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Parallelization of Two Three-Phase Converters by Using Coupled Inductors Built on a Single Magnetic Core

Abstract. This paper describes the parallelization of three-phase converters by using coupled inductors. The device allows to parallelize two three phase converters by using a single magnetic core and it is equivalent to use three Inter-Phase Transformers (IPT). Two versions of the three-phase IPT are presented and the differences between them are explained. The first one consists of a 5 limbs magnetic core whereas the second one is based on a 3 limbs magnetic core. The analytical model of the three-phase IPT is obtained. It has been simulated in Saber and the simulation results have been validated with experimental results.

Streszczenie. W artykule przedstawiono możliwą konfigurację do pracy równoległej przekształtników trójfazowych poprzez zastosowanie sprzężenia dławikami. Proponowane urządzenie pozwala na wykorzystanie pojedynczego rdzenia magnetycznego oraz jego odpowiednika w postaci trzech dławików wyrównawczych. Przedstawiono porównanie znanych rozwiązań. Zbudowano model symulacyjny w programie Saber i wykonano badania weryfikacyjne. (Praca równoległa dwóch trójfazowych przekształtników napięcia z wykorzystaniem dławików sprzężonych na pojedynczym rdzeniu magnetycznym).

Keywords: Converter Parallelization, Coupled inductors, Inter-Phase Transformer (IPT).
Słowa kluczowe: praca równoległa przekształtników, dławiki sprzężone, dławik wyrównawczy (IPT).

Introduction

The power rating of a converter depends on the converter topology and on the thermal and electrical limits of the switching devices. In order to achieve the power ratings required by the application, new converter topologies have been developed [1]. These topologies are based on the association of modular and standardized power converters. These standardized power converters can be inter-connected by using magnetic elements or by using isolated DC buses [2]. The serialization of power modules with isolated DC buses is a suitable solution for high power applications [3]. However, the stored energy at their DC buses is relatively high [4].

Magnetic devices are commonly used to associate three phase VSC (Voltage Source Converter) in order to increase the converter overall power rate. For example, Phase Shifted Transformers (PST) are used to associate VSCs and to improve the harmonic content of the VSC output voltage without increasing the switching frequency [5]. The magnetic elements are efficient and robust but they have the disadvantage of the volume, weight and cost. These three characteristics are related to the VA rating of the magnetic elements. The VA rating of a magnetic device for serialize VSCs is much higher than the VA rating of a magnetic device needed to parallelize VSCs. That is way the use of inductors is a suitable solution to connect more than one power electronics converters in parallel [6, 7]. On the one hand, if decoupled inductors are used to parallelize VSCs, the output current of each VSC must be controlled to assure that the current is equally shared between all the parallelized converters. On the other hand, if coupled inductors are used, the current is equally shared between the VSCs because of the coupled inductors. These inductors are known in the literature as Inter-Phase Transformers (IPT) [8]. In both cases relatively high impedance is needed between the parallelized converters. Otherwise, high currents are produced between converters. These currents can be classified as differential and common mode currents. Thus, the impedance between the parallelized converters also can be classified as differential mode impedance and common mode impedance. Depending on the impedances that are used between the parallelized converters, three cases are defined:

Case 1: Inductances with relatively high impedance for differential mode and common mode currents, single phase inductances [9] or 5-limb magnetic core based inductances [10, 11], for instance.

Case 2: Combination of differential mode inductances and common mode inductances [12].

Case 3: Combination of differential mode inductances and galvanic isolation with split DC buses [13] (high impedance for common mode currents).

The cases 1 and 2 are the most popular choices [14]. Two three phase converters can be parallelize by using three single phase IPTs (case 1), as is shown in Fig 1. The challenge when IPTs are used is to minimize their volume, weight and cost. For that purpose modulation techniques that minimize magnetic flux through the magnetic cores are used [15, 16].
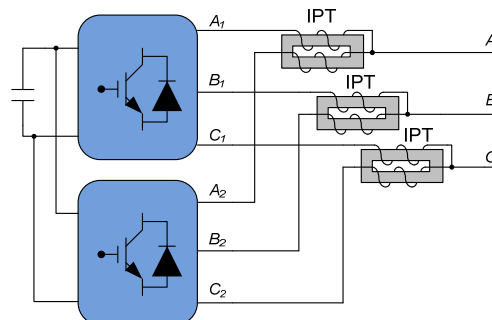

Fig 1. Parallelization of two three-phase converters with three single-phase IPTs.

The use of the IPTs ensures a good current sharing between the inverters without the need of further control action. This issue is not an important characteristic when relatively high switching frequencies are used because the current of each leg can be determined by the control system. However, in high power applications, where low switching frequencies are used it is an advantageous feature. The behavior of the overall system after combining the converters is the same as a single VSC. So, only the output current must be controlled, simplifying the control system and minimizing cross currents between converters. Apart from that, they permit a better harmonic cancellation and therefore, a better power quality of the converter output voltage is obtained [17]. The VSC topology shown in Fig 2 is presented in [17]. Four three-phase 3-L NPC inverters that share a common dc-bus are combined by using magnetic elements. The twelve converter poles are parallel connected in pairs by means of IPTs to obtain two sets of three-phase systems. The IPTs, not only ensure an equal current sharing, but they also support any instantaneous

voltage difference between the two inputs, allowing for the use of harmonic cancellation or mitigation techniques.
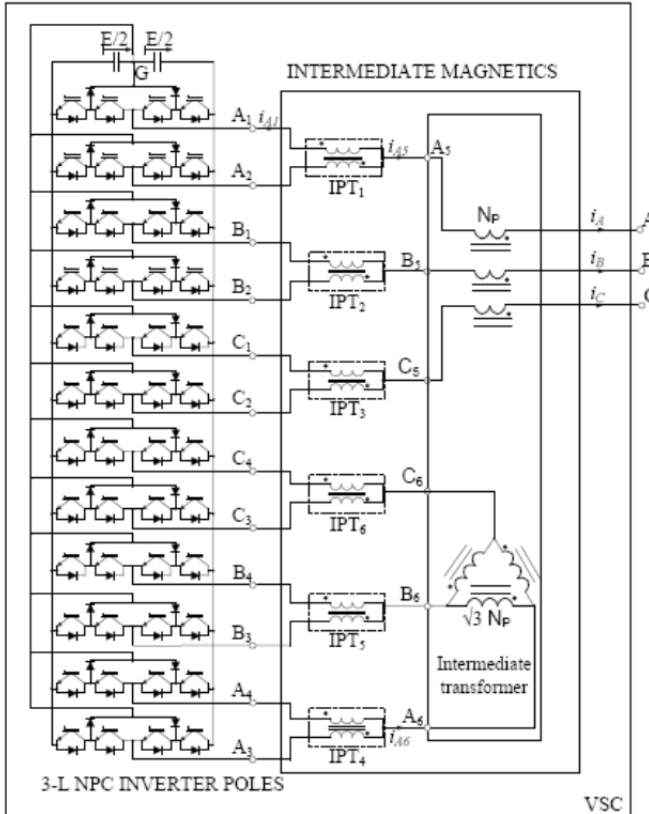

Fig 2. VSC topology for FACTS application, combining four three-phase converters [17].

In [18, 19, 20, 21, 22] a new family of converter topologies are presented by inserting a split wound coupled inductors between the upper and lower switches in each inverter leg, as shown in Fig 3. In doing so, the apparent switching frequency of the output voltage is doubled, enhancing the power quality of the converter output voltage.
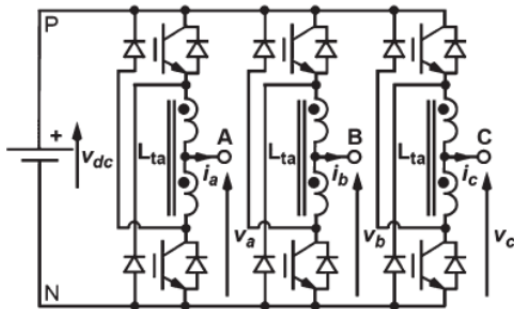

Fig 3. Multilevel three-phase inverter topology using split-wound coupled inductors [18].

In [23] a coupled three-phase inductor is used instead of three single phase coupled inductors. The coupled three-phase inductor has some switching restrictions. However, the core requirements are significantly smaller comparing to three single phase coupled inductors.

In this paper two three phase converters are parallelized by using the three phase IPT. In Section II the single phase IPT is described whereas in Section III the configuration of the three phase IPT is shown. Two alternatives for the three phase IPT are presented. The first one consists of a five limbs magnetic core and the second one is based on a three limbs magnetic core. In Section IV the simulation results obtained in Saber are presented. The simulation is focused on the parallelization of two three-phase converters with isolated DC buses by using the three phase IPT.

Finally, in Section V, the experimental results are shown and discussed.

Description Of A Single-Phase IPT

The coupled inductors allow to associate converters and increase the converter output power with increasing relatively low the weight, cost and volume of the overall converter [24]. By using the IPT the current is inherently shared by each parallelized converter leg.

Fig 4 (a) shows the basic configuration of an IPT by using a "U" type magnetic core. It consists of a magnetic core with two windings where the ends of them are connected to each other, forming the output terminal of the IPT.

In Fig 4 (b) the equivalent electrical circuit of the IPT is shown. The magnetic flux through the magnetic core is only generated by a difference between the leg currents i_{a1} and i_{a2}.

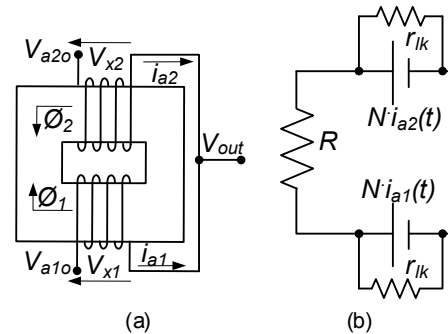(a)   (b)

Fig 4. (a): IPT basic configuration with a U type magnetic core. (b): The equivalent electrical circuit of the IPT.

The instantaneous value of the currents i_{a1} and i_{a2} trend to be the same because the IPT imposes a high impedance to their difference. The current that flows through each winding of the IPT, generates a magnetic force in opposition to each other. Therefore, when both currents are identical, no flux is generated through the magnetic core. Instead, the magnetic flux is closed through the air. Hence, when the two currents are equal, the impedance imposed by the IPT is the leakage inductance. So, the magnetic flux through the magnetic path is only generated by a difference in the phase currents.

Therefore, neglecting the leakage flux, the magnetic flux through the core is given as:

$$(1) \qquad \phi_m = \phi_1 - \phi_2 = \frac{N \cdot (i_{a1} - i_{a2})}{R}$$

So, the voltage drop across the phase "a" is given as:

$$(2) \qquad V_{x1} = L_m \cdot \frac{d(i_{a1} - i_{a2})}{dt}$$

where

$$(3) \qquad L_m = \frac{N^2}{R}$$

Description Of The Three-Phase IPT
The Three-Phase IPT based on a 5 limbs magnetic core.

In this Subsection the three-phase IPT that is based on a five limbs magnetic core is described. This IPT has 6 windings connected as in Fig 5 is shown. In the external limbs there are not any winding and the magnetic flux that flows through them is only generated by the difference of common mode currents.

The equivalent electrical circuit of the magnetic path is shown in Fig 6. The magnetic path has been simplified by assuming that all the columns have the same reluctance (R).
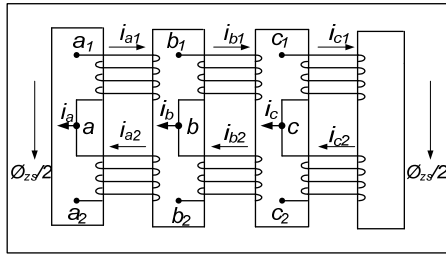
Fig 5. Three phase IPT by using a five-limb magnetic core.
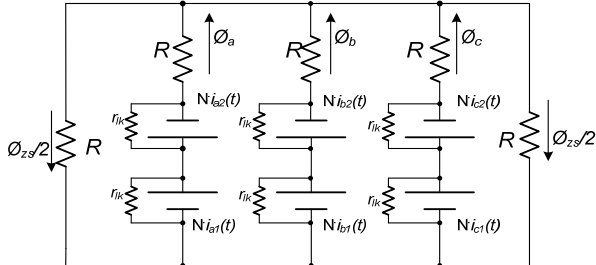

Fig 6. The equivalent electrical circuit of the Three-Thase IPT.

The equivalent electrical circuit of Fig 6 is solved neglecting the leakage inductance. The voltage drop across the phase a is defined:

(4) $$V_{a1a} = L_m \cdot \left[4 \cdot \frac{d(i_{a1} - i_{a2})}{dt} - \frac{d(i_{b1} - i_{b2})}{dt} - \frac{d(i_{c1} - i_{c2})}{dt} \right]$$

where

(5) $$L_m = \frac{N^2}{5 \cdot R}$$

On the one hand, for the difference of differential mode currents ($i_{a1} + i_{b1} + i_{c1} = 0$ and $i_{a2} + i_{b2} + i_{c2} = 0$) the imposed inductance by the IPT is the same as the obtained in (3). On the other hand, the imposed inductance for the difference between common mode currents ($i_{a1} = i_{b1} = i_{c1} = i_{zs1}$ and $i_{a2} = i_{b2} = i_{c2} = i_{zs2}$) is:

(6) $$L_m = \frac{2 \cdot N^2}{5 \cdot R}$$

It can be observed that the three phase IPT works as three single phase IPTs, imposing relatively high impedance to the difference of differential mode currents as well as to the difference of common mode currents.

The Three-Phase IPT based on a 3 limbs magnetic core.
When two three-phase converters with a common DC bus are parallelized, common mode currents can flow from one converter to the other. For that reason the IPTs must impose a high impedance to common mode currents which is the case of the single phase IPTs or the three phase IPT presented in the previous Subsection. However, if the two three-phase converters are parallelized with isolated DC buses, common mode currents can not flow between them. Subsequently, the IPT has not to impose a high impedance to common mode currents. It has to impose a high impedance only to the difference between differential mode currents.

The three phase IPT described in this subsection can be used to connect in parallel two independent three phase converters (with isolated DC buses) as is shown in Fig 7. One of the consequences of isolating the DC buses is that higher capacitors are needed for a given voltage ripple. So, the stored energy in the capacitors increases. However, the size, weight and cost of this IPT is low comparing to three single phase IPTs [23]. Hence, this converter association can be a suitable solution to parallelize standardized three phase converters.
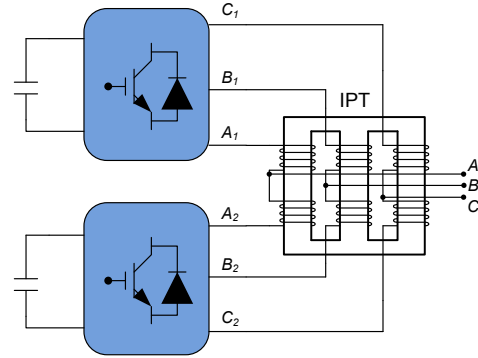

Fig 7. Two three phase converter parallelization by using the three phase IPT.

This IPT is based on a three limbs magnetic core as it is shown in Fig 8.
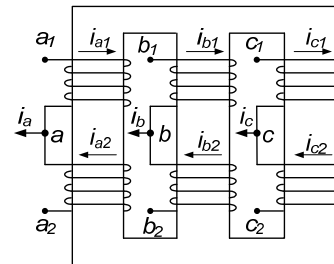

Fig 8. Three phase IPT by using a three limbs magnetic core.

The electrical equivalent circuit is shown in Fig 9. Note that only differential mode magnetic fluxes can be flown through the magnetic core. Subsequently, the next can be defined:

(7) $$\phi_a + \phi_b + \phi_c = 0$$

Thus, the magnetic flux through the magnetic core is generated only by the difference between the differential mode currents.
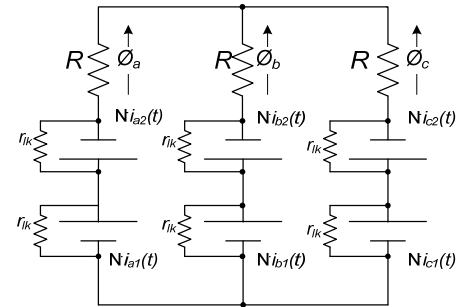

Fig 9. The equivalent electrical circuit of the Three-phase IPT.

As stated previously, common mode currents can not flow between the converters. So, these considerations can be done:

(8) $$i_{a1} + i_{b1} + i_{c1} = 0$$
$$i_{a2} + i_{b2} + i_{c2} = 0$$

Taking into account (7) and (8), and according to (4), the imposed impedance for differential mode currents is the same as the obtained in (2). Hence, the three-phase IPT can be used as an alternative of three single phase IPTs if common mode currents can not flow, which is the case of parallel connection of two converters with isolated DC buses.

Simulation Results

In the simulation carried out in Saber, two three-phase voltage sources are parallelized by using the three-phase IPT based on three limbs magnetic core. The IPT has been modelled by using the Magnetics tool of Saber.

The configuration of the IPT is the same as the classical three-phase transformer. The leakage and the magnetizing inductances have been set to values of 1mH and 2.9H, respectively.

In order to verify that the three-phase IPT can be used to parallelize converters, two three-phase voltage sources have been connected in parallel through the IPT as it is depicted in Fig 10.
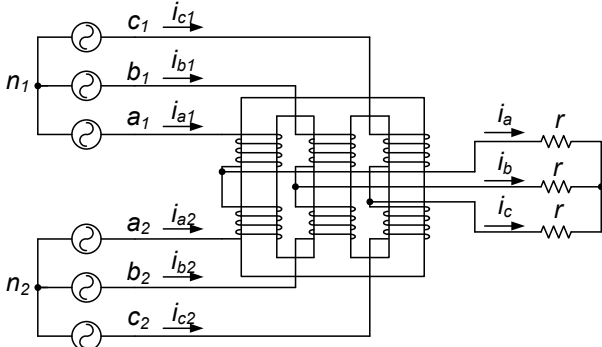

Fig 10. Electrical scheme of the simulation.

In order to emulate two three-phase converters with isolated DC buses, the neutral points of the voltage sources are isolated. The fundamental components of the voltage sources have been phase shifted by 30 degrees. The rms value of the first three-phase voltage sources is $25\sqrt{3}$ V whereas the rms value of the second one is 25V. In addition, a third order harmonic has been added only to the second voltage source.

In Fig 11 the simulation results are depicted. The output voltage of the phase a (Va) is the average between the voltages of each parallelized leg, Va_1 and Va_2 which is in phase with the output current. In the second sub-graphic the currents through the parallelized legs are shown. The both currents have almost the same instantaneous value and they are in phase with the output voltage. So, a balanced current sharing is assured by the three-phase IPT.
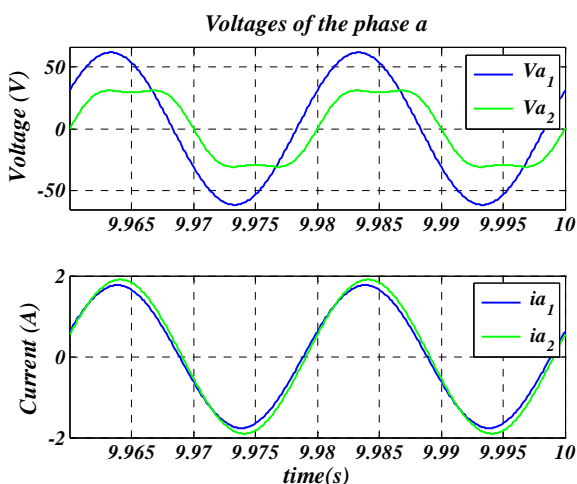

Fig 11. Simulation results of the three-phase IPT.

Experimental Results

The electrical circuit simulated in the previous Section has been validated with an experimental test. In order to obtain two isolated three-phase voltage sources, a three phase transformer has been used in delta-wye connection

as it is shown in Fig 12. Because of the delta-wye connection, the fundamental components of the secondary side voltage leads 30 degrees the primary side voltage and the amplitude is $\sqrt{3}$ times higher, the same case as in the previous Section is obtained. As in the simulation, both three-phase voltage sources are paralleled by using the three-phase IPT as is shown in Fig 12.
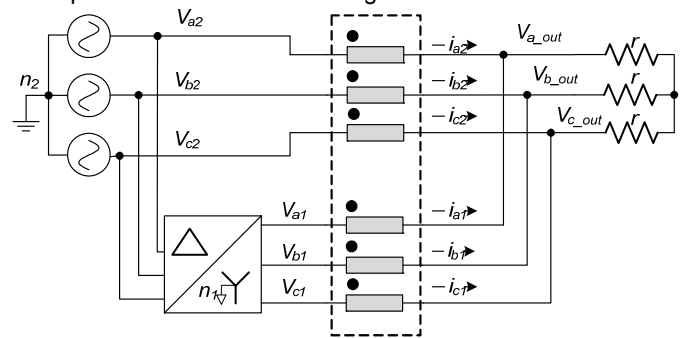

Fig 12. Electrical scheme of the experimental test.

The three-phase IPT consists of a conventional three-phase transformer. The magnetizing inductance of this transformer is 2.9H and the leakage inductance is 1mH. In Fig 13 the test bench is shown, which consists of: the programmable AC source, the wye-delta transformer, the three-phase IPT, the oscilloscope and the output resistors.
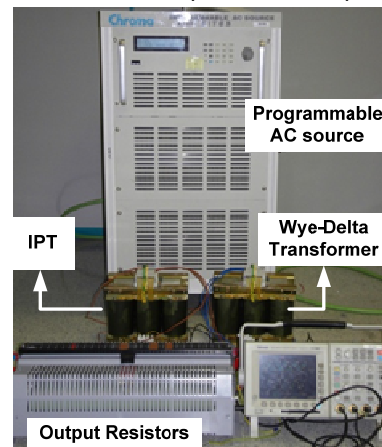

Fig 13. Test bench.

The waveforms that have been obtained experimentally are shown in Fig 14. It can be observed that the experimental results are close to the results obtained in the simulations carried out in Saber.
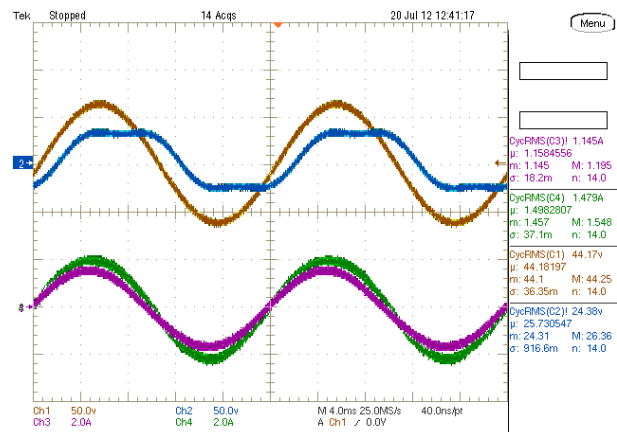

Fig 14. Experimental results: Top: ia1 and Va2. Bottom: ia1 and ia2.

Conclusion

In this paper the way to parallelize two three-phase converters by using a single magnetic core is proposed. Instead of using three single phase IPTs, a single core based on a five limb magnetic core is used. In addition, if the DC buses of the converters to be parallelized are isolated, a magnetic core of three limbs can be used instead of three single phase IPTs, which is a suitable solution to parallelize standardized three phase converters.

A simulation has been carried out in Saber. Two different three-phase voltage sources have been parallelized by using the three-phase IPT.

Finally, the analysis and the simulation have been validated experimentally by using a conventional three-phase transformer as the three-phase IPT.

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