A New Transformer with Ability to Suppress Conducted Interference

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Abstract: -An interference-free transformer named IFT which has the ability to suppress conduction-interference is proposed in this paper. Comparing with the traditional common transformers, it has a special magnetic structure, namely magnetic air-gap shunt， and adds a resonance coil on the secondary side. It is in series with the parallel resonance-circuit to construct a filter-network, which makes the difference-mode (DM) interferences be attenuated obviously, while nearly doesn't affect the fundamental signal. In order to suppress the common-mode (CM) interferences, two coils with few turns and opposite direction, which are in series with the primary coil, are also added. It is noticeable that the magnetic core of the transformer must always works in its linear area. The simulation and experimental results prove the model, analysis and conclusion are right. The proposed transformer in the paper can substitute the EMI-filter to suppress the conduction-interferences in the power supply and provide another selection.

Key-Words: - IFT, magnetic air-gap shunt, DM interference suppression, CM interference suppression

1 Introduction

In recent years, a lot of differential-mode (DM) and common-mode (CM) interferences are generated and transmitted into the power source system by the power line and ground. Such interferences are usually called conducted interferences. The interferences have great effect on the work of all kinds of devices and equipments. In order not to impose the interferences on the system, the EMI filter is always used between the power and intermediate bus [1-2]. Considerable research has focused on how to improve the performance of the EMI filter including the passive and active EMI filters in different kinds of power circuits [3-6]. But those EMI filters are connected the two sides between the power sources and loads without any electrical isolation directly. Now the transformers have been used widely in order to supply the appropriate voltage and isolation. Therefore it will be significant if the transformer has also the ability with the interferences suppression.

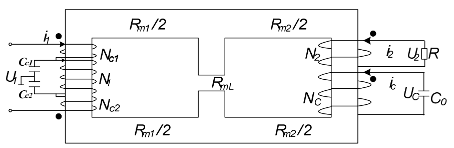
This paper proposes a new transformer. It has an interference-free ability to supply the power. The proposed Interference-free Transformer (IFT) is based on the resonance-circuit & magnetic air-gap shunt. With the help of special magnetic structure of the transformer, it is easy to form the inductance of DM interferences suppression. In the meanwhile, the CM inductor will exist by adding the CM windings on the iron core of the IFT. Under the prerequisite that the devices do not increase their bulks, electrical isolation and interferences suppression will be realized simultaneously. Simulation and experimental results prove that the IFT not only obviously restrains the interferences which includes the DM and CM, but also does not affect the fundamental wave signal.

2 IFT Structure

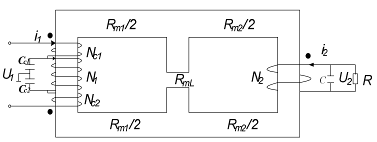
The IFT structure is shown in Fig.1 (a). In the figure, R_{m1}, $R_{m2,}$ and R_{mL} are magnetic reluctances of the primary, secondary and magnetic shunts of the IFT respectively. N_1, N_2 and N_c, are the numbers of turns of the primary, secondary and resonance windings of the IFT respectively. N_{c1} and N_{c2} are the numbers of turns of common-mode winding. C_{c1}, and C_{c2} are common mode capacitors.

The structure is similar to that of the constant voltage transformer (CVT). The major difference between these two structures is that the secondary iron core of CVT works in the saturation range of magnetization curve forming ferroresonance, while that of the IFT works in the range of linearity and resonates with parallel C_0. The efficiency of the CVT is low and its output voltage contains harmonics components. But the IFT can output the sinusoidal waveform, achieve higher efficiency, and suppress the interferences.

Because the secondary winding couples with the resonance winding closely, C_0 of the IFT can be converted into C of the secondary winding, as shown in Fig.1 (b), where $C = \left(N_c / N_2\right)^2 \cdot C_0$.



(a)



(b)

Fig.1 Structure & Equivalent structure of IFT (a) Structure of IFT (b) Equivalent structure of IFT

3 DM-interference suppression

3.1 Equivalent circuit

In section II, we have introduced that the IFT structure is similar to that of the CVT. Some studies have been done to analyze the magnetic circuit of the CVT, and obtained its equivalent circuit in the last few years [7]. [8] deals with the CVT circuit using the duality principle between magnetism and electricity. Besides, Ref.[9] elaborates a method of analyzing the performance of CVT.

This paper presents a simple method based on combination of the magnetic and electrical circuit, which adds an ideal transformer ingeniously.

The equivalent magnetic circuit of the DM part of IFT can be achieved (see Fig. 2) from Fig.1. By inspection of Fig. 2, two equations can be written

$$\begin{cases} i_1 N_1 = \left(R_{m1} + R_{mL}\right)\cdot \Phi_1 - R_{mL} \cdot \Phi_2 \\ i_2 N_2 = \left(R_{m2} + R_{mL}\right)\cdot \Phi_2 - R_{mL} \cdot \Phi_1 \end{cases} \quad (1)$$

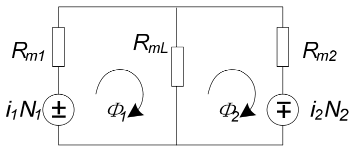


Fig2 Equivalent magnetic circuit

From (1), we can obtain

$$\begin{cases} \Phi_1 = \dfrac{\left(R_{m1} + R_{mL}\right)\cdot i_1 N_1 + R_{mL} i_2 N_2}{R_M} \\ \Phi_2 = \dfrac{\left(R_{m2} + R_{mL}\right)\cdot i_2 N_2 + R_{mL} i_1 N_1}{R_M} \end{cases} \quad (2)$$

where, $R_M = R_{m1}R_{m2} + R_{m1}R_{mL} + R_{m2}R_{mL}$.

According to the common transformer model, (3) can be written, regardless of the resistance of the primary and secondary windings.

$$\begin{cases} U_1 = j\omega N_1 \Phi_1 = j\omega L_1 i_1 + j\omega M i_2 \\ U_2 = j\omega N_2 \Phi_2 = j\omega L_2 i_2 + j\omega M i_1 \end{cases} \quad (3)$$

where, L_1 is the equivalent self-inductor of the primary winding;

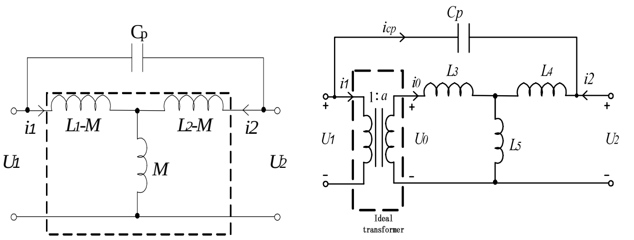
L_2 is the self-inductor of the secondary winding;

M is the equivalent mutual induction between the primary and secondary windings.

Fig.3 (a) is the IFT T-circuit. The distributed capacitance C_p is considered in the figure. Three inductors in the frame of the dotted line will be negative in some condition. So we add the ideal transformer to solve the problem of the negative inductors (see Fig.3 (b)).

Substitution of (2) into (3) gives:

$$\begin{cases} L_1 = \left(R_{m2} + R_{mL}\right)\cdot N_1^2 / R_M \\ L_2 = \left(R_{m1} + R_{mL}\right)\cdot N_2^2 / R_M \\ M = \left(R_{mL} N_1 N_2\right) / R_M \end{cases} \quad (4)$$



(a) (b)

Fig.3 Analytic circuit (a) T-circuit (b) analytic circuit with ideal transformer

$$\begin{cases} U_0 = aU_1 \\ i_0 = i_1 / a \end{cases} \quad (5)$$

$$U_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \quad (6)$$

In Fig.3 (b), the turns ratio of ideal transformer is $a(a \in R^+)$, hence

Substitution of (5) into (6) gives:

$$U_0 = a\left(L_1 \frac{a \cdot di_0}{dt} + M \frac{di_2}{dt} \right)$$

$$= \left(a^2 L_1 - Ma\right)\frac{di_0}{dt} + Ma\left(\frac{di_0}{dt} + \frac{di_2}{dt}\right) \quad (7)$$

According to Fig.3 (b),

$$U_0 = L_3 \frac{di_0}{dt} + L_5\left(\frac{di_0}{dt} + \frac{di_2}{dt}\right) \quad (8)$$

As the same derivation, the other equation can be written

$$U_2 = \left(L_2 - Ma\right)\frac{di_2}{dt} + Ma\left(\frac{di_0}{dt} + \frac{di_2}{dt}\right) \quad (9)$$

$$U_2 = L_4 \frac{di_2}{dt} + L_5\left(\frac{di_0}{dt} + \frac{di_2}{dt}\right) \quad (10)$$

We can derive equations (7), (8), (9) and (10), and Equ.(11) can be obtained.

$$\begin{cases} L_3 = \left(a^2 L_1 - Ma\right) \\ L_4 = \left(L_2 - Ma\right) \\ L_5 = Ma \end{cases} \quad (11)$$

For the special case of $a = \dfrac{L_2}{M} = \dfrac{R_{m1} + R_{mL}}{R_{mL}} \cdot \dfrac{N_2}{N_1}$, (12) is an explicit solution of equation (11)

$$\begin{cases} L_0 = L_3 = \dfrac{\left(R_{m1} + R_{mL}\right) \cdot N_2^2}{R_{mL}^2} \\ L_4 = 0 \\ L_S = L_5 = \dfrac{\left(R_{m1} + R_{mL}\right) \cdot N_2^2}{R_{m1}R_{m2} + R_{m1}R_{mL} + R_{m2}R_{mL}} \end{cases} \quad (12)$$

Considering C, C_p and R, an equivalent circuit of the DM part of IFT is shown in Fig.4.

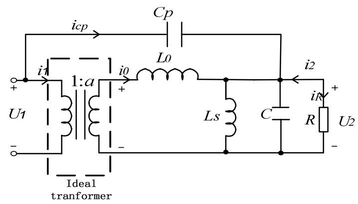


Fig.4 Equivalent circuit of the DM part of IFT

The state equation of the part of DM interferences suppression, whose equivalent circuit is shown in Fig.4, can be described as

$$\begin{cases} \dfrac{di_0}{dt} = \dfrac{U_0 - U_2}{L_0} = \dfrac{aU_1 - U_2}{L_0} \\ \qquad = \dfrac{R_{m1} + R_{mL}}{R_{mL}} \dfrac{N_2}{N_1} \cdot \dfrac{U_1}{L_0} - \dfrac{U_2}{L_0} \\ \dfrac{dU_2}{dt} = \left(i_0 + i_{cp} - i_R - i_s\right) \cdot \dfrac{1}{C} \\ i_{cp} = \left(\dfrac{dU_1}{dt} - \dfrac{dU_2}{dt}\right) \cdot C_P \end{cases} \quad (13)$$

From equation (13), the structural diagram is built, as shown in Fig.5.

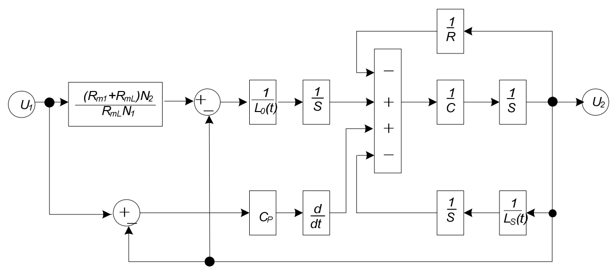


Fig.5 Systematic configuration of the DM part of IFT's

3.2 Simulation Results

Using Matlab6.5, the DM part of IFT will be simulated based on Fig.5 with the following parameters:

Input Voltage U_1 & U_2 (50Hz): 110V & 20V (RMS);

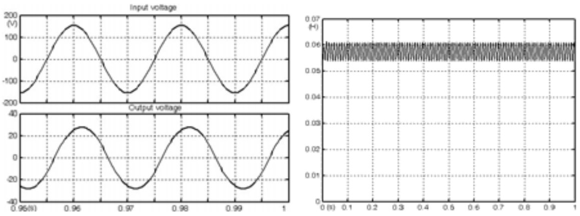
Power: 100VA;

Resonance capacitance C_0: 3.6μF (C=257.2 μF);

Rating load R: 4Ω.

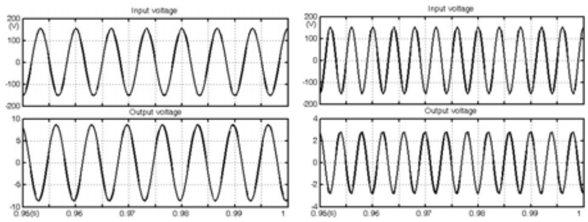
Fig.6 (a) is simulated with the rating input & output voltage and load, and Fig.6 (b) shows that $L_S(t)$ varies with the time under the state of Fig.6(a). From Fig.6 (b), we can conclude the secondary iron corn of IFT works in the non-saturation area.

Fig.7 (a) & (b) show the simulation of the high-frequency input voltage (110VAC). Fig.7(a) shows the input and output waveforms of 150Hz and Fig.7 (b) is those of 250Hz. From Fig.7, we can conclude the IFT can suppress the high frequency signal, and higher signal frequency is, the more obvious the suppression is.



(a) (b)

Fig.6 Simulation waveform (50Hz input voltage with rated load) (a) input and output voltage waveforms (b) $L_S(t)$



(a) (b)

Fig.7 Simulation waveform of high frequency input and output voltage (a) 150Hz (b) 250Hz

3.3 Experiment Results

An IFT prototype is made in the lab. The parameters of the simulation and experiment are the same. In order to test the suppression abilities of IFT, we use the SmartWave™ MODEL SW5250A.

Fig.8 (a), (b) &(c) show the outputs in the different frequency, namely 50Hz, 150Hz, and 250Hz respectively. Their input voltages are all 110VAC (RMS) with rated loads. The top one (1st waveform) is the input voltage and the bottom one (2nd waveform) is the output voltage in Fig (8). (Fig.9& 10 have the same notation). In contrast to the simulation ones (see Fig.6 (a) and Fig.7), the output voltage values and phases of experimental results are the same. These matches also prove that equivalent circuit of the DM part of IFT (see Fig.4) is right and the IFT has strong DM suppression of the high-frequency signal.

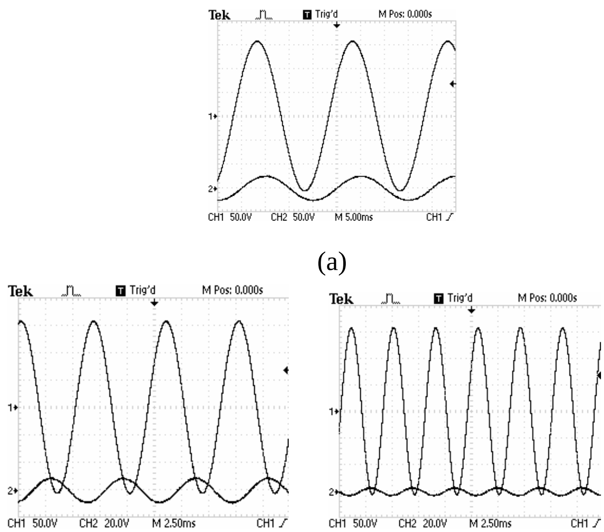
3.4 Discussion

Because of the magnetic shunt in the IFT structure, only a part of input flux linkage interlink to the secondary winding. It is equivalent to add step-down impedance between the primary and secondary winding, named as L_0. Analyzing equation (12), the smaller figure of the magnetic-reluctance of magnetic shunt is, the larger L_0 is. That adjustment of R_{mL} can change L_0.

①When $R_{mL}\rightarrow\infty$,namely $L_0\rightarrow 0$, the model becomes a common transformer one. The transformer only has the ability to transmit signals.

②When R_{mL} becomes larger, the model will be a magnetic shunt transformer with the air-gap. The value of R_{mL} relies on the width of air gap. At the time, because L_0 is smaller, low frequency signal has less attenuation on L_0 and the signal attenuation of high frequency is greater.

In Fig.4, L_S and C constitute a 50Hz parallel-resonant circuit. Its impedance Z_C is close to ∞ when the frequency is close to 50Hz. The 50Hz signal can be transmitted to the loads without any attenuation. When the signal frequency becomes high, Z_C will be decreased rapidly. So high frequency signals will be filtered and suppressed, while not be interfered with loads.



(a)

(b) (c)

Fig 8 Experiment waveforms in different frequency with rated loads (a) 50Hz (b) 150Hz (c) 250Hz

4 CM interference suppression

Considering that there exists lots of CM interferences which can be changed into DM interferences to affect the devices, the precautions must be taken.

In Section III, we have introduced the abilities of DM interferences suppression of the IFT. With the help of the magnetic structure of the IFT, it is easy to realize to suppress the CM interferences. As shown in Fig.1, two CM windings, which have a few turns and opposite direction, are in series with the primary coil. Those windings can be equivalent to two common-mode inductors, named as L_{c1} and L_{c2}. Besides, two common-mode capacitors, namely C_{c1} and C_{c2}, are also added (see Fig.11). By using the common-mode inductors and capacitors in the circuit, the CM interferences of power line can be filtered.

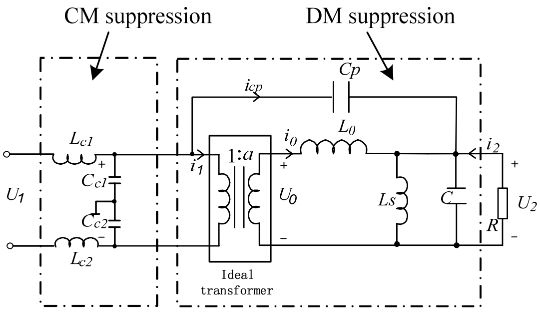


Fig.11 Equivalent DM and CM circuits of IFT

4.1 Experiments

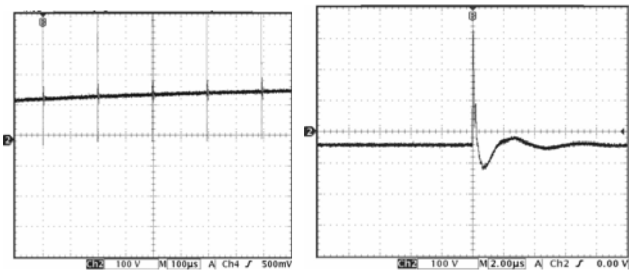
In order to test the ability of CM interferences suppression of IFT, some experiments have been done to test based on Electrical Fast Transient/burst (EFT/B) according to IEC61000-4-4 standard. The EFT/B is imposed on the loads via the lines and ground. It is always considered as the CM interferences test when the EFT/B is conducted on power lines [10]. In the experiment, NS64000-4A (EFT/B generator) is used, which is made in Shanghai Sanki Electronic Industries Co., LTD. The type of oscilloscope is TDS3014 and the bandwidth of probe is 120MHz.

Fig.12 (a) & (b) show the bursts and single burst waveforms of NS64000-4A, respectively. Fig.13 (a) & (b) is the bursts input and output voltages of the IFT.

4.2 Discussion

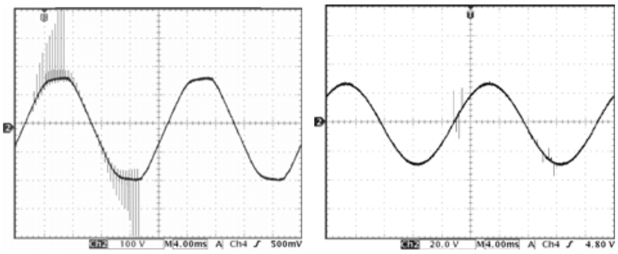
Fig.13 shows that both the value and number of the bursts have been attenuated and suppressed after the IFT transmission. Via analysis, it reveals the two main reasons why some bursts are still transmitted to the loads.

The first factor is the core material of the IFT. The laboratory prototype is made of the common silicon steel plate, whose initial magnetic inductivity is less than ferrite's. The second is radiated interferences. The leading edge of EFT/B is so steep that the spectrum is too wide. So the bursts produce not only conducted interferences but also radiated interferences. The prototype hasn't taken any action of shielding and grounding, which is in response to the radiated interferences. When the IFT has no inputs and the NS64000-4A is working, a lot of interferences will be still existed (see Fig.14).



(a) (b)

Fig.12 Output waveform of NS64000-4A (a)Bursts' waveform (b) Single burst waveform



(a) (b)

Fig.13 Input and output voltages of IFT (a) Input voltage (b) Output voltage

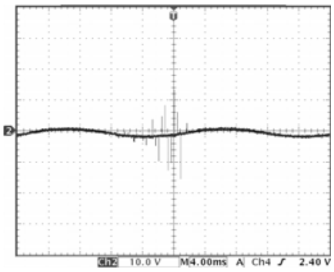


Fig.14 IFT output waveform without any inputs

5 Conclusions

In this paper, a new transformer (IFT) has been proposed and its equivalent circuit has been introduced. By using the proposed IFT, it is possible that electric isolation and CM&DM interferences suppression can be realized simultaneously. Therefore, it can be widely applied to power electronics systems. Its excellent effectiveness has been verified by the simulation and experiments.

Meanwhile, this paper only studies the possibility of interferences suppression explanatorily. As to the optimized design of length of the air-gap and other parameters to improve the suppression abilities, this paper doesn't study. It is the authors' hope that the research of this special transformer will continue.

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