant inductor L will be regulated [1], [10].

This principle is similar to the functioning of the "magnetic amplifier" or the "saturable reactor core" as they are often called. This circuit was invented by E. F. W. Alexanderson in 1916, USA, and was used during long time for the theatre light dimming [1].

During the World War II, the German scientists gave a big boost to those circuits, by using them in the V2 missiles and in the airplanes' navigation equipment.
The magnetic amplifier has the AC source and the load in series with the primary winding while in the secondary a DC control signal is applied. To avoid that the powerful AC signal appears in the secondary of that "transformer" and provoke problems in the control system, it is necessary to use a special "three legs transformer". This type of connection gives a possibility to isolate the two circuits: the control circuit and the power (source) circuit [1] [10].

The application of this type of circuit that provides regulation of the inductance, in the Wireless Power Transfer (WPT) will make possible to adjust the frequency of the transmitter and/or the receiver. This will permit to obtain impedance adaptation in order to achieve a maximum energy transfer.

The limit of the proposed method is set by the highest achievable frequency that is determined mostly by the eddy current losses in the core material.

2 Relationship to Collective Awareness Systems

The resonance based energy transfer is important solution for efficient energy application in electric and hybrid vehicles, very fast trains, embedded medical systems, home automation, biomedical systems and the emerging field of Internet of Things that includes also the energy transport. By the proposed resonant frequency adjustment through simple and robust regulation, it will be possible to achieve a widely spread and massive production of cheap wireless energy transmission equipment. The developed regulated inductive element would be useful also in the power quality compensation which is the main concern of the modern society and in particular, the emerging Smart Grids.

3 Saturable Reactor

The saturable reactor is a magnetic device that consists of a single magnetic core, having two windings. One is connected to AC source and the (power) load, normally designated by "load coil" and another is connected to a DC source namely "control coil". The idea is to control of the load current and voltage by the control coil, similarly to what is done in a transistor or another electronic device. In Fig. 1 (left) is shown a saturable reactor. In the left side of the magnetic core is the DC control winding (a variable resistance is representing the regulator). In the right side of the core are shown the AC power source and the load connected in series.

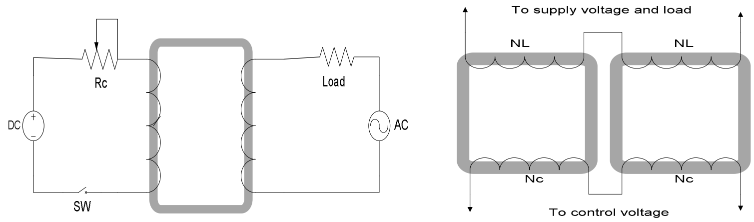

Fig. 1. Simple saturable reactor circuit (left); Saturable reactor having two cores (right).

When the control current is varied, the impedance of the load winging is changing, once the permeability of the magnetic circuit varies, producing a change of the inductance. However, in this basic circuit, exists a problem: it is the mutual induction between the DC and AC windings that provokes interaction between both circuits. The power current in the AC winding will induce undesirable feedback to the DC side.

One way to solve this problem is the circuit presents in Fig. 1 (right), with two cores construction that separates the cores and the windings.

This circuit, having two separate cores with series control and series load windings, makes possible to cancel the induced voltages and to minimize the unwanted effects. The saturable reactor is based on magnetization curve of the applied magnetic core material. A generic magnetization curve is shown in Fig. 2.

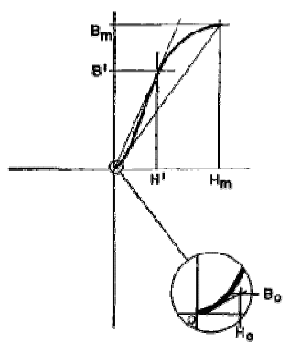

Fig. 2. Generic magnetization curve.

The relation of B to H at any point on the curve is the *normal permeability* for that value of B. For the maximum flux density B_m the normal permeability is:

$$\mu = \frac{B_m}{H_m} \tag{1}$$

It is the slope of a straight line drawn starting in the origin.

A similar line drawn tangent to the curve at its “knee” is called the *maximum permeability* and its value is:

$$\mu_m = \frac{B'}{H'} \tag{2}$$

The slope B_0/H_0 of the normal induction at the origin (enlarge in Fig. 2) is the permeability for very low induction value B_0; it is called initial permeability and it is usually much lower than μ_m [2].

The most common saturable reactor consists of a three legged core as it will be shown in Fig. 5, where each coil is wound on separate magnetic "leg". The two AC coils in Fig. 6 should have relatively low and equal number of turns and the middle coil usually has much higher number of turns. This gives the possibility of amplification: through lower control current to obtain control over powerful circuits. Because of this in many cases the (regulated) saturable reactor is used as a "Magnetic Amplifier".

In open circuit condition of the control circuit, the imaginary part of the complex impedance value is much higher than the real part of the impedance (the winding DC resistance). It must be recalled that a relatively small amount of direct current flowing into the control winding of the core reactor, because of the high number of turns and in case of no air gap, is easily capable to produce core saturation. Thus, the reactance of the core reactor may be varied by a small amount of DC power. In this way, the AC winding of the core regulates the amount of power delivered to the load by the AC source, controlled by a small amount of DC power flowing in the DC winding.

Usually, when one winding of the core reactor is used to control the power in the other winding through reactance variation, the magnetic device is called a saturable reactor [2], [3], [4]. The concept is the same for the magnetic amplifier: the lower DC component of the impedance permits regulation of the permeability. The main difference between a magnetic amplifier and a saturable core reactor is that the magnetic amplifier uses a half of the magnetic loop and the amplifier uses the complete magnetic loop. Because of this the term "Saturable Core" is often substituted by the term "Magnetic Amplifier".

Basically a saturable reactor consists of three essential elements (Fig. 3): Direct current source, Magnetic core with windings and Alternating current source.

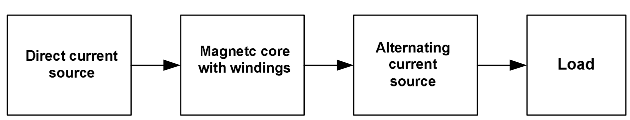

Fig. 3. Three essential elements of the saturable reactor.

These three elements, when connected together, form the essentials of the Saturable reactor. Its operation is based upon the above mentioned principle: the current flowing in the coil wound on the magnetic core can be regulated by varying the core saturation [4], [5], [6]. In order to optimize the magnetic amplifiers, the choice of magnetic core is very important. It is also important to choose which part of the core is more convenient to saturate.

The main goal of any magnetic core is to supply an easy path for the magnetic flux in order to guarantee the flux linkage (magnetic coupling), between two or more elements. The energy storage in a magnetic core is an undesired parasitic effect. In order to minimize this problem, the choice of a magnetic material with high permeability and thin hysteresis loop is the right option.

Today, the wound magnetic cores used in practice are made by amorphous metal alloy. These cores are used in SMPS (Switch Mode Power Supply) application up to 100-200kHz, and especially in magnetic amplifiers [6], [7].

As it was shown, the magnetic amplifier is a relatively simple device. However, this simplicity is very misleading when mathematical analysis of its operation is attempted, because of the extremely nonlinear characteristics of the core material. The linear circuit theory may be applied only to carefully selected parts of its operation regimes. In order to simplify the analysis the common practice is to make the assumptions of perfect core material. As it was mentioned before, the AC winding voltage will induce undesired voltage in the DC winding. This influence may short circuit the DC winding if the impedance of the DC winding is low and by this, it would effectively short circuit the AC voltage in the power winding. This difficulty might be overcome by using high impedance in the DC control circuit [8], [9].

In Fig. 4 (a) a common solution is shown, in which two reactor cores are used. The DC current is applied in opposite direction in each winding. The AC current is applied in the same direction in both coils. A similar solution is shown in Fig. 4 (b).where the connection is parallel in order to reduce the necessary AC voltage [2], [3].

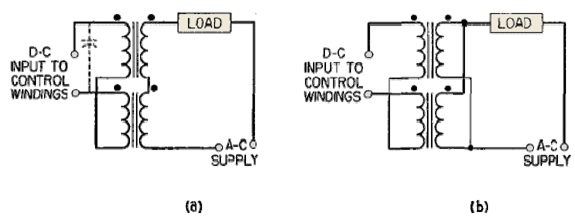

Fig. 4. Magnetic amplifier structures: (a) series; (b) parallel [2].

When there is zero direct current in the control winding of Fig. 4, both reactor impedances are large and prevent any load current except a small exciting current to flow in the AC loop in the lower parts of the voltage sinusoids. When non-zero direct current is applied to the control winding, the impedance remains large for the first part of a cycle, until the saturation flux density is reached. Then the reactor impedance is reduced and larger load current may flow.

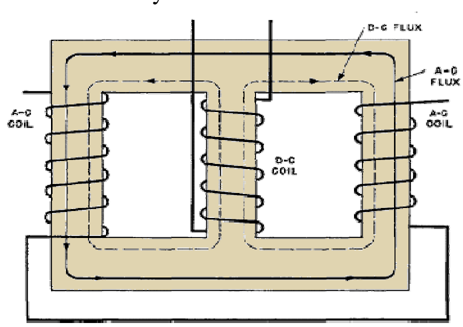

Fig. 5. Three legs transformer applied to magnetic amplifier [2].

In Fig. 5 a three-leg magnetic core is shown. The current in the DC coil will produce a change in the total flux and hence a change of inductance [9], [10]. This core has one DC coil and two AC coils and the total AC and DC flux is a changing sum: alternatively in each of the lateral legs it is either sum or difference of the fluxes. The figure shows the virtual paths for the AC and DC fluxes. The number of turns of the AC half-windings is equal and symmetric. The equal number of turns in the AC coils will provoke equal AC magneto-motive force, which will be cancelled in the centre leg and cause fluxes to flow as indicated by solid line. In consequence, no fundamental AC voltage is induced in the DC coil, but the DC flux is injected in both outer legs as indicated by the dotted lines.

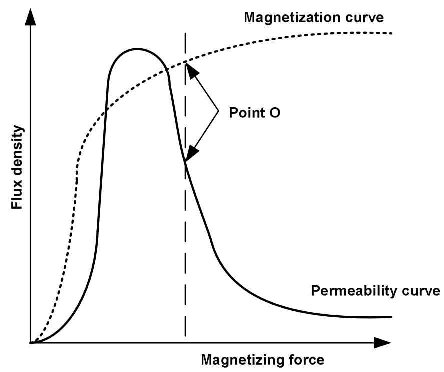

Fig. 6. Variation of flux and permeability with magnetization force.

Fig. 6 shows the magnetization and permeability curves for the saturable core reactor with the ideal operating point indicated (point “O”).
It is important to notice that this point is located on the “knee” of the magnetization curve. The “knee” of the curve corresponds to the maximum curvature. Saturable core reactor and magnetic amplifier should operate on this “knee” of the magnetization curve [9], [10].

When the saturable core reactor is set at the “knee” of the magnetization curve, any small increase in control current will cause a large increase of load current, and any small decrease in control current will cause a large decrease of the load current. This is why the point “O” is the ideal operating point: the small changes in control current will cause large changes of load current, in other words, the saturable core reactor can better and efficiently amplify the control current [9], [10].

The saturable reactor AC winding inductance depends on the flux provoked by the DC winding (-s). The inductance depends also on the geometry of the magnetic core and its permeability, having in mind that the effective permeability depends on the DC control winding function [1]. In simplified form and in case of flux concentrated only in the core, the equation of the inductance is:

$$L = \frac{4\pi N^2 A}{l} \times \mu \times 10^{-7} [H] \quad (3)$$

Once the geometry of the core is fixed by the manufacturing, the unique variable is the permeability μ. In this case the permeability will control the inductance L.

4 Results Presentation

In this section the results obtained from measurements during the experimentation are shown. The circuit that was used as a basis for different tests is the one shown in Fig. 5. The experiment was executed in circuit corresponding to the one in Fig. 7:

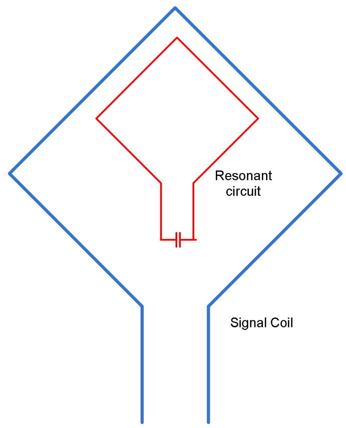

Fig. 7. The circuit base to the different tests.

This circuit (Fig. 7) consists of two parts. The one in blue (external coil), is the signal coil with 10 turns, another is the resonant circuit, shown in red (internal coil). This coil has 30 turns and two capacitors 0,1μF each, connected in series.
The inductance of the resonant coil (shown in red) was measured and the (initial) value of $L=7{,}58mH$ has been obtained.

In these conditions the calculated resonant frequency is:

$$f_r=\frac{1}{2\pi\sqrt{L\times C}}=\frac{1}{2\pi\sqrt{7{,}58\times 10^{-3}\times 50\times 10^{-9}}}=8{,}175kHz \quad \textbf{(4)}$$

In fact, this value was confirmed when the experiments were executed, i.e. close to 8,2 kHz. The magnetic amplifier was constructed on a tree legs transformer, where the middle leg (control) have a coil of 30 turns and the two legs (one on each side) form two half-coils in series with 20 turns each.

In Fig. 8 the schematic diagram of the three legs transformer is represented. The “green” coils are the AC half-coils, A1 and A2, and the “red” coil, C, is the control coil, connected to the variable DC.

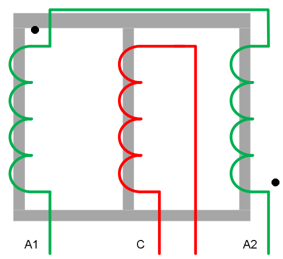

Fig. 8. Schematic of three legs transformer.

The graphic shown in Fig. 9 presents the values obtained during the tests of the magnetic amplifier.

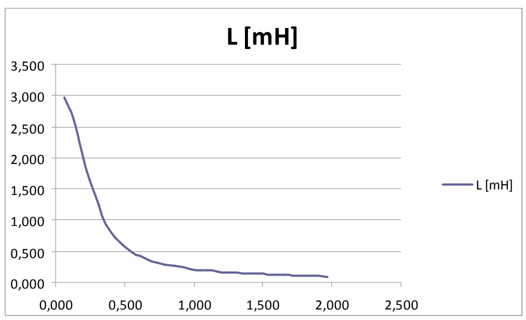

Fig. 9. The values obtained during the tests of the magnetic amplifier.

The illustration in Fig. 10 shows the series connection between a fixed inductor (4,7 mH) and the regulated inductance of the magnetic amplifier. The values obtained are shown in Fig. 11.

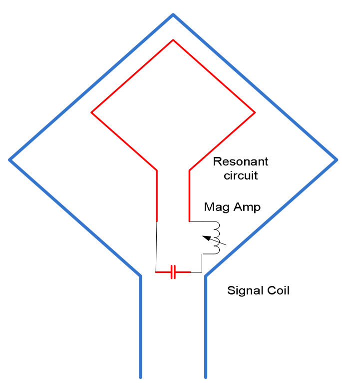

Fig. 10. Schematic of the tests on the saturable reactor in series with the resonant circuit inductor.

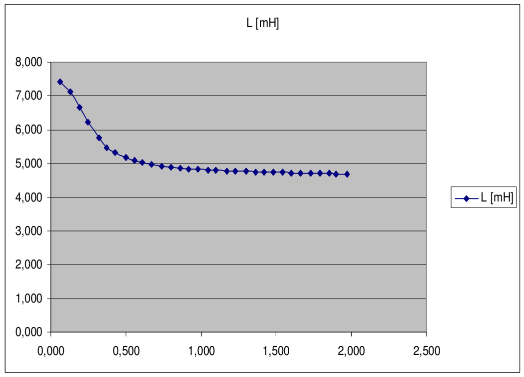

Fig. 11. The values obtained with Saturable reactor in series with resonant circuit.

5 Conclusions and Future Work

A confirmation was found that the magnetic amplifier gives the possibility to adjust the inductance L, by a DC current control The correct starting point for the regulation (zero DC control current) of the power should be the in which the inductance guarantees the minimum output power. All the other points of operation will be achieved by the non-zero current of the DC coil.

By some value of a fixed (initial) and applying a regulated additional inductance, the resonant circuit will obtain the necessary capacity to regulate its resonant frequency and thus to regulate the power of the resonant converter.

The future work should involve the study of magnetic cores applied to optimize this circuit in terms of frequency and maximum allowed AC current along with the large spectrum of frequencies. The necessary electronic circuits should be constructed to control the completed system

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