Characterization of miniaturized transformers at varying operating power

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***Abstract*—The trend towards miniaturization and integration, observed in all the fields of electronics, also applies to systems requiring galvanic isolation. A key aspect is the development of miniaturized transformers, to be integrated at silicon level or package level in a SoC (System-on-Chip) or SiP (System-in-Package) approach. This paper proposes a methodology to characterize such micro-transformers through electromagnetic simulations, extracting a set of key performance parameters, the accuracy of which was experimentally verified. Results are valid under certain load conditions and rated power level but, in a real application, devices need the flexibility to work in a certain range of operating power with a negligible performance variation. Focus of the work is to evaluate the effect of this variable power. The transformers geometry was initially optimized for a rated power of 1W. Different transformer configurations have been tested with power ranging from 0.6 W to 1.4 W, and checking the variation in terms of voltage ratio and efficiency. Depending on the application, this variation can be impactful or negligible. Additionally, results have been compared with similar transformers optimized for each specific power level, to verify the improvement in case of a dedicated optimization.**

Keywords— miniaturized transformers, rated power, efficiency, voltage ratio, optimization

I. INTRODUCTION

The ongoing advancements in integrated circuit (IC) technology result in growing demand for performance, compactness and cost-effectiveness, directing research towards miniaturized passive components for electronic systems.

This study focuses on planar transformers [1], [2] compatible with an integration at package level (SiP approach), having an area in the range of 30 mm² or lower. Geometry optimization to find the best trade-off between performance improvement and area reduction is a key challenge for cost competitiveness [3]. The considered technology is based on an air-core structure with no magnetic materials involved.

Components are designed for applications such as DC-DC converters [4]; operating frequencies should be as low as possible (typically in the MHz range) and an efficiency above 65% is pursued. The expected output power is in the range between 0.6 W and 1.4 W, and an almost constant performance level is required across this range, to ensure the correct functionality under the flexible conditions of a real application.

This paper explores the performance characteristics and optimization of miniaturized transformers with a particular focus on the impact of different rated powers. Initially, the key performance indicators are defined, by deriving them from a virtual characterization based on broadband S-parameter simulation [5]. Subsequently, a metamodel-based optimization procedure is introduced to determine the optimal design parameters. An insight is then proposed on the performance variation of a sample transformer, having 16 mm² area, across a range of operating powers from 0.6 W to 1.4 W. The results quantify the sensitivity of voltage ratio and efficiency to changes in operating power and demonstrate the effectiveness of the optimization procedure in maintaining performance consistency. By extending the analysis to transformers of different dimensions, the influence of size on performance metrics is also discussed, facilitating more informed design choices for any application.

II. TRANSFORMER MODELLING AND DESIGN

A. Transformer Performance Indexes

The considered transformers are realized by two planar windings located on different layers of the same substrate, which measures few millimetres per side. An example of this structure is reported in Fig. 1. With the two-fold aim of optimizing the transformer design first, and to investigate the effect of different rated powers on the overall performance later, it is necessary to identify a suitable transformer model and its relevant performance indicators, which, in turn, allow users to fruitfully compare different design options.

Traditionally, voltage ratio and efficiency are the most common indexes used to describe transformers performance. However, these quantities are well-defined if the operating

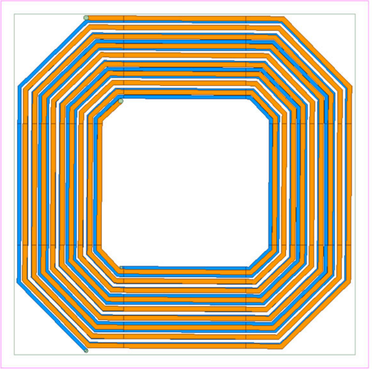

Fig. 1. Example of the geometrical structure of the considered miniaturized transformer: primary winding (orange), secondary winding (blue).

frequency is fixed, which is not the case for the targeted applications and becomes a design parameter in the present research. Generally speaking, voltage ratio and efficiency are both frequency dependent quantities, which should be evaluated over a specific frequency interval. The definition of voltage ratio and efficiency is also not unique, as they both depend on the specific conditions under which they are evaluated. In this paper, the following hypotheses are considered. First, the transformer primary winding is fed by an ideal, sinusoidal voltage source, with amplitude equal to the rated primary voltage. Second, the operating frequency is swept across the pre-determined transformer operating frequency interval. Third, the transformer secondary winding is loaded by a resistor R_L, whose value allows absorbing the transformer rated power when subjected to the rated secondary voltage.

The voltage ratio and efficiency are calculated as functions of the transformer 2 × 2 S-parameters matrix

$$\mathbf{S} = \begin{bmatrix} S_{11} & S_m \\ S_m & S_{22} \end{bmatrix} \tag{1}$$

which can be obtained by measurement or full-wave 3-D simulation. Under the aforementioned conditions, the transformer voltage ratio k_V is obtained by:

$$k_V = \frac{\left(1+\Gamma_L\right) S_m\left(f\right)}{\Gamma_L S_m{}^2\left(f\right) + \left(1+S_{11}\left(f\right)\right)\left(1-\Gamma_L S_{22}\left(f\right)\right)} \tag{2}$$

where

$$\Gamma_L = \frac{R_L - Z_0}{R_L + Z_0} \tag{3}$$

is the load reflection coefficient, and $Z_0 = 50\ \Omega$ is the reference impedance for S-parameter definition. Similarly, the transformer efficiency is obtained by:

$$\eta = \frac{\left|S_m\right|^2 \left(1-\left|\Gamma_L\right|^2\right)}{\left(1-\left|\Gamma_{in}\right|^2\right)\left|1-S_{22}\Gamma_L\right|^2} \tag{4}$$

where

$$\Gamma_{in} = S_{11} + \frac{S_m{}^2 \Gamma_L}{1-S_{22}\Gamma_L} \tag{5}$$

In principle, the transformer voltage ratio (2) peak should be close to the transformer rated voltage ratio, and the overall frequency response should be quite flat around its peak to provide predictable performance when the operating frequency is varied slightly. As the voltage ratio is the most relevant performance indicator of a transformer, its efficiency (4), ideally as high as possible, should be evaluated at the frequency of the voltage ratio peak. The correlation between full-wave simulations performed by a commercial software and measurements was verified, both in terms of S-parameters and voltage ratio/efficiency, showing good agreement up to 100 MHz, as shown in Fig. 2.

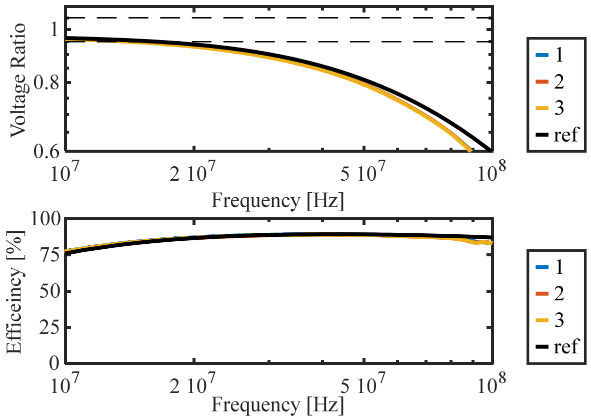

Fig. 2. Comparison of the measured voltage ratio k_V and efficiency η frequency responses of three sample miniaturized transformers (blue, red, and yellow) vs voltage ratio k_V and efficiency η frequency responses calculated from a full-wave 3-D simulation of the same transformer.

B. *Transformer Design Optmization Procedure*

The procedure for determining the optimal transformer design is based on physical and functional constraints, namely: substrate size and stack-up, primary voltage, and secondary voltage. For each specific case, the procedure should identify the optimal number of turns of the two windings and their trace width to maximize efficiency while matching the voltage ratio requirements, with the optimal operating frequency being obtained as a side-product.

Unfortunately, this is hardly achievable with reasonable computational effort by traditional global optimization methods available in commercial software packages. In fact, the presence of multiple optimization variables leads to a large number of combinations to be evaluated by full-wave simulation. With the available workstation (ten 3.7 GHz cores, 256 GB of RAM), the simulation of each transformer sample requires up to forty minutes for most cases, with some exceptions requiring up to several hours, leading to expected computational times in the order of one month for the optimization of every single design.

To overcome this limitation, a metamodel-based optimization procedure was developed, which allowed reducing the time required to optimize a single design to no more than one week. The proposed procedure encompasses the following steps.

Step no. 1: Data acquisition. Few hundreds of full wave simulations with different, randomly chosen turns numbers and trace widths are run, and their results processed to obtain voltage ratio and efficiency.

Step no. 2: Metamodel training. On the basis of the data obtained by step no. 1, a metamodel is developed to correlate turns number and trace widths with voltage ratio and efficiency. The obtained metamodel provides a numerical approximation of the relationships between the optimization variables (turns number and trace widths) and the performance indexes of interest (voltage ratio and efficiency) and, while of no use outside of the considered optimal design procedure, it allows for a significant reduction in the overall computational burden.

Step no. 3: Optimization. Since obtaining the voltage ratio and efficiency from a set of turns numbers and trace widths by the metamodel in step no. 2 requires few seconds at worst, a traditional global optimization method is applied to look for the optimal solution. All the tentative solutions are recorded, and the few tens providing the best expected results are exported.

Step no. 4: Validation. The transformer designs selected in step no. 3 are validated by full-wave simulation, and the effective best design is eventually selected.

Overall, it was observed that the proposed metamodel-based optimization procedure provides comparable results to traditional methods, while reducing the required number of full-wave simulations by one order of magnitude, from few thousands to several hundreds.

III. PERFORMANCE AT DIFFERENT OPERATING POWERS

The effect of different operating powers is investigated starting from a sample design obtained from the optimization procedure described in Section II.B. The sample is built on a 16 mm² substrate optimized for a 1:1 voltage ratio. The analysis has a twofold scope. The former is to understand the effect of a different operating power on the voltage ratio and efficiency of a specific design. The latter is to assess the effectiveness of repeating the optimization procedure with a different rated power in limiting the variation of said performance indexes.

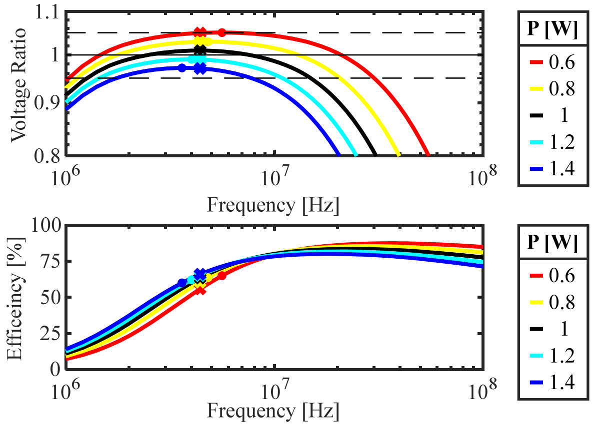

Fig. 3. Voltage ratio k_V and efficiency η frequency responses of a single transformer design, evaluated at different output power levels: round markers highlight operating frequency points corresponding to the voltage ratio peak, cross markers highlight the operating frequency at 1 W rated power.

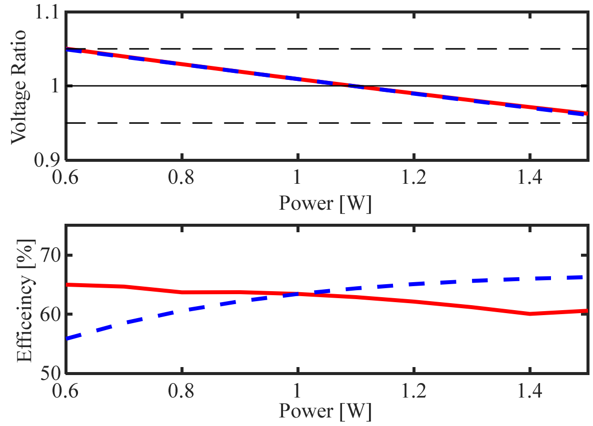

Fig. 4. Voltage ratio k_V and efficiency η trends of a single transformer design, as function of the output power: identified, for each power, at the frequency of the voltage ratio peak (red, continuous line); identified at a fixed frequency corresponding to the voltage ratio peak at 1 W (blue, dashed line).

As far as the first scope is concerned, the voltage ratio and efficiency of the considered design were evaluated for different powers, ranging from 0.6 W up to 1.4 W (i.e. secondary winding connected to a variable resistor absorbing the specified power when subjected to the transformer rated secondary voltage). The obtained results are collected in Fig. 3 and Fig. 4.

In Fig. 3 the voltage ratio and efficiency frequency responses are plotted for each considered power, and two sets of operating frequencies are identified. First, the operating frequency is selected, for each power, to correspond to the peak of the voltage ratio curve. The resulting working points are highlighted with round markers. The trends of efficiency and voltage ratio as functions of the transformer output power are reported with a continuous red line in Fig. 4. This allows the user to estimate the performance of a transformer employed in an application requiring a power different from the rated one (i.e., the power assumed for design optimization), with the operating frequency being selected accordingly.

Second, the operating frequency is selected, for each power, to correspond to the voltage ratio peak at the reference power of 1 W. The resulting working points are highlighted with cross markers. The trends of efficiency and voltage ratio as functions of the transformer output power are reported by a dashed blue line in Fig. 4. This allows users to estimate the performance of a transformer designed for a 1 W power and used for an application with a variable power, a fixed operating frequency.

Considering Fig. 3 and Fig. 4, it can be appreciated that, as expected, the voltage ratio reduces as the output power increases. The efficiency, on the contrary, reduces as the output power increases if the comparison is made at different

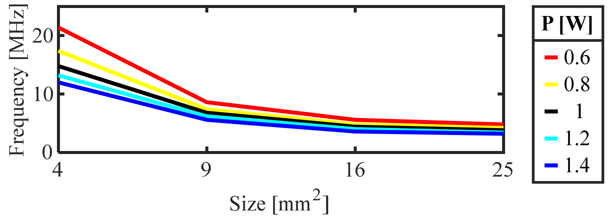

Fig. 5. Transformer operating frequency as a function of the substrate size, evaluated as the peak of the voltage ratio curve for different output powers.

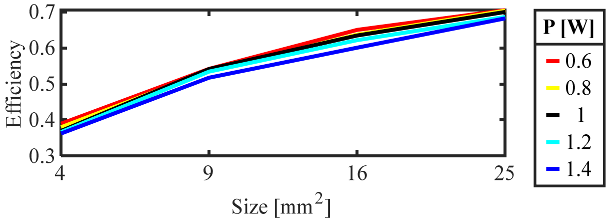

Fig. 6. Efficiency η as a function of the substrate size, evaluated at the frequency corresponding to the peak of the voltage ratio curve for different output powers.

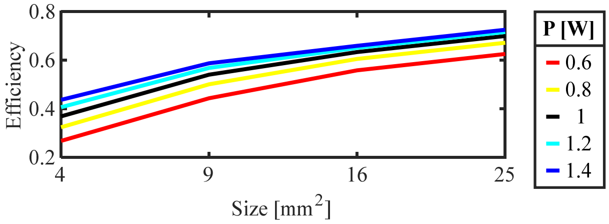

Fig. 7. Efficiency η as a function of the substrate size, evaluated at fixed frequency (voltage ratio peak at 1 W).

frequencies. If the comparison is performed at a fixed frequency, the efficiency increases with the output power. In both cases, the variation in efficiency is small, but not negligible (i.e. few percentage points). The worst case is the operation at lowest power (0.6 W) and fixed frequency.

The evaluation has been repeated on a family of transformers designed by the same procedure on substrates of the same type, but different sizes ranging from 4 mm² to 25 mm². The general trends emerging from the simulation campaign are reported in the figures from Fig. 5 to Fig. 7, where an overview of the transformer operating frequency and efficiency is provided, for different output powers, as function of the substrate size. A similar analysis has been carried out also for the voltage ratio. The obtained results – omitted here for brevity – do not reveal any specific trend vs transformer size. Also, the variation vs power confirms what already described.

It can be appreciated that the operating frequency, selected at the peak of the voltage ratio curve, decreases as the power increases, and the transformer size increases. The sensitivity of the operating frequency to power is higher for smaller transformers, lower for larger ones. Regarding the efficiency, it can be appreciated that the transformer size is by far the most impacting parameter. Comparing the efficiencies evaluated at the voltage ratio peak frequency (i.e., ideal operating frequency for each power), the sensitivity to a variation in output power seems small and almost the same for all transformer sizes. Conversely, repeating the comparison with fixed operating frequency (selected at 1 W rated power), the effect of output power variations on the efficiency is significant for small transformers and limited as the transformer size increases. As far as the second main scope is concerned, the same sample case built on a 16 mm² substrate was re-optimized for different output powers, ranging from 0.6 W up to 1.4 W, with 0.2 W steps. The results are collected in Fig. 8 and Fig. 9. As expected, the voltage ratio is less sensitive to different powers if the full optimization procedure is performed with a different output power. On the contrary, the efficiency is overall reduced as the output power increases, despite the re-optimization. The only improvement with respect to Fig. 4 is the mitigation of the efficiency drop previously observed for very low powers. Overall, the variation in efficiency is in the range of few percentage points.

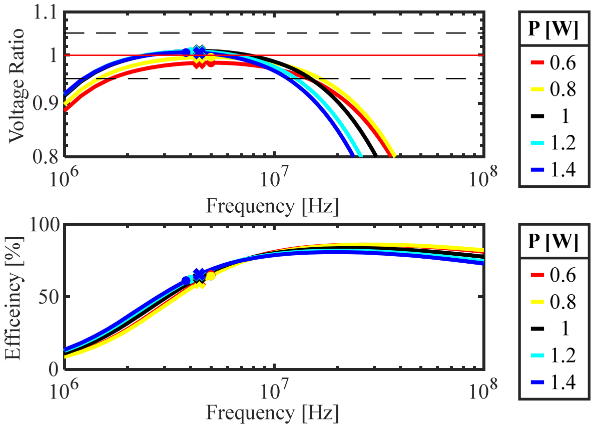

Fig. 8. Voltage ratio k_V and efficiency η frequency responses for different transformer designs, optimized for different output power levels: round markers highlight operating frequency points corresponding to the voltage ratio peak, cross markers highlight the operating frequency at 1 W rated power.

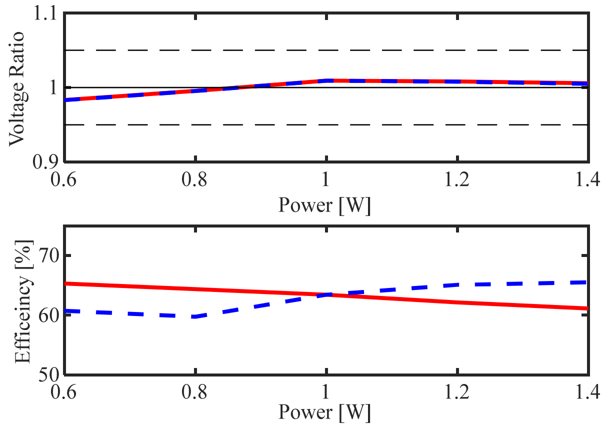

Fig. 9. Voltage ratio kV and efficiency η trends of different transformer designs optimized for different output power levels, as function of the output power: identified, for each power, at the frequency of the voltage ratio peak (red, continuous line); identified at a fixed frequency corresponding to the voltage ratio peak at 1 W (blue, dashed line).

IV. CONCLUSION

In this paper, the effect of different operating powers on the performance of a miniaturized transformer was investigated. To this end, a power variation from 60% to 140% of the rated power was considered and its impact on the transformer operating frequency, voltage ratio, and efficiency was estimated. The analysis of a first sample design highlighted that the voltage ratio reduces as the output power increases, regardless of how the operating frequency is selected. Instead, the efficiency trend is proven to depend on the operating frequency, yet showing a variation of few percentage points. By extending the analysis to different transformer sizes, it is observed that the optimal operating frequency decreases as the power or the size increases, with smaller transformers being more sensitive to power variations than larger ones. The voltage ratio is scarcely sensitive to size variations, while the efficiency can be significantly affected by the transformer size especially for smaller transformers. Lastly, by repeating the design optimization procedure for different output powers, it was proved that voltage ratio can be effectively compensated, while efficiency cannot.

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