High Frequency Multiphase Travelling Field Configuration For Direction Controlled EM Forces Production

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Abstract
Some EPM applications require travelling field inductors able to create stirring or pumping forces whose direction can be inverted if necessary. These inductor configurations are multiphased and come from the well known 50 Hz (or 60 Hz) 3-phase asynchronous motor. But in the middle or high frequency area the problem is that most of the induction generators are single phase self resonant oscillating generators. This paper shows how it is possible to transform this kind of single phase inductor into a double phase one made of two oscillating circuits whose one is feed by the single phase generator and the other is coupling on it by mutual inductance. This double phase inductor, which is based on the "single phase asynchronous motor" is then able to produce a middle or high frequency travelling field. In a first part the design of such inductor is presented. Then in a second part the electrical working of this double oscillating circuit with several possible resonance frequencies is explained. At last some induction applications using this principle and which have been experienced on lab scale prototypes are shown.
Key words:
Multiphase induction systems, middle or high frequency travelling field, electromagnetic pumps, electromagnetic stirrers, asynchronous motor, linear motor.

Introduction

Some high frequency EPM applications require direction controlled forces for instance for reversing the stirring or the pumping of electro-conductive liquids [1, 2]. These driving Lorentz forces are produced with multiphase inductors based on the well-known 50 Hz (or 60 Hz) asynchronous motor principle [3]. If this is easy to do at this low frequency by using the 3-phase mains, it becomes much more difficult at higher frequencies since most of the commercial induction generators are single phase generators working at resonance frequency with an oscillating circuit. Thus an interesting idea is to use the "single phase asynchronous motor" principle, which is in fact a double phase inductor set, and to adapt it on a high frequency single phase induction generator to transform it into a multiphase generator able to create a travelling field. At first such a multiphase inductor, working as a linear motor [4], is described and it is shown how it is connected to the generator. Then the electrical working of such a multi resonance frequency double oscillating circuit is explained. At last three applications using this kind of multiphase travelling field configuration are presented in the area of metallic liquids and electrolyte stirring and also of electromagnetic waste sorting systems. These applications have been successfully experienced on lab scale prototypes.

Description of the double phase inductor and connection to the single phase induction generator

The double phase inductor and its connection to the single phase induction generator is sketched in Fig.1. The first phase, called "forced phase", is made of an inductor with two opposite series windings connected to a C1 capacity, thus building a first oscillating circuit which is connected to the generator. The second phase, called "induced phase", is also made of an inductor with two opposite series windings connected to a C2 capacity, thus building a second oscillating circuit which is autonomous

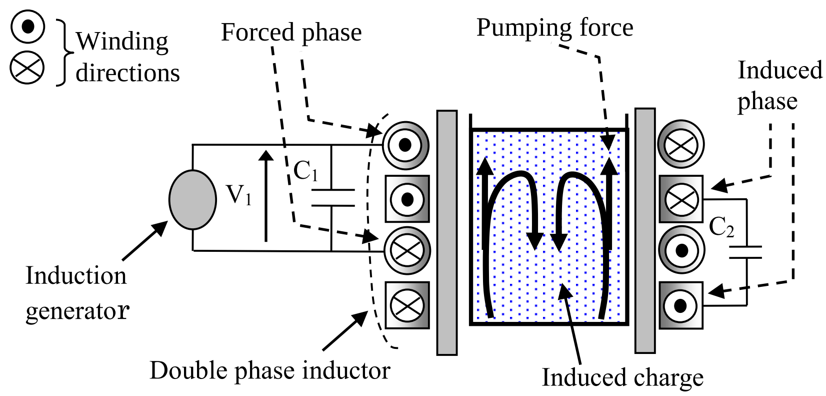

Fig. 1: Double phase inductor configuration and connection to the generator.

and couples inductively on the forced phase thanks to the mutual inductance M between the two similar inductors. By properly setting parameters like C1, C2, and M it is possible to get a phase shift between the forced phase and the induced phase which approaches 90°. This inductor acts then as a linear motor by creating a vertical travelling field with a synchronous velocity equal to f*λ , f being the generator's frequency and λ the linear motor wave length close to the motor's height. This travelling field gives the required stirring or pumping force in the electro-conductive media set inside the inductor. It is also important to notice that, as this is an asynchronous motor configuration, the direction of the travelling field, meaning of the driving force, can be reversed simply by reverting the two phases connections, which is very interesting for applications which require direction controlled forces.

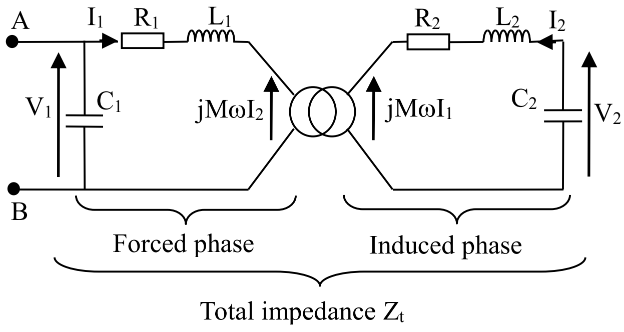

Fig. 2: Electrical equivalent diagram.

Electrical working conditions of the double phase inductor

Assuming that the two phases build a transformer whose primary and secondary are respectively the forced phase and the induced phase, we consider the simplified electric equivalent diagram of the double phase inductor given on Fig. 2. The two phases have the characteristic resistance and self-inductance values R1, R2, L1 and L2 and are both connected in parallel with the capacity values C1 and C2. The inductive coupling between the two phases is due to the mutual inductance M. The generator which works, thanks to a feedback system, at the resonance frequency of the whole inductor, is connected to the forced phase (points A and B) and gives the feeding voltage V1. The resulting currents respectively in the forced and induced phases are I1 and I2. By writing the Kirchhoff's equations, the currents ratio $(\vec{I}_2 / \vec{I}_1)$ may be expressed as following:

$$\frac{\vec{I}_2}{\vec{I}_1} = \frac{-jM\omega}{R_2 + j\left(L_2\omega - \frac{1}{C_2\omega}\right)} \quad (1)$$

where ω is the resonance pulsation (ω is related to the resonance frequency f by ω=2πf) and j is the square root of –1. The whole system is equivalent to a total impedance Z_t which is "seen" by the generator. As this circuit is made of two coupled oscillating circuits, there are several possible resonance frequencies. In order to determine the working conditions for the generator, it is convenient to express the evolution of Z_t with respect to the pulsation ω. An analytical calculation is made with some simplifications like assuming that the primary elements and the secondary elements are similar (R_1=R_2=R, L_1=L_2=L, C_1=C_2=C) and neglecting the resistive term (like R) compared with the reactive terms (like Lω, 1/Cω or Mω). The results are summarised on Fig. 3: the real part $Z_{tr}(\omega)$ (dashed line) and the imaginary part $Z_{ti}(\omega)$ (continuous line) of Z_t are sketched on the upper part. The modulus ratio $K(\omega) = |\vec{I}_2| / |\vec{I}_1|$ of the two forced and induced phases currents and their phase shift $\varphi(\omega)$ (with I_1 as phase reference) are respectively sketched in the middle and the lower part of Fig. 3. Z_{ti} cancels for 3 pulsations ω_1, ω_3, and ω_4. Only ω_1 and ω_4 are resonance pulsations

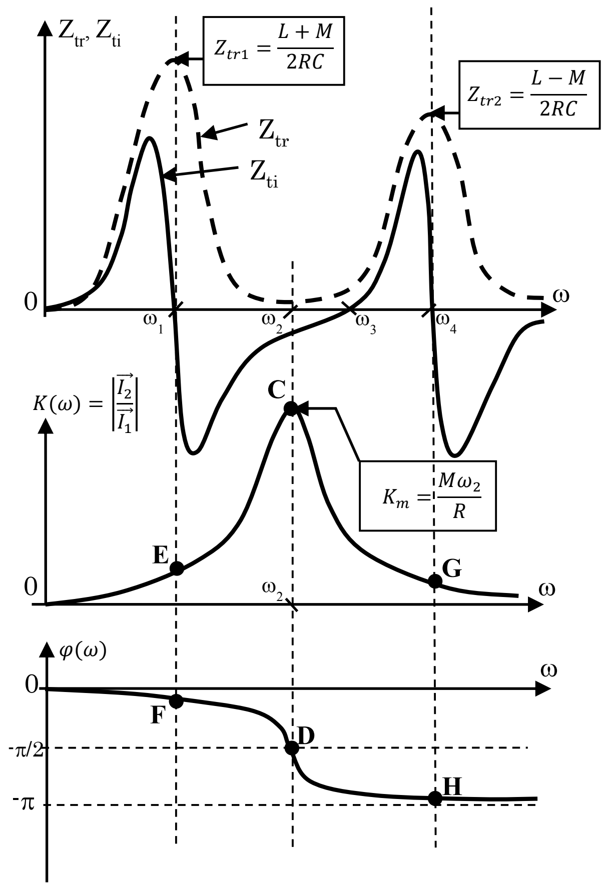

Fig. 3: Electrical working conditions.

corresponding to the two resonance peaks Z_{tr1} and Z_{tr2} of Z_{tr}. K(ω) shows a maximum for ω= ω_2 corresponding to φ(ω)=-π/2 (points C,D). These four specific pulsations are given in Table 1.

ω_1	ω_2	ω_3	ω_4
$1/\sqrt{(L+M)C}$	$1/\sqrt{LC}$	$1/\sqrt{LC(1-(M/L)^2)}$	$1/\sqrt{(L-M)C}$

Table 1. Values of the possible resonance pulsations

The best stirring efficiency (by keeping in mind that this inductor is an asynchronous motor) is obtained when K(ω)=1 (equality of the two currents amplitude) and when φ(ω)=-π/2. According to Fig. 3, these optimal conditions may only be obtained at ω= ω_2 (points C, D) if, furthermore, M is set so that the maximum value $K_m = (M\omega_2/R)$ of K is equal to 1. These optimal conditions for ω= ω_2 can be approached by acting on the mutual inductance M so that the two resonance frequencies ω_1 and ω_4, which frame ω_2, tend toward one another.

Applications using high frequency multiphase travelling fields

Three applications using this kind of multiphase inductor configuration have been successfully experienced on lab scale prototypes. The first application is the Cold Crucible Continuous Casting (4C) process for which a prototype with a double phase inductor surrounding a 50 mm diameter cold crucible has been tested at 25 kHz (power level: 50 kW) on liquid tin as seen in Fig. 4 with the two phases connected so as to give an ascending travelling field in the peripheral electromagnetic skin depth. The top view shows centripetal stirring vortices on the free surface which greatly improves the feeding scraps ingestion in the bath compared with a classical single phase inductor which gives a centrifugal stirring of the top free surface. The strong mean velocity is about 0.5 m/s.

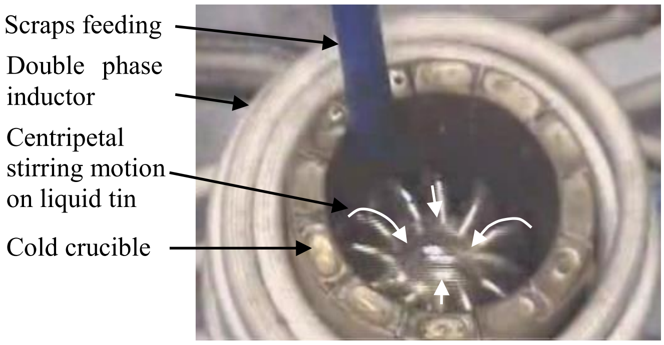

Fig. 4: Cold Crucible Continuous Casting (4C) prototype with double phase inductor (25 kHz) (top view).

This has bee extended at higher frequency for a second application meaning the stirring ability of low conducting fluids like electrolytes or also glasses. Fig. 5 shows a prototype of a 30 cm diameter salt water container surrounded by a double phase inductor working at 200 kHz (power level: 15 kW). The two phases are also connected so as to give an ascending travelling field in the peripheral electromagnetic skin depth. The white dashed lines show the resulting bulk stirring motion of the salt water with a mean velocity of several cm/s. This shows the possibility of homogenizing the temperature or also the constituents of multiphase fluids. Furthermore, by still keeping in mind that the inductor is an asynchronous motor, it is possible to revert the travelling field direction meaning also the resulting electromotive forces acting on the fluid, hence the stirring direction. This is an interesting advantage compared with classical single phase inductor configurations for which the stirring motion, mainly resulting from electromagnetic pressure gradients, cannot be reversed.

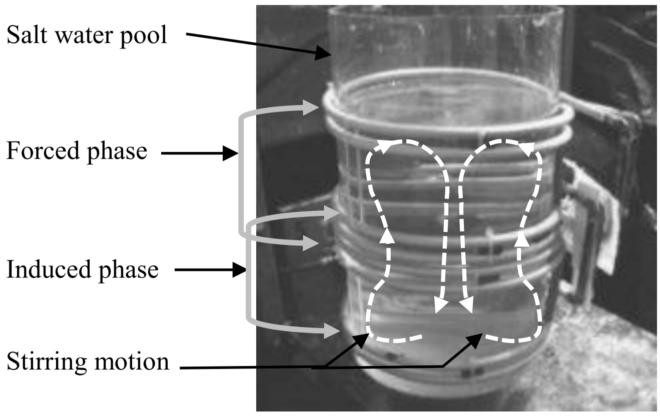

Fig. 5: Multiphase stirring of salt water (200 kHz).

The third application concerns the electromagnetic waste sorting process for which an industrial waste conveyor belt prototype has been fitted out with a planar version (flat active part size: 200*200 mm²) of the former presented double phase inductor working at 20 kHz (power level: 25 kW) located just under the belt output as seen in Fig. 6. Fig. 6(a) shows this flat inductor giving a forward expulsion force due to the forward linear travelling field and Fig. 6(b) and (c) show respectively the expulsion of tetra-packs (like milk packs) including a thin 10 μm thick aluminum sheet and of about 100 μm thick aluminum beverage cans (like beer cans) with different trajectories (white dashed lines) due to the thickness

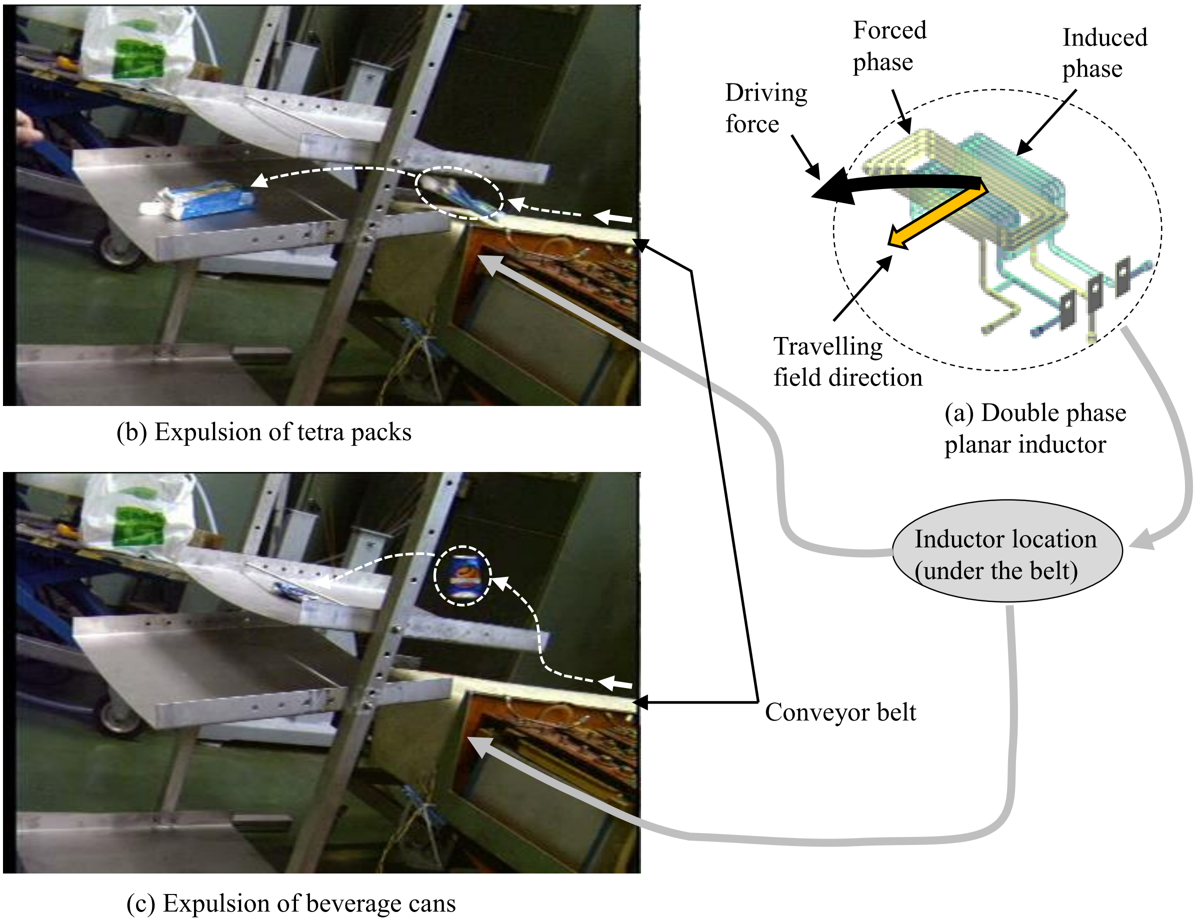

Fig. 6: Electromagnetic sorting of metallic wastes (tetra-packs and cans) on conveyor belt.

and shape differences in different reception baskets. This is another interesting potential application of this kind of double phase inductor acting like a linear motor, making it a generic process for producing a travelling field for middle or high frequency applications requiring reversible stirring or driving forces.

Conclusion

This paper explains how it is possible to get a high frequency magnetic travelling field by transforming a single phase inductor connected to a single phase induction generator into a double phase inductor. With appropriate settings this double phase inductor acts then as a linear motor producing reversible electromagnetic stirring or driving forces in a large frequency area since it works thanks to a double oscillating circuit whose first one is classically connected to the single phase generator and the other one is autonomous and couples inductively on the first one. This innovating multiphase induction configuration, which finds all its interest since almost all the commercial induction generators are single phased, has been successfully tested on lab scale prototypes for three potential applications meaning the centripetal top free surface stirring for better scraps ingestion in the Cold Crucible Continuous Casting process, the stirring of low conducting liquids, and the electromagnetic metallic wastes sorting. Thus this multiphase inductor configuration can be considered as a generic process which could be used on industrial scale for any kind of EM process requiring reversible direction controlled linear or rotating stirring or driving forces.

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