Research on Reducing Electromagnetic Torque Ripple in Compressor Motors

1 Introduction

Wherever electric drives are being utilized, torque fluctuations might be an issue. They may cause speed fluctuations, noise, vibration and wearing and shall therefore be avoided whenever feasible. The closer one gets to this goal, the better is the performance and therefore the competitiveness of the product.

The combination of an electric drive and a compressor, as it is used in air-conditioning and fridges, is a good example for this problem. In this application, torque ripple can be caused by two sources. First, the design of the motor may lead to an uneven spatial flux distribution. Second and more important, the torque of the compressor depends on the position of the shaft which inevitably leads to a periodic torque ripple. In order to get a motor run which is as smooth as possible, the sum of the electro-magnetic motor torque and the load torque should be as close to zero as possible at every time instant.

This paper describes an approach to address this challenge by optimizing the design of both the motor and the drive control. Based on measurements of a compressor torque characteristic, simulations were carried for different motor designs and control strategies.

2 Drive Modelling

2.1 Simulation Tools

The subsequent paragraphs deal with the investigation of the drive performance by means of simulation. The simulation tools used for these purpose were “EasiMotor” by EASITECH and “Portunus” by Adapted Solutions. “EasiMotor” has been used for the design and finite-element calculations of the motor whereas “Portunus” provided the platform for simulations of the drive comprising inverter, motor and compressor load. Drive simulations were done with two levels of details for the motor modelling. The motor model taken from the “Portunus” library uses an equation set based on a d-q representation which allows for short calculation times but ignores some effects as the cogging torque. This disadvantage can be resolved by using a coupled simulation of “Portunus” and “EasiMotor” where “Portunus” performs the system simulation but the motor model is calculated by “EasiMotor”.

2.2 Compressor Load Characteristic

The counter torque produced by a compressor may be expressed by means of the sum of a number of harmonics:

$$T_{Load} = A_0 + \sum_n [A_n * \cos(\theta + \varphi_n)] \quad (1)$$

Figure 1 shows the load torque curve for one motor turn based on measurements and a subsequent curve fitting.

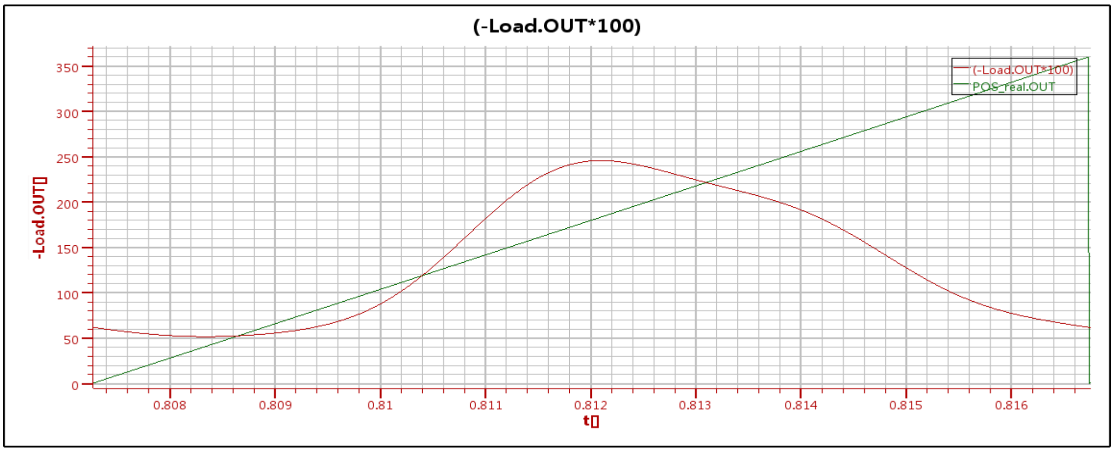

Figure 1: Relationship between compressor characteristics and rotor position (0-360°)

The torque curve was calculated using four frequencies:

n	A	φ
0	1.34495	-
1	0.972914	2.693
2	0.169765	-0.19031
3	0.089629	-2.04367
4	0.040717	0.906086

These coefficients have been used by the respective load model in the simulations that are described in the following paragraphs.

3 Suppression of Electromagnetic Torque Ripple

3.1 Initial Drive Performance

In the case of a controlled drive, the electro-magnetic torque produced by the motor is affected by the load torque, the design of the motor and the motor control.

Figure 2 shows the simulation results for the electro-magnetic torque (red) and the load torque (green) of a compressor drive that uses traditional MTPA (maximum torque per ampere) vector control with space vector pulse-width modulation. The harmonic content of the torque is extremely high which seriously affects the performance of the motor. It is obvious to see that the base oscillation of the motor torque follows the load torque. However, very significant additional harmonics are visible which depend on the design of the motor and its control.

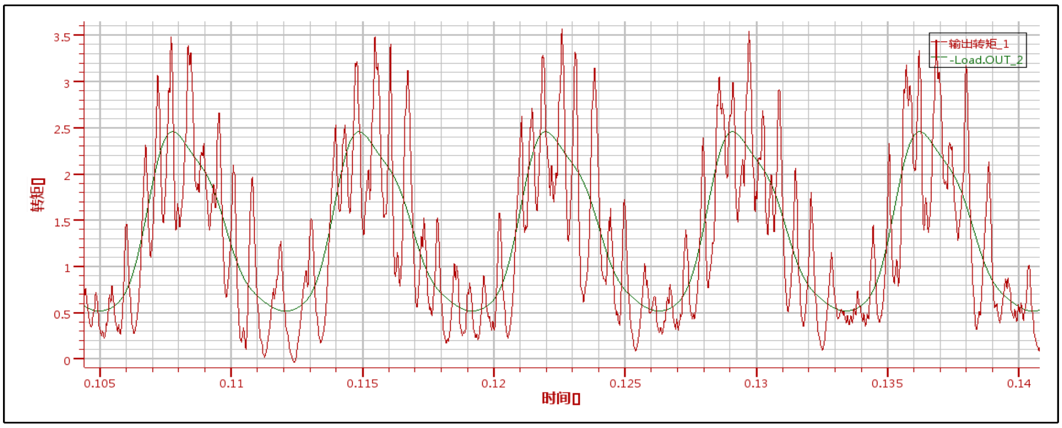

Figure 2: Motor torque and load torque of a motor-inverter combination

3.2 Optimization of the Motor Design

As mentioned above, the design of the motor has a big influence on the torque ripple and shall therefore by a subject to optimization. Figure 3 shows two variants of a synchronous reluctance motor. In order to reduce the ripple of the electro-magnetic torque, slot fill factor and thickness of magnet were increased for the second design (right).

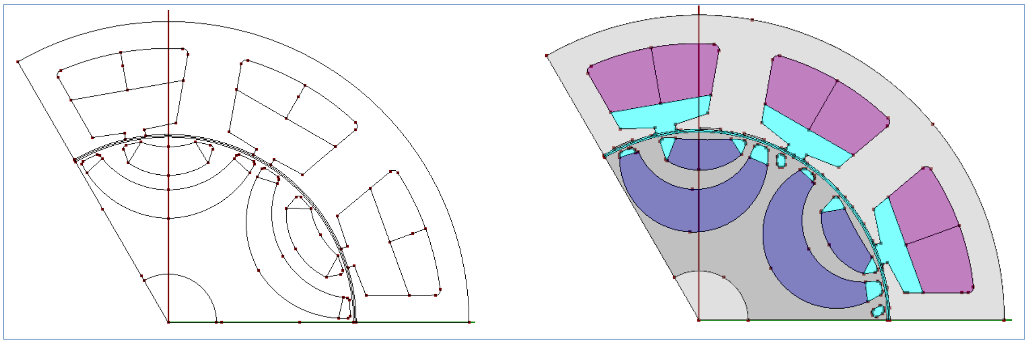

Figure 3: Design of two synchronous reluctance motors with different slot fill factors and magnet thicknesses

The electro-magnetic torque produces by the two motors can be seen in Figure 4 (results obtained by "EasiMotor"). Although the same control algorithm and parameters were used, the torque ripple of the second variant is significantly lower.

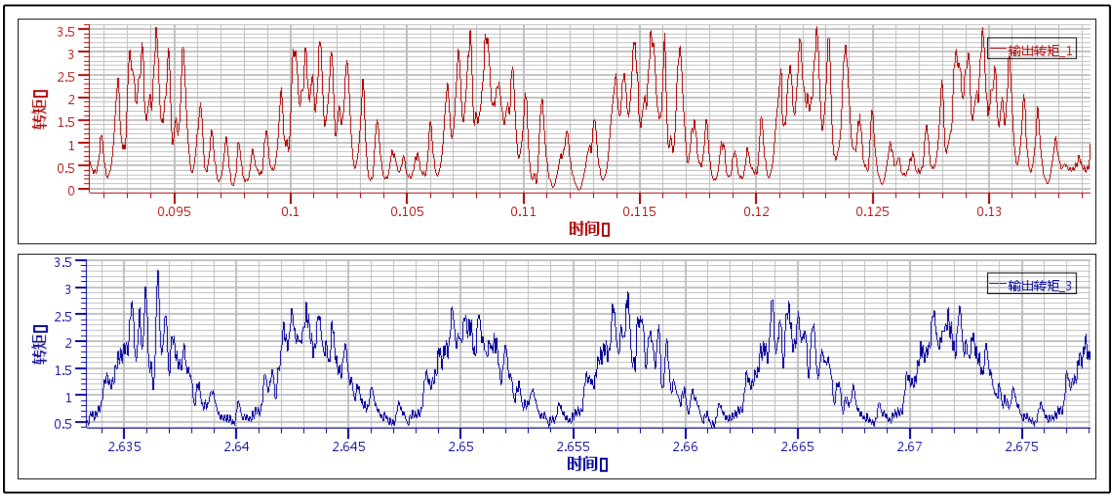

Figure 4: Electro-magnetic torque of the two investigated motors

Despite the improvements in the design, a certain ripple level, which originates from the current control strategy, still remains. As a consequence, its optimization should be the next step.

3.2 Optimization of the Control Strategy

Mechanical motion equation and torque equation of permanent magnet synchronous motor are:

$$T_e - T_{load} - B * \Omega = J * \frac{d\Omega}{dt} \tag{2}$$

$$T_e = \frac{3}{2} * p * [\varphi_f * i_q + (L_d - L_q) * i_d * i_q] \tag{3}$$

In these equations, T_e and T_{load} are electromagnetic and compressor torque respectively, B is the linear friction torque coefficient (which can be ignored at low speed), Ω is rotational speed of rotor, J is the moment of inertia of the compressor, p is the number of pole pairs and φ_f is the rotor flux.

Merging equation (2) and (3) yields to

$$T_{load} = \frac{3}{2} * p * [\varphi_f * i_q + (L_d - L_q) * i_{d*} i_q] - J * \frac{d\Omega}{dt} \tag{4}$$

With a "torque measurement coefficient" $K_t^{'}$, one may define the "equivalent torque current input" i^* as

$$i^* = \frac{\frac{3}{2} * p * [\varphi_f * i_q + (L_d - L_q) * i_d * i_q]}{K_t^{'}} \tag{5}$$

The compensator model is obtained from equation (4) and (5):

$$T_{load}^{'} = -K_t^* * i^* + J * \frac{d\Omega}{dt} \tag{6}$$

with $T_{load}^{'}$ being the calculated load torque of the compensator model.

Thus, the block diagram of the torque current feed-forward compensation is obtained as shown in Figure 5.

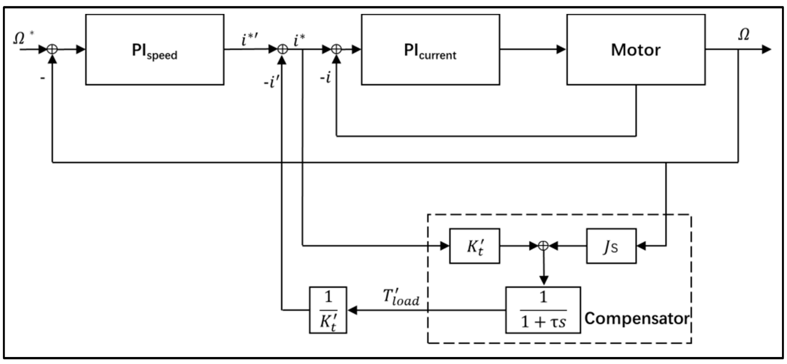

Figure 5: Block diagram of torque current feed-forward compensation

The drive model featuring a modified MTPA vector control algorithm was built in Portunus as shown in Figure 6.

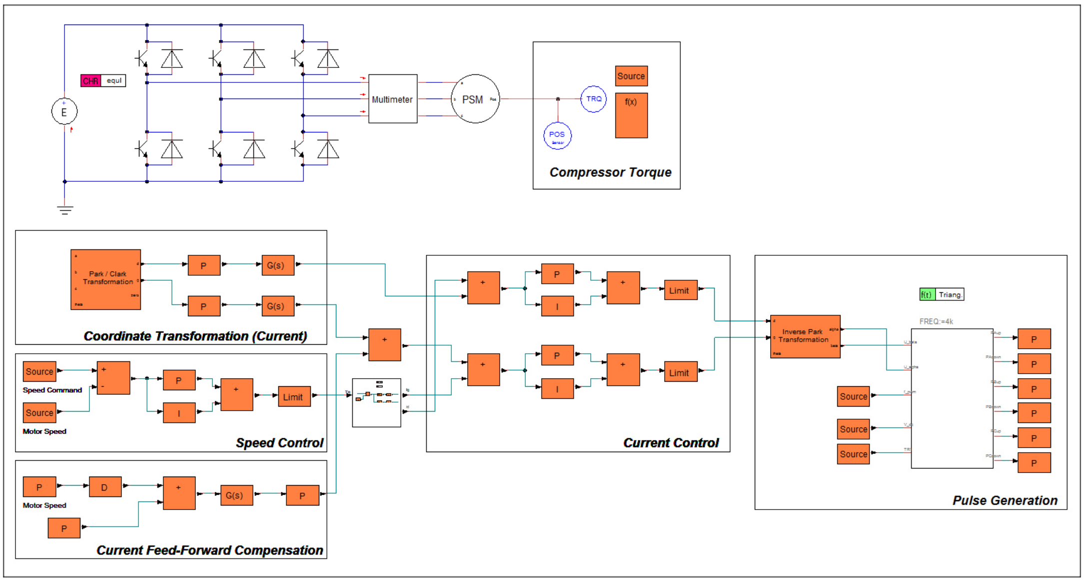

Figure 6: Portunus Drive Model

The Portunus simulations allow for the consideration of all effects that come from the position dependent load torque, the speed and current control loop as well the PWM generation.

Figure 6 shows the implementation with the motor model taken from the Portunus standard library ("d-q model"). This model can be replaced by a coupling model that establishes a link to "EasiMotor" for a more complex calculation of the motor performance. As both the "Portunus" and the "EasiMotor" model provide exactly the same interface (electrical and mechanical pins), the rest of the system model remains unchanged.

Using the system model described above, simulations have been carried out in order to evaluate the effect of the current feed-forward compensation. Figure 7 and Figure 8 show the electromagnetic torque (red curves) obtained by the d-q model for the cases without and with the additional torque current feed-forward compensation. It can be clearly seen that the use of the current feedback compensation leads to lower maximum values of the electromagnetic torque. It also introduces a delay between load and motor torque but this has no negative impact on the system performance. Please note that, due to the use of the d-q- model, cogging torque is not considered.

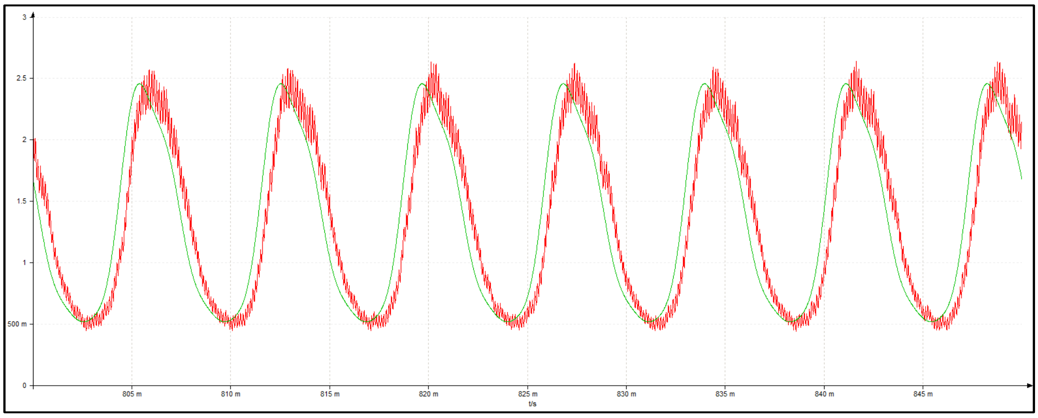

Figure 7: Electro-Magnetic Motor Torque w/o Current Feed-Forward Compensation (d-q Motor Model)

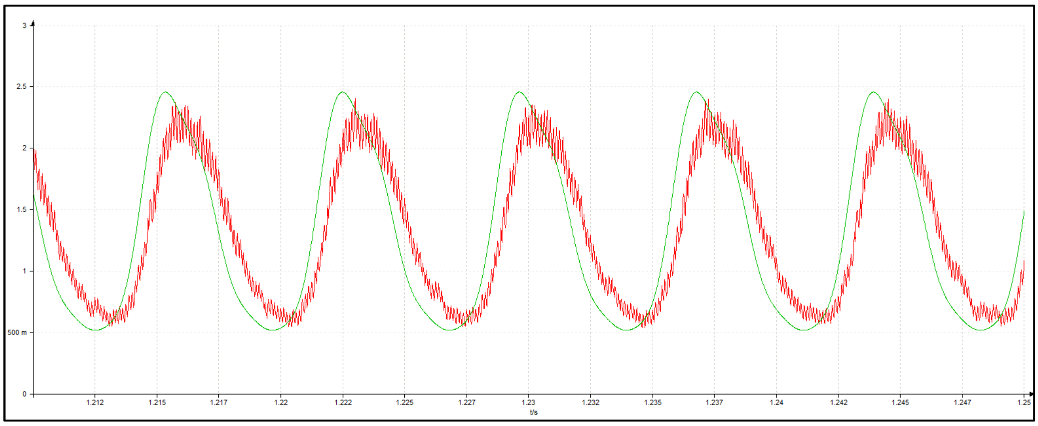

Figure 8: Electro-Magnetic Motor Torque with Current Feed-Forward Compensation (d-q Motor Model)

Figure 9 shows the electromagnetic torque (green curve) obtained by the coupled simulation with “EasiMotor” for the additional torque current feed-forward compensation. Now, the effects of the PMW (higher torque harmonics) and the cogging torque (lower torque harmonics) can be seen.

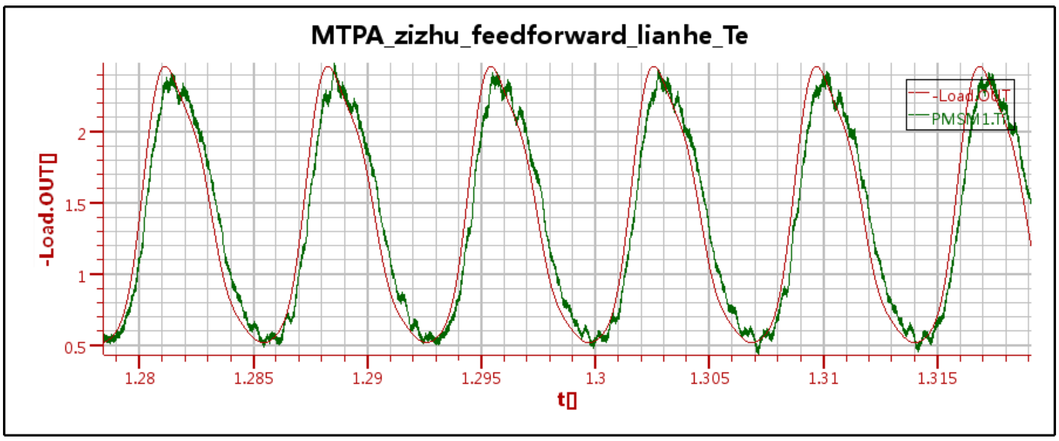

Figure 9: Electro-magnetic Motor Torque with Current Feed-Forward

Compensation (FEM Motor Model)

The robust control of the torque leads to a smooth speed curve. Figure 10 shows the start-up of the motor and details of the motor operation at a steady speed of 2800 rpm (results from coupled simulation with “EasiMotor”). There is just a minor speed fluctuation caused by the compressor load.

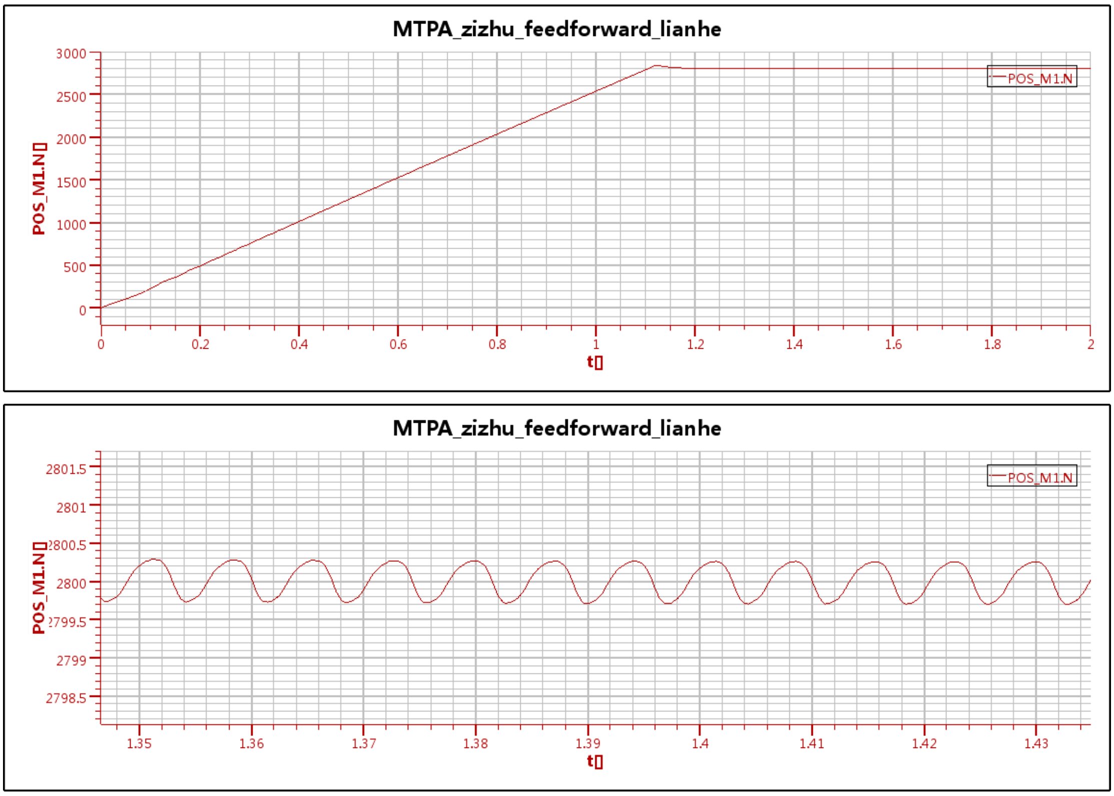

Figure 10: Simulated Motor Speed

Due to feed-forward compensation, the three phase currents have slightly different magnitudes as shown in Figure 11.

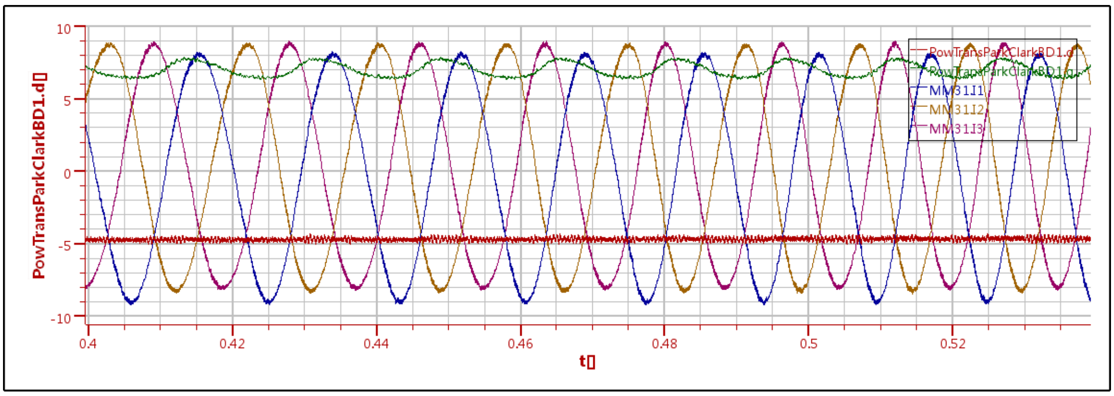

Figure 11: Winding Currents

4 Conclusions

The particularity of a compressor load leads inevitably to torque ripple which can be the cause for a number of problems. Although this ripple cannot be eliminated entirely, proper motor and control design including current feed-forward compensation may reduce it significantly.