Magnetic and circuital modeling of a low harmonic pollution three phase transformer

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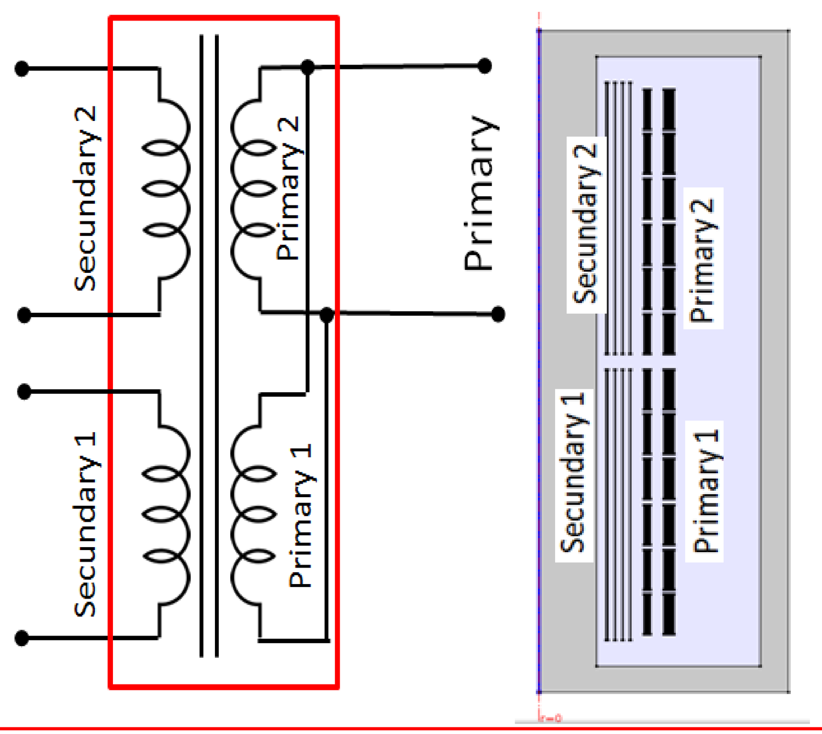
A three phase transformer with very low harmonic pollution transferred back to power line is here presented. The configuration of one of the three columns of this transformer is described in the box below with sketch and caption.



Two secondary windings are placed one above the other and feeding a rectifier (here not drawn). The primary, fed by the power line is accordingly split in two parts, so that each one is (mainly) coupled with the secondary winding in front of it.

The output after the rectifier is resulting into a signal whose first harmonic ripple is at 12 times the base frequency. Due to this setup, intermediate harmonics (5th and 7th) are not going out back to the power line feeding the primary.

This setup is intriguing as it requires just this transformer for feeding the rectifier giving the 12-pulse output and no other components (e.g. absorbing inductor) are involved, thus reducing the cost for construction & maintenance.

The reason for the abrupt decrease in 5th and 7th harmonic of the currents in the signal going out on the power line is due to the fact that currents at these frequencies is flowing into the two primaries (secondaries) with opposite sign.

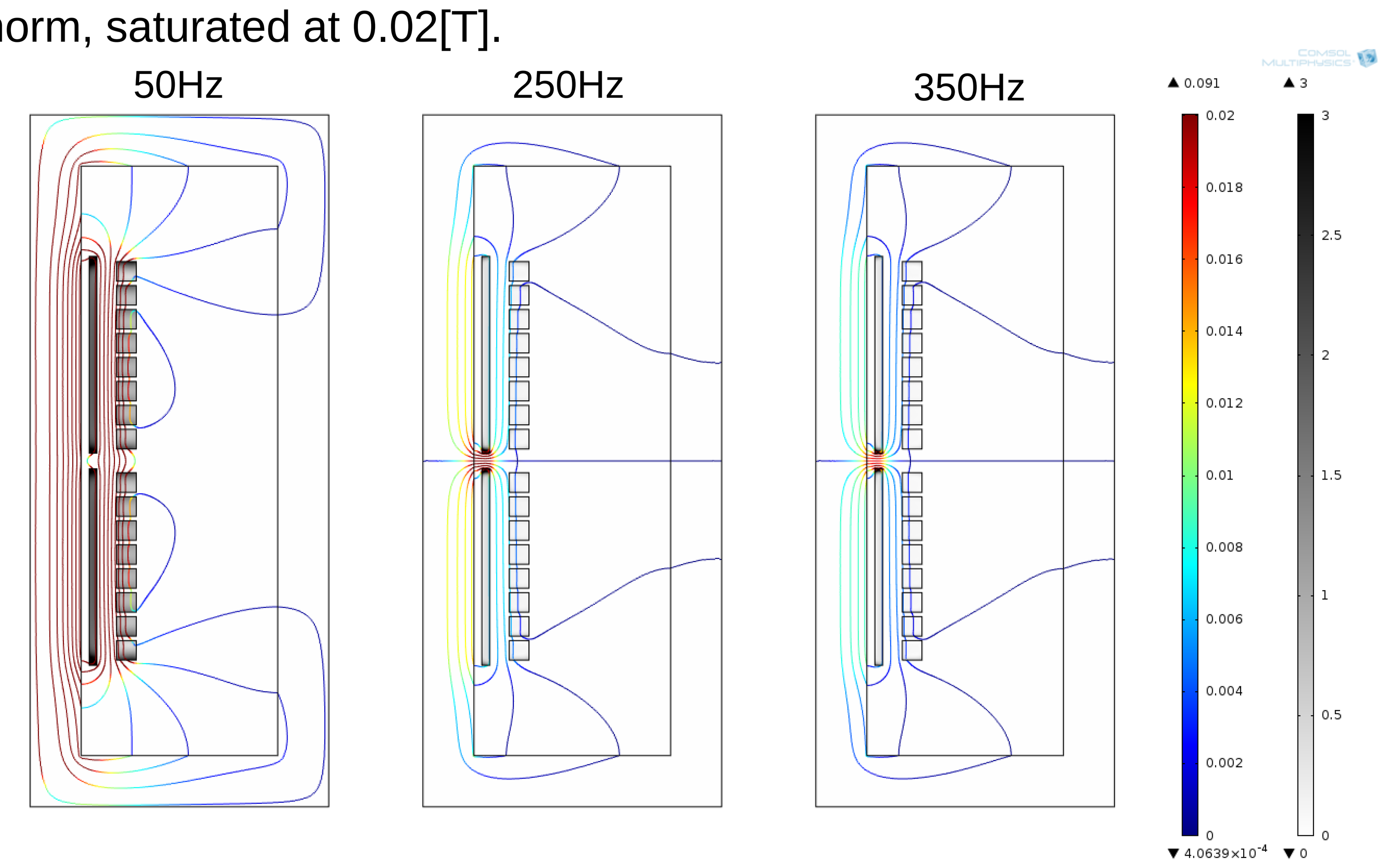
However the currents at the 5th and 7th harmonic, even if not exiting to the power line, are still flowing inside the windings and producing the corresponding extra losses. These are essential to be correctly estimated in order to have a proper design. Furthermore (as for these higher harmonic components of the current, primary1 alone is not exactly compensating the flux generated by secondary 1 - same happening for 2) a radial flux having a maximum in the middle of the machine is occurring. A radial flux then is producing highly concentrate losses in the conductors as these are made of lamina whose long direction is crossed perpendicularly by this radial flux. A proper design needs to properly take care of these losses and this is why a FEM analysis becomes necessary.

The above mentioned technical evaluations turn out to be correctly exploited by solving (with a 2D-axisymmetric magnetic induction current model) just one of the three columns (given the chance to have proper circuital connection among the four windings and being able to describe the shape/interaction of each conductor turn). In the following of this contribution some typical results of such an analysis are shown. As TMC is producing this kind of transformer under many different flavors depending on the specific need of its customer, in the table below we report the number used to get the results of this poster, which represents some sort of typical for the given transformer configuration.

	Primary		Secondary	
	1	2	1	2
Number of turns	1000		10	
Typical size of conductor lamina	0.4 X 50 mm		2 X 500 mm	
Current* 1st harmonic	-1	-1	1	1
Current* 5th harmonic	-0.15	0.15	$0.2=\frac{1}{5}$	-0.2
Current* 7th harmonic	-0.11	0.11	$0.14=\frac{1}{7}$	-0.14

* Note on rows about current in the table. Currents are here expressed in arbitrary units and the ratio are representing a typical value. For the simulation done later it has been taken for the 1st harmonic a 2kA (peak value) current on each of the secondaries. 1/5 and 1/7 of this value for respectively the 5th and 7th harmonic. The exact coupling on primaries at the different frequency is instead coming out as a result of the simulation.

Figure1 (below) shows in the gray-print scale the norm of the (peak) current density for the three harmonics. This scale is saturated at 3[A/mm^2]. The colored lines represents the streamline of the magnetic flux density at 0 phase - color is proportional to the flux norm, saturated at 0.02[T].



In Figure1 a radial flux for the 5th and 7th harmonic is clearly visible looking at the streamlines. This is causing large and highly concentrated losses. Peak value for current density in each primary is 3.0, 1.1 and 0.9 [A/mm^2] respectively for 50, 250 and 350 Hz. While for the each secondary it is respectively 7.0, 11 and 10 [A/mm^2].

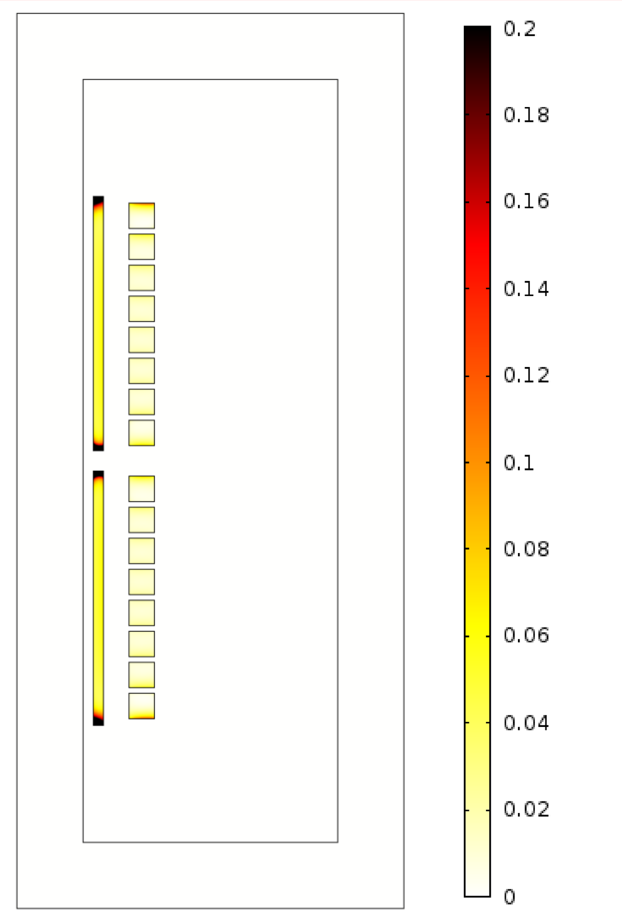


Figure 2 (left) shows the sum** of the losses over the three frequencies. Color scale is saturated at 0.2[kW/dm^3] while peak value of this quantity arrives up to 3.4[kW/dm^3].

****Note on the use of COMSOL: in order to do this sum (as the solver was a parametric over the three frequencies) we just needed to plot with(1,mf.Qrh)+with(2,mf.Qrh)+with(3,mf.Qrh)**

Regarding the losses integrated over the winding volumes, it results for each primary into about 500W (divided in 478, 14.4 and 8.1W respectively for 50, 250 and 350 Hz). Notice this number is 25% higher than an estimate of DC losses from a very low single frequency 2kA peak current where you get 400W. On each secondary there are 742W (divided among frequency as 591, 94.4 and 57.5W). This is 40% higher than 532W resulting from the previous DC estimate.

A final look can be given into currents induced back on each primary by the current flowing on the secondaries. These information are filling in quantitatively the values of the table on the first column of this poster about the currents on the primary. In this case we get for each of the primary a (phasor) currents of -19.95-0.002i, -2.94+0.09i and -2.09+0.06i respectively for 50, 250 and 350 Hz. If we look at the same quantity amper-turn rescaled over the input current on the secondary we have for the three frequency a coupling which results respectively into -0.998-0.0001i, -0.734+0.022i and -0.730+0.020i respectively for the three frequencies 50, 250 and 350Hz.

These results has been extensively validated versus measurements performed on produced and shipped machine. Now that this system has been implemented, TMC is able to know the electromagnetic results for a new design of the same kind in less than half an hour. With these knowledge, TMC is then featuring thermal and structural studies in order to know before the construction the working temperature and mechanical stresses of different parts both in normal working configuration and in presence of internal or external failures. In this way, TMC is then able to motivate and assure his customers about the employment of given materials and technical solutions.

Concluding remarks. In this poster a particular transformer has been presented. We highlighed the advantage (low cost) and difficulties (need to give a better description of couplings and localized heating), of this product. We showed how the raised design difficulties has been solved thanks to the use of COMSOL Multiphysics and its AC/DC Module.