# Time-harmonic design approach for saturable filter inductors in power electronic applications

Raymond Quinn[a], Joonas Vesa[a], Paavo Rasilo[a]

[a] *Tampere University, Tampere, Finland.*

A time-harmonic design method for saturable filter inductors in power electronic applications is presented. The method achieves good accuracy in determining the optimal number of turns required to minimise current ripple whilst reducing computation time compared to a time-stepping model.

*Keywords:* saturable inductors; power electronics; time-harmonic analysis

## 1. Introduction

In the traditional filter inductor design for power electronic applications, analytical methods such as the area-product method are used to provide a core geometry and winding arrangement to meet a specific inductance value which will keep switching ripple in the current within a desired range [1]. We describe here a method for saturable inductor design which instead provides the optimal flux density level and number of turns to minimise the ripple for a given geometry, core material, and current in the steady state determined by a time-harmonic analysis of the system. A single-phase inverter supplying a resistive load is considered in this case.

In the time-harmonic case, we deal only with the fundamental components of time-varying signals and express them using peak-valued complex phasors (denoted using an underline). This approximation speeds up computation, describes accurately the operating point in terms of the transferred power, and provides a good initial condition for time-stepping models.

We posit that differential inductance $L_\mathrm{d} = d\psi / di$ evaluated at the peak of the fundamental flux linkage correlates strongly with the ripple reduction capabilities of an inductor and that this inductance can be maximised with time-harmonic analysis by optimising the flux-density level. Using the time-harmonic approach, to calculate the differential inductance, we must first solve for the fundamental flux density $\underline{b}_0$ in the steady state. Due to the nonlinear magnetic properties of the inductor core material, the fundamental inductance is a function of the flux density and is found from $\underline{L}(\underline{b}_0) = N^2 A_\mathrm{Fe} / (\underline{\nu}(\underline{b}_0) l_\mathrm{Fe} + \nu_0 \delta)$, where $N$ is the number of winding turns, $A_\mathrm{Fe}$ the core-cross sectional area, $\underline{\nu}$ the fundamental reluctivity, $l_\mathrm{Fe}$ the magnetic path length, $\nu_0$ the reluctivity of free space, and $\delta$ the air gap length. Fixed-point iteration is used to solve for the fundamental flux density such that $\underline{b}_0 - \underline{L}(\underline{b}_0)\underline{i} / NA_\mathrm{Fe} = 0$, where $\underline{i}$ is the fundamental current. When we have solved the magnitude of $\underline{b}_0$, we can find the differential reluctivity and inductance at that flux density.

To calculate $L_\mathrm{d}$ and $\underline{L}$, the differential reluctivity $\nu_\mathrm{d}$ and fundamental complex reluctivity $\underline{\nu}$ must be calculated. $\nu_\mathrm{d}$ is found by determining the derivative of the single-valued magnetisation curve $dh_\mathrm{sv}(b) / db$ evaluated at $b = |\underline{b}_0|$. For a laminated core, the $\underline{\nu}$ required to calculate $\underline{L}$ is found by supplying the time-domain core-loss model expressing the surface field strength $h_\mathrm{s}(b_0(t))$, which accounts for the hysteresis, eddy-current, and excess losses [2], with a sinusoidal flux density and evaluating the fundamental $\underline{h}_\mathrm{s}$ and successively $\underline{\nu} = \underline{h}_\mathrm{s} / \underline{b}_0$.

When $\underline{i}$ is fixed, $|\underline{b}_0|$ increases when $N$ increases. To find the optimal number of turns $N$ we select an initial number of turns and perform the time-harmonic analysis to find the differential inductance. We then increase $N$ and repeat the process until the differential inductance begins to decrease due to the differential reluctivity increasing faster than $N^2$. The maximum differential inductance achieved and the corresponding number of turns are expected to minimise the current ripple are therefore optimal for the given core geometry and material for this application in the steady state.

## 2. Results and discussion

Initial optimisation results for an EI-96 core of Cogent steel with a stack height of 30 mm and air gap length of 1 mm as a filter inductor in a single-phase inverter application found an optimal number of turns to be 78 with the computation time taking 65 ms. It is not possible to quantify the ripple using the time-harmonic method alone, therefore, the time-stepping model presented in [2] is used to verify using the initial conditions provided by the time-harmonic model. Using the time-stepping model it is found that 81 turns minimises the ripple for this inductor but at a computation time of 4.89 s. Figure 1 shows the optimal number of turns predicted by both methods. The time-harmonic design method predicts the optimal number of turns by calculating the maximum $L_\mathrm{d}$ based on $N$. The time-stepping method yields the optimal $N$ more accurately but at the cost of increased computation time.

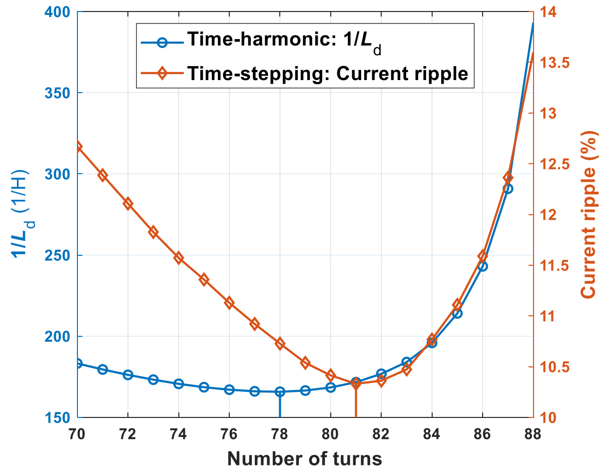


Figure 1: Optimal number of turns predicted by time-harmonic and time-stepping methods.

### References

[1] D. K. Saini et al., IEEE Trans. Ind. Electron. 65(3), 2234–2244 (2018).

[2] P. Rasilo et al., IEEE Trans. Power Electron. 34(2), 1683-1695 (2019).