Method to design the leakage inductances of a multiwinding transformer for a multisource energy management system

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***Abstract*—The paper at hand proposes to employ a multisource DC-DC converter to interconnect energy sources, storage devices, drives and the motion control unit of an electric vehicle. This converter topology is well suited to interconnect more than 2 sources/loads that need galvanic isolation. It is particularly advantageous in the case of different voltage levels to be connected, with the power flowing in any direction. The multisource DC-DC converter employs a single magnetic core with multiple windings. The maximum transmissible power for each pair of sources, the energy efficiency and the controllability of the system depend on the multiwinding transformer's leakage inductances. The paper presents a solution to adjust the leakage inductances in order to obtain a given converter characteristic. The approach works with uneven transformation ratios and is validated experimentally for 4 sources/loads.**

***Index Terms*—Energy Management, Multisource DC-DC Converter, Multiwinding Transformer, Multiport DC-DC converter**

I. Introduction

The multisource DC-DC converter with multiwinding high frequency transformer was introduced in [1] as a solution to interconnect an arbitrary number n of DC sources. The multiwinding transformer provides isolation between the interconnected sources. By suitable selection of the transformation ratios efficient voltage/current ratio transformation can be obtained between the sources. Due to the two-quadrant nature of the interconnected voltage source inverter cells, the DC sources are unipolar in voltage, but they are bidirectional in power such that they can act as power source, power sink or alternate between the two mode of operations. This results in the possibility to have arbitrary power flow between the sources coupled magnetically within the multiwinding transformer core. The topology has been first proposed and applied to provide bidirectional isolated DC-supply to the cells of cascade multilevel inverters where the power flows between cells according to the multilevel inverter operating point [1]–[4]. It has then been used for UPS applications in [5] and more recently proposed as a solution to interconnect aircraft HVDC busses in [6]. It is also called multiport DC-DC converter in these latter applications. Finally, similar transformer topologies are also used in interleaved DC-DC converters [7].

Compared to multiple independent two-source DC-DC converters, the multisource DC-DC converter allows to both improve the overall energy efficiency of the converter system and to reduce its volume and cost, especially for applications with variable power flows. This topology is moreover an attractive solution in applications where a galvanic isolation between different power sources/loads is required or when conventional DC-DC converters (e.g. buck or boost) have a low efficiency, as when the DC voltage levels are significantly different.

In these type of power converters, the leakage inductance of the multiwinding transformer is a crucial parameter that affect dramatically the performance of the overall system. The leakage inductance of a multiwinding transformer is defined for each pair of the n windings, i.e. it is represented by a matrix of dimension n by n. The power flows depend on the phase shift of the applied voltage waveforms and the leakage inductance of the multiwinding transformer between the different DC-AC inverter cells. The first order harmonic gives a good approximation of the transmitted power:

$$P_{i\rightarrow j} \propto \frac{\sin(\alpha_j - \alpha_i)}{L_{\sigma,i\rightarrow j}} \qquad (1)$$

From (1) follows that the maximum power that can be transmitted between each pair of modules and the sensitivity of the power flow to phase changes strongly depend on the multiwinding transformer's leakage inductances.

In order to be able to transmit a given power between sources i and j, there is an upper limit to the leakage inductance $L_{\sigma,i\rightarrow j,\max}$. In order to control the power flows accurately there is a lower limit $L_{\sigma,i\rightarrow j,\min}$. *All the leakage inductances must lie in a given interval*. The leakage inductances could, of course, be adjusted (increased) by serially connecting additional inductances to each winding. The main advantage of this setup is the good and individual controllability of the windings' total inductances. However, additional coils would outweigh the design objective of reducing size and weight, and are therefore not considered any further.

The crucial issue that was not addressed so far in literature is how to design the multiwinding transformer in order to obtain leakage inductances in a given range, such that the desired

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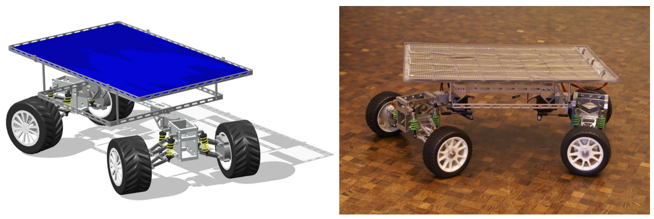
power flow can be established and satisfactorily controlled, resulting in a high energy efficiency. In this context, the paper at hand presents transformer multiwinding topologies such that the leakage inductances are similar and adjustable. The concepts are tested by the realization of a low power converter for a reduced scale autonomous solar electric vehicle illustrated in Fig. 1.



(a) vehicle CAD sketch *(b) vehicle*

Fig. 1. Construction stages of the reduced scale electric vehicle and of its energy management system.

II. Multisource DC-DC converter

A. *Topology*

The topology comprises n DC-AC H-bridge inverters, each connected to a winding of the same transformer, as illustrated in Fig. 2(a) for $n = 4$.

B. *Control*

The control inputs are the relative phase angles of the inverter 3-level rectangular waveforms and the duty cycle of the positive and negative pulses, which affect the shape of the voltage and current waveforms as illustrated in Fig. 3 for two interconnected sources. The power flow is controlled by adjusting the relative phase angles (1). The accuracy of the power flow is directly linked to how small the phase angle step is. This depends on the clock frequency used to generate the associated DPWM signal. The accuracy can be increased by increasing the value of the leakage inductance, or for small phase angles by reducing the magnitude of the waveform first harmonic. The maximum achievable power flow and the power flow step determine the controllability of the system. The duty cycle can also be adjusted in order to reduce the switching losses (for a two-source converter ZCS can be achieved [8]). During transients, the duty cycle must be changed in an appropriate way to avoid low frequency current harmonics, which would saturate the transformer [4].

C. *Comparison to $n-1$ two-source DC-DC converters*

1) Benchmark topology: In order to obtain the same functionality by using isolated two-source DC-DC converters instead, $n-1$ modules would be required as shown in Fig. 2(b).

2) Required material: Comparing the multisource DC-DC converter of Fig. 2(a) with the topology of Fig. 2(b), only one core is required for the multisource topology, while the number of required windings is reduced from $2n-2$ down to n. When comparing the rating of the required devices, it has to be noticed that the maximum magnetic flux is the same in all cores of the two topologies. If the winding window is large enough to add additional windings, which is often the case in high frequency applications, the same core can be used. The overall core volume and weight would then be reduced by a factor $n-1$.

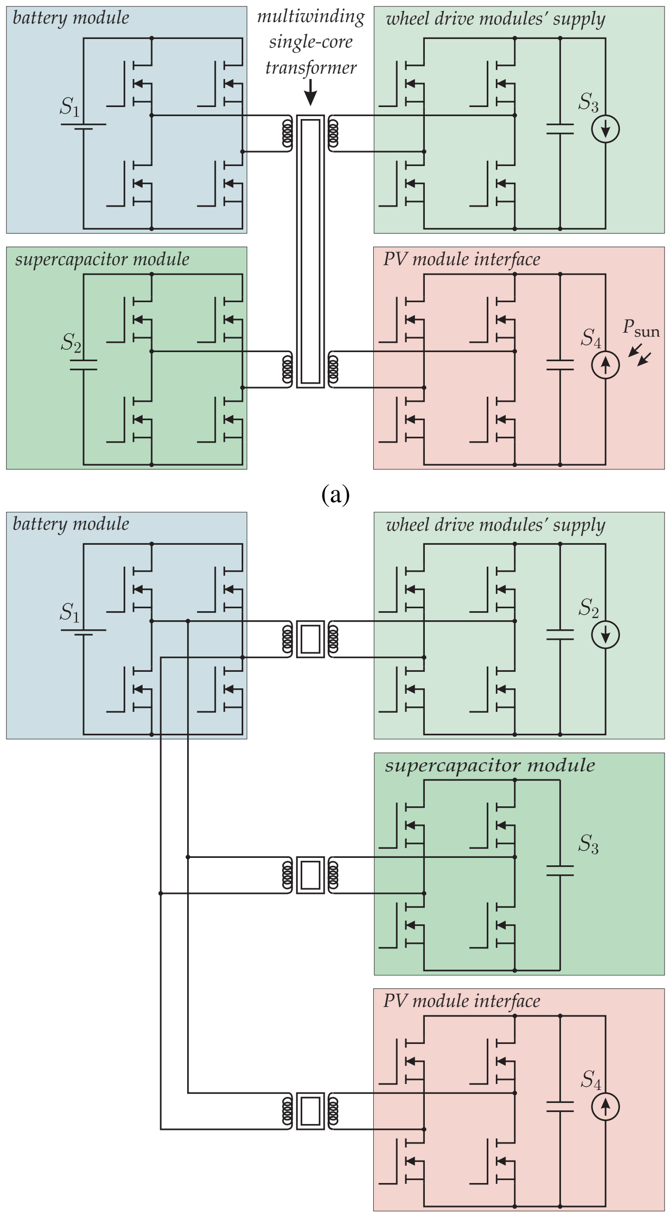


Fig. 2. (a) Multisource DC-DC converter with multiwinding transformer. Configuration with four sources. Three sources can act as sources or sink: battery (S_1), ultracapacitors (S_2), electric drives (S_3); two sources are voltage sources: battery and ultracapacitors; the solar panel (S_4) acts as a current source only. The leakage inductances between each pair of windings allows to control the power flow. (b) Topology with separate DC-DC converters and transformers.

3) Losses: The current magnitudes and losses are comparable in all windings connected to the sources S_2 to S_4. The losses in the windings connected to the source S_1 are generally smaller in the multiwinding transformer as the power flows

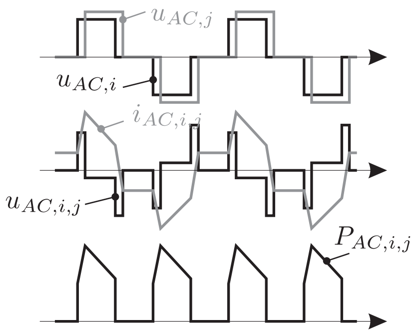


Fig. 3. Waveforms between two sources. To obtain real currents and power waveforms, the partial waveforms need to be summed up.

from sources S_2 to S_4 sum in the magnetic core and as only the balance causes a current to circulate in the winding of S_1. The switching devices and winding conduction losses are therefore smaller for the multisource DC-DC converter. The exact characterization of the losses including switching losses is more complex as it depends on the switching angles.

III. Transformer design

A. Design objective

It has been shown above that the transformer leakage inductances play a crucial role in the multisource converter's characteristics. Careful design of these leakage inductances therefore proves vital. The design objectives that follow are: a) keeping the leakage inductances in a specified range, where the upper limit is given by the power specification (the maximum power flow to be achieved between each pair of modules) and the lower limit is set by the controller time resolution; and b) minimizing the discrepancy between the different leakage inductances in order to provide good controllability and energy efficiency. In the considered application—the solar electric vehicle (Fig. 1)—the allowed range of the total leakage inductance between a pair of windings is $20-32$ μH, relating to 20 V.

B. Discussion of possible approaches to design the leakage inductances

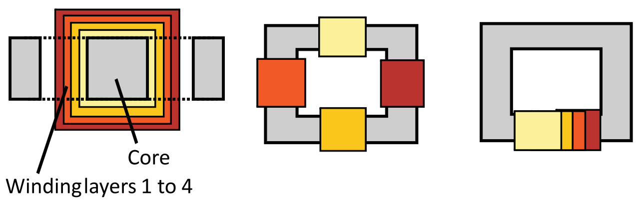
The leakage inductances are mainly dependent on the winding arrangement and the core geometry. The problem of adjusting the leakage inductances, therefore, is of geometrical nature. While this task can easily be accomplished for two windings, it becomes increasingly difficult with three or more windings, as the leakage inductances are strongly interdependent. Corrections in the placement of one winding relative to a second winding, e.g., can lead to substantial changes in all other leakage inductances associated with this first winding. In the paper at hand, the focus was set on experimental testing of promising transformer layouts. The leakage inductance matrices of different transformer design prototypes have been measured. In contrast to the application of analytical or numerical modeling, real values reflecting the full complexity of magnetic leakage could thus be obtained.

The basic transformer designs included in the measurements are discussed in the following. All tests have been done with four windings *1, 2, 3, 4* (and corresponding turns ratio 1:2:3:4), and so are the following figures. The principles stated, however, are applicable to any number of windings.

1) Coaxial winding geometry: As the most obvious solution, a coaxial arrangement where the windings are wound in layers on top of each other is considered. The winding is done on the center leg of two joint E-cores (Fig. 4(a)). This layout yields very low leakage inductances due to the coaxial winding geometry. For the considered application, the leakage inductances equal approx. 2 to 5 μH relating to winding *2* (20 V), which is by a factor of 4 to 10 too low for acceptable controllability ($L_\sigma \geq 20\mu\text{H}$). The discrepancy between the individual leakage inductances, however, seems to be small, though hard to quantize by measurement at these low inductance levels. It remains an open question whether this simple and easily reproducible layout would prove suitable for applications where very low but even leakage inductances are required, such as with ultra-fast controllers.

2) Distributed winding geometry: In order to increase the leakage, the windings are physically distributed on the 4 legs of a rectangular core (Fig. 4(b)). This again simple layout results in dramatically increased leakage inductances. In the considered solar vehicle setup, they reach up to 150 μH (relating to winding *2*), showing some additional 25 % increase for the opposing winding pairs due to their larger physical separation. The corresponding arrangement on a ring core presents somewhat lower leakage fluxes than the rectangular core arrangement, as leakage-enhancing corners are lacking. In any case, however, the leakage inductances are by a factor of approx. 5 too high, meaning that the required power transmission capacity cannot be reached ($L_\sigma \leq 32\mu\text{H}$). This geometry is to be abandoned, too.

3) Partially overlapping winding geometry: The results of the coaxial and distributed winding geometries suggest suitable leakage inductances in an arrangement where windings partially overlap. A rectangular core with one movable and one fixed winding was built (Fig. 5), allowing for measuring the leakage inductance as a function of the displacement of the two windings on the core. Figure 6 shows the high sensitivity of the leakage inductance to the winding displacement, with acceptable values ($20\mu\text{H} \leq L_\sigma \leq 32\mu\text{H}$, indicated as target band in Fig. 6) at partial overlapping of the windings.



(a) Coaxial winding arrangement (cross-sectional view). (b) Distributed winding arrangement (top view). (c) Partially overlapping winding arrangement (top view).

Fig. 4. Considered winding geometries.

Translating this result to the multiwinding transformer means that each pair of windings should overlap and that the degree of overlap should be equal for all pairs in order to yield even leakage inductances. This requirement is easily satisfied for $n = 3$, using a symmetrical arrangement of the windings on a ring core, where the winding centers are displaced by 120 degrees. Such solution is, however, impossible for $n > 3$, as in no case the windings can be arranged such that all of them are adjoining each other, for obvious geometrical reasons. Without mutual adjacency, of course, no partial winding overlap is possible. No solution to this problem is provided if the windings are densely arranged as seen in Fig. 4(c), since the degree of overlap would vary massively between the different winding pairs.

The above investigations show that both the coaxial and distributed winding geometries have to be discarded, as they don't provide acceptable controllability and power transfer capacity, respectively. The concept of partially overlapping windings, offering suitable leakage inductances, is adapted and modified in the next section in order to make it applicable for transformers with 4 or more windings, i.e. for converter topologies with 4 or more modules.

C. *Proposed method to design leakage inductances*

Considering the previous results, a winding layout has been developed that provides both partial overlap for *all* windings as well as a high degree of symmetry in the winding arrangement, ensuring both appropriate and sufficiently even leakage inductances for $n = 4$. The proposed design splits all windings into 2 serially connected parts and arranges them on a ring core in the following order: 1 3 4 2 3 1 2 4, where the numbers represent a section of the respective winding (Fig. 7(a)). This layout provides at least one mutual adjacency for each possible winding pair, enabling partial overlap (Fig. 7(b)). However, 2 out of the 6 pairs (1–3 and 2–4) are adjacent to each other twice, which significantly reduces the leakage of these pairs. This is counterbalanced by a reduced overlap between these windings (Fig. 7(c)) compared to the overlap of the other 4 pairs of windings (1–2, 1–4, 2–3, 3–4; Fig. 7(b)). Predicting the optimal degree of overlap as a function of the targeted leakage inductance interval is difficult, since the

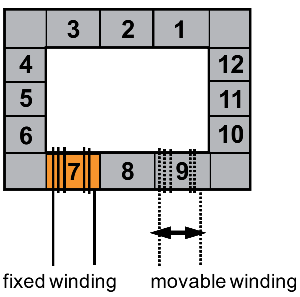


Fig. 5. Setup for measuring the leakage inductance as a function of distance between a pair of windings. The winding at slot 7 is fixed and fed with a test waveform (3-level rectangular), while the second winding is short-circuited and moved along the slots of the core.

leakage inductance shows its highest sensitivity to the winding placement just at partial overlapping (Fig. 6). Furthermore, the degree of overlap is also dependent on other factors such as the distance of the turns to the core and to each other.

A ring core is preferred to a rectangular core, as no corners complicate the required overlaps between all the winding sections. However, if the required leakage inductances were higher and thus no overlap was necessary at all, the same winding arrangement should be applied to a rectangular core (similar to the design discussed in III-B2). In this case, advantage of the corners can be taken by placing the windings such that the pairs occurring twice are separated by the 4 corners of the core. This measure increases the leakage flux between these windings in comparison to the pairs occurring once.

IV. Experimental validation

A 4-winding transformer according to the proposed design was realized (Fig. 8). Specific data is summarized in Table I. The windings were made by hand and sequentially from 1 to 4, with measurements and slight corrections in overlap after adding a new winding. A major challenge in tuning the leakage inductances was due to their interdependence, which does not allow to change one value without affecting the others.

A. *Measuring method*

All measurements have been carried out such that one transformer winding was fed with a waveform according to Fig. 3, one of the other windings being short-circuited. The remaining windings were left open, their influence on the leakage inductance thus being negligible. The total leakage inductance of a winding pair was measured via the corresponding current. To this end, a precision $1\,\Omega$ shunt resistance was inserted in the current path of one half-bridge of the test DC-AC inverter. The voltage across the shunt was displayed by an

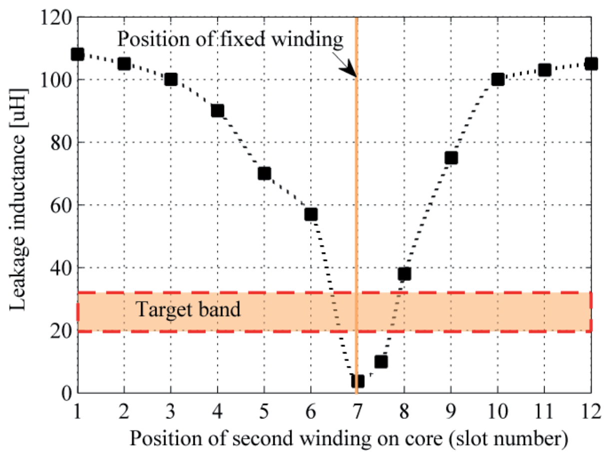
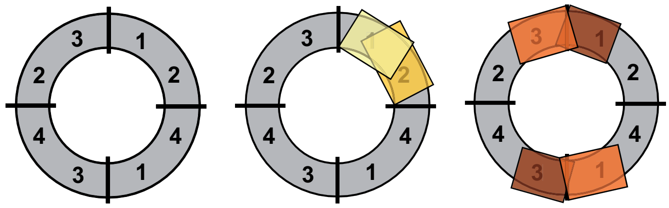


Fig. 6. Leakage inductance as a function of distance between a pair of windings. The core is sectioned into 12 slots (3 on each leg, see Fig. 5), both windings have a width of one slot. The fixed winding is at slot 7. The black rectangles indicate the value of the leakage inductance between the two windings when the movable winding is at the corresponding location on the core.



(a) Winding section positions on the core.

(b) Windings adjacent to each other once: medium overlap.

(c) Windings adjacent to each other twice: little overlap.

Fig. 7. Proposed winding arrangement on a ring core. Each winding is split into two parts and connected serially. The four bars visually separate the pairs occuring twice.

oscilloscope and compared to known inductances. Therefore, the accuracy of the measurements is limited to approx. $\pm 20\%$.

B. Measured leakage inductances

The results in Table II show good evenness of the leakage inductances while mostly lying within the targeted range (20–32 µH). The outlier value of pair 1–4 might be due to the large difference in the corresponding turn numbers (1:4), leading to different coil geometries. More turns lead to thicker coils, whereupon the outer turns produce more leakage flux due to their larger distance from the core. Manufacturing mismatches due to the hand-made winding process may be another reason for the raised value of pair 1–4.

The multiwinding transformer has successfully been inserted into a test setup with four sources.

C. Possible improvement of transformer manufacturing

Due to the hand-made winding process and the absence of appropriate coil formers, the manufacturing of the transformer was relatively complex. The use of coil formers and winding machines could substantially increase the accuracy of the winding arrangement and thus further improve the results.

Fig. 8. Realized transformer.

TABLE I
DATA OF REALIZED 4-WINDING TRANSFORMER.

Parameter	**Value**
Power rating	40 VA
Winding ratio	1:2:3:4
Voltage rating	10 V/20 V/30 V/40 V
Operating frequency	20 kHz
Core material	Ferrite N30
Core diameter	34 mm
Wire material	Copper
Wire diameter	1 resp. 2 x 0.4 mm

TABLE II
MEASURED MATRIX OF LEAKAGE INDUCTANCES OF PROPOSED TRANSFORMER DESIGN IN μH.

winding	1	2	3	4
1	0	19	21	30
2	19	0	18	19
3	21	18	0	19
4	30	21	19	0

V. CONCLUSION

The paper has shown that multisource DC-DC converters reduce the required core material and copper windings in comparison to a set of separate 2-source converters at identical power ratings. The reduction is achieved both in number of units and in the overall system volume and weight. Moreover, the efficiency of the system is improved by reducing the number of required DC-AC inverter modules from $2n-2$ down to n. It is emphasized that the matrix of leakage inductances is the key parameter that determines the transmissible power and the conversion efficiency.

A multiwinding transformer design method has been introduced which allows to achieve even leakage inductances that lie within a given range. The method is based on the use of splitted and partly overlapping windings. It is suitable for transformers with both even and uneven transformation ratios. As the method is based on fundamental geometrical properties, it is relatively robust. The concept has been tested with a 4-winding transformer with different voltage transformation ratios. The method can probably be extended for more windings but this has not been verified.

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