INFLUENCE OF THE DC LINK COIL INDUCTANCE ON THE HARMONICS OF SLIP ENERGY RECOVERY SYSTEM

M. T. Outeiro
ISEC, PORTUGAL

E. S. Saraiva
IT, PORTUGAL

This paper presents the study of the influence of the DC link inductance on the harmonics of the rotor current, the stator current and the electromagnetic torque of a slip energy recovery system (SERS). A brief explanation of the circuit configuration will be made. To perform the harmonic study, a special Matlab code program is developed, with several special features.
To perform the quality of the waveform of the rotor current, a non-quality factor is defined.
The experimental results are in agreement with the simulation ones.

1. INTRODUCTION

A slip energy recovery system is a method of motor speed control, which increases efficiency, by returning the slip power, back to the system.

As it is well known, power electronic converters are generators of harmonics, both on the mains side and on the motor side, and these harmonics are transferred from one side to the other. In a slip energy recovery system (SERS), harmonics are produced and exist, not only on the rectifier side, but also on the inverter side and on the motor through the DC link. These harmonics will cause some problems on the functionality of the system and are also sent into the network. Therefore, they have been object of study by several investigators.

L.Refoufi and P. Pillay, [1] analyzed the impact on the power system of a slip energy recovery induction motor drive system in terms of harmonic generation. A hybrid dq/abc model to predict key waveforms of a chopper-controlled slip energy recovery induction motor drive (SERIMD) was used. They studied in detail the waveforms of the supply, stator and inverter currents, for a wide operation range. They concluded that this drive generates subharmonics of the supply frequency which could possibly cause flicker in the electrical systems. The phase of the subharmonics is shown to be important with different supply phases experiencing different time domain waveforms, even with the same harmonic content.

G. Marques and P. Verdelho [2] presented a circuit configuration that includes a boost-chopper that connected the diode rectifier bridge to the dc-link voltage, which is generated by a capacitor and a voltage-source inverter (VSI). To solve the drawbacks caused by the harmonics introduced by the rotor rectifier they presented two different solutions. The first solution introduces additional inductances connected to the ac side of the rotor circuit and the second solution compensates the stator current harmonics by a PWM-VSI that can work simultaneously as an inverter and as an active power filter.

J. Faiz and al [3] studied the harmonics and performance improvement of a slip energy recovery induction motor drive, based on the hybrid model dqabc. The sinusoidal pulse-with modulation (SPWM) control technique is used to improve the power factor of the drive and to weaken the low order harmonics injected into the supply. With the PWM technique, self-commutated switches (GTO or IGBT) replace the inverter thyristors and the inverter may operate with a zero reactive power.

N. Hoshi and al [4] presented a study of a slip power recovery system having sinusoidal rotor currents. The proposed system uses a PWM boost rectifier as a substitute for a diode rectifier and a boost chopper in a conventional compact-type slip-power recovery system. The system proposed, solves the problem of the distorted stator and rotor currents as the rotor currents become sinusoidal waves.

The novelty of the present study is the comparison of the amplitudes of the harmonics present on the slip energy recovery system**.**

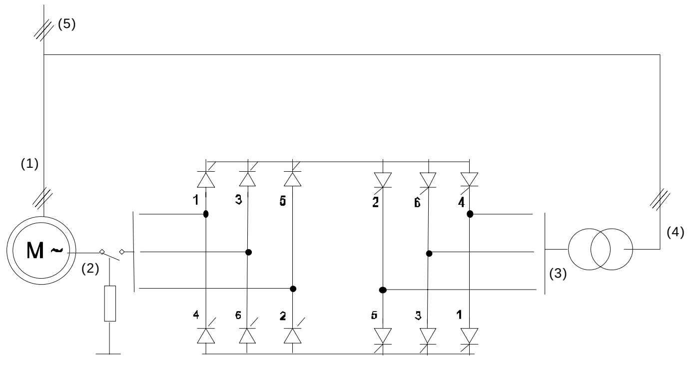


Figure 1: Circuit configuration of the slip energy recovery system**.**

2. CIRCUIT CONFIGURATION

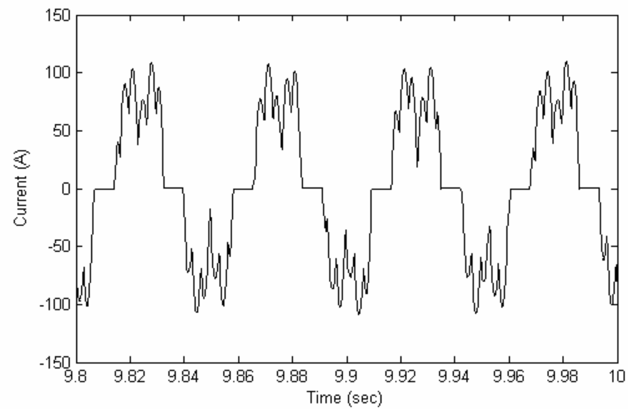
Figure 1 shows the circuit configuration of the slip energy recovery system in study. This circuit is composed by: (1) asynchronous motor (2) starter rheostat (3) the three-phase thyristor bridges, (4) three-phase feedback transformer. The circuit is fed through the three-phase mains (5). It this circuit there is no DC coil in the intermediate circuit.
The figure does not give emphasis to the control strategy but only to the power circuit.

3. HARMONIC ANALYSIS

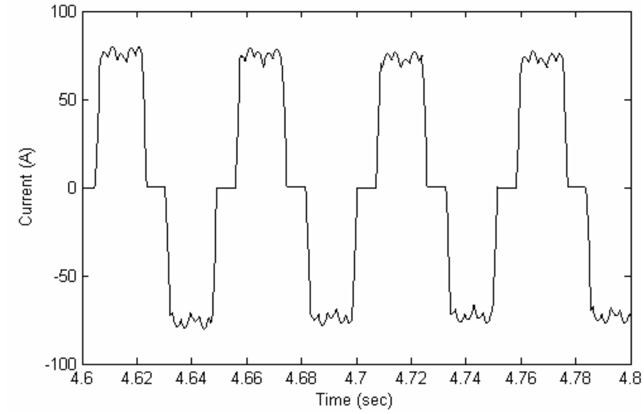
To perform the harmonic study a special Matlab code program was developed, with several special features, namely, the possibility to observe a large frequency range (frequencies until 2500Hz can be observed) and high plot resolution. The obtained results for stator and rotor currents and for the electromagnetic torque are shown on this paper on Figure 5 to Figure 7. These figures show the signal amplitude versus frequency modulus. In order to take the maximum information concerning the spectrum of the variable, a logarithmic y-axis scale is adopted.
The Discrete Fourier Transform (DFT) was used in this study and its moduli coefficients a_0, a_k and b_k were calculated. A total of 10000 samples were used for the calculations.

3.1 ROTOR CURRENT, I_r

In steady state, the non quality factor, defined as $NQFir=(i_{rmax}-i_{rmin})/(i_{rmax}+i_{rmin})$ corresponding to the top of the waveforms of the rotor current is 0.4628 without inductance and 0.062 with an inductance of 10mH. In Figure 2a and Figure 2b show these two situations.



(a) Without inductance L.



(b) With an inductance of 10mH.

Figure 2: Plots of rotor current referred to the stator in steady-state.

The harmonic components of the rotor currents due to the six-pulse rectifier converter (SR1), due to the DC side average value, appears at frequencies given by equation (3), with k=0, 1, 2, 3

$$f^{R}_{r,h} = (1 \pm 6k)\, s f_{ms} \qquad (1)$$

From equation (1), when k=0 and s=0.3906 the fundamental rotor frequency will be equal to 19.53Hz. The 5th, 7th, 11th, and 13th harmonic orders are also present in the rotor current and according to equation (1) they will be equal to -97.66Hz, +136.7Hz, -214.8Hz and +253.89Hz, respectively.
As can be observed by the rotor current spectrum shown in Figure 3 and Table 1, the rotor current frequencies reflects the DC current frequencies with two side-bands of the fundamental rotor frequency which is 19.53Hz. Harmonic components due to the six-pulse inverter that appear on the DC current at frequencies multiples of 300Hz, appear in the rotor currents with two side-bands of m300Hz±19.53Hz, which for m=1 corresponds to frequencies of 285.47Hz and 319.53Hz.
The DC current distortion introduced by the six-pulse inverter is reflected on the rotor currents, resulting in the appearance of additional harmonics, given by equation (4), with k,m=0, 1, 2, 3,…

$$f_{r,h} = (1 \pm 6k)\, s f_{ms} \pm 6m f_{ms} = \big((1 \pm 6k)\, s \pm 6m\big)\, f_{ms}, \qquad (2)$$

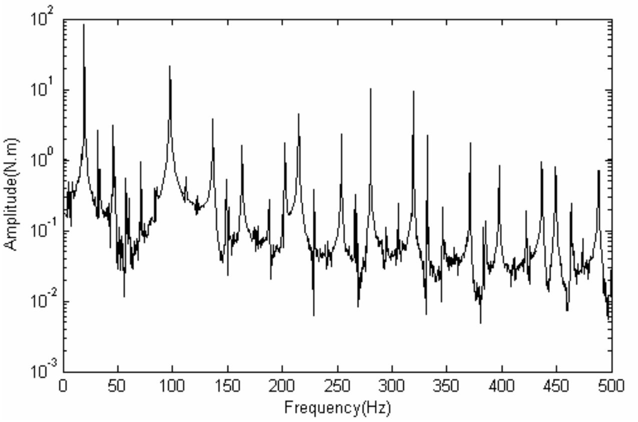


Figure 3: Frequency spectra of the rotor current referred to the stator without inductance.

Observing the figures above and comparing the values of amplitude on Table 1, for different values of inductance, it is possible to conclude that the value of the inductance of the DC link coil, affects directly the ripple of the waveform of the rotor current, which is reflected in the values of the amplitude of the frequency spectrum.

Table 1: Frequencies and amplitudes of the rotor current referred to the stator in phase a, for slip=0.3906.

Frequency (Hz)	Amplitude (A)			
	without L	with L=1mH	with L=5mH	with L=10mH
19.53	82.16	81.33	81.17	79.7
-97.66	21.52	17.92	14.35	14.49
+136.71	3.8	4.436	5.7	7.26
-214.83	4.5	4.69	5.2	3.1
+253.89	12.3	3.1	2	2.9
-280.47	10.5	6.3	1	1.2
+319.53	9.3	5.5	-	1.1

3.2 STATOR CURRENT, I_s

It was observed that in steady state the peak-to-peak value of the stator current is not much affected by the value of the inductance placed on the DC link coil.

A DC component of the rotor current, establishes a rotating magnetic field in the air gap and induces voltages in the stator winding at frequency given by equation (5),

$$f_m = (1-s)\, f_{ms} \qquad (3)$$

where s is the slip and f_{ms} is the fundamental frequency. For s=0.3906 and f_{ms}=50Hz, this corresponds to a 30.47Hz with positive sequence.

Similarly a rotor current frequency f_r, manifests itself in the stator current frequencies of (f_r+f_m) with f_r>0, for positive sequence rotor currents, and f_r<0, for negative sequence rotor currents. Adding the effect of motor speed to the rotor-current frequencies, the reflected stator frequencies are given by equation (4), with k=0,1,2,3,....

$$\begin{aligned} f_{s,h}^{R} &= \left(f_r + f_m\right) = \\ &= (1 \pm 6k) s f_{ms} + (1-s) f_{ms} = \\ &= (1 \pm 6ks) f_{ms} \end{aligned} \qquad (4)$$

Adding the effect of rotor side-band frequencies due to the inverter harmonics, the frequencies of the induced harmonics present in the stator, considering these two effects are given by equation (5), with k, m=0, 1, 2, 3.

$$f_{s,h} = (1 \pm 6ks \pm 6m)\, f_{ms}, \qquad (5)$$

This equation will be reduced to equation (4) for m = 0.

Figure 6 shows the stator current spectrum and Table 2 the corresponding frequencies amplitudes. Using equation (4), if s=0.3906 and k=0, the fundamental frequency, will be equal to 50Hz.

Using equation (5), if k=1 and m=0, the 5th and 7th harmonics orders of the rotor current appear in the stator at frequencies moduli of |-97.66 +30.47|=67.19Hz and |+136.7 +30.47| = 167.1Hz. If k=2 and m=0, the 11th and 13th harmonics of the rotor current appear in the stator at frequencies of moduli 184.36 Hz and 284.36Hz. If k=0 and m≠0, equation (4) gives the effects of frequencies due to the inverter harmonics. The 300Hz inverter referred to the stator introduces side-band frequencies moduli $|\pm 300 + 30.47 \pm 19.53|$: of 250Hz, 289Hz, 310.9Hz and 350Hz. The large peaks of stator frequency moduli of 250Hz and 350Hz correspond to the rotor frequencies of 285.47Hz and 319.53Hz, respectively.

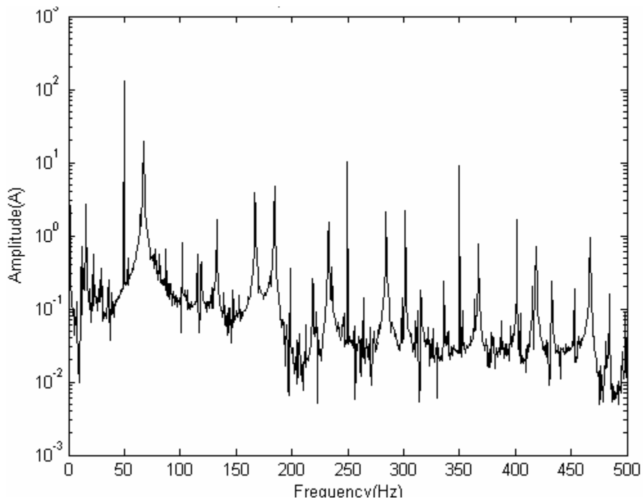


Figure 4: Frequency spectra of the stator current without inductance L.

Figure 4 above and Table 2, show that the value of the inductance of the DC link coil, affects the stator current waveform, which is reflected on the amplitude values of the frequency spectrum.

It is verified that, as the value of the DC inductance increases, the values of the amplitude for the non fundamental frequencies, decrease.

Table 2: Frequencies and amplitudes of the stator current in phase A for slip=0.3906.

Frequency (Hz)	Amplitude (A)			
	without L	with L=1mH	with L=5mH	with L=10mH
50	130.5	129.6	129	127.2
-67.19	19.5	18	12.8	13.2
+167.18	6.5	-	6.2	7.55
-250	10.1	9.2	2.36	1.18
+350	9.1	9	2	1.12

3.3 ELECTROMAGNETIC TORQUE, T_{em}

Figure 5 shows the harmonics of the electromagnetic torque, considering the situation without inductance; which can be explained by the interaction of the magnetomotive force waves set up by the stator and the rotor fundamental and harmonics. The electromagnetic torque can be calculated using equation 8 obtained from [5], in the stator reference frame.

$$\Gamma_{em} = \frac{3}{2} \times p \times L_{sr} \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \qquad (6)$$

The spectrum of the electromagnetic torque component due to the interaction between a sinusoidal stator current component and a sinusoidal rotor current component can be obtained as follows:

$$\Gamma_{em} = k \times \left(\cos\left(w_s \right) t \right) \times \left(\cos\left(w_r + w_m \right) t + \varphi \right) \qquad (7)$$

$$= \frac{k1}{2} \times \left[\cos\left(2\Pi \left(f_s - fr - fm \right) t - \varphi \right) + \cos\left(2\Pi \left(f_s + fr + fm \right) t + \varphi \right) \right]$$

where, k and k1 are constants, w_s the angular speed of the stator currents; w_r the angular speed of the rotor currents, w_m the mechanical speed in radelec/s , f_s the stator current frequency; f_r the rotor current frequency and f_m=(1-s).f_s the mechanical frequency in electrical Hertz.

The values of w_s and w_r can be positive or negative depending on the positive or negative characteristics of the sequence.

In Table 3, are shown the spectral components corresponding to the amplitude of the torque greater than 10N.m. If all components were considered, the frequencies of the spectrum would be the same for all values of the DC inductance.

As shown in Figure 5, the most relevant peaks of the electromagnetic torque spectrum appear at frequencies multiples of 117 Hz and at 300Hz.

The Table 3 shows that for these frequencies, as the DC coil inductance increases from zero to 10mH, the amplitudes of the spectral components, generally decreases.

For the 300 Hz component of the electromagnetic torque, the amplitude passes from 1287 N.m for L=0mH to a value o f 156.4 N.m for L=10mH.

For the 117Hz component of the electromagnetic torque, the amplitude passes from 1223 N.m for L=0mH to a value o f 513.4 N.m for L=10mH.

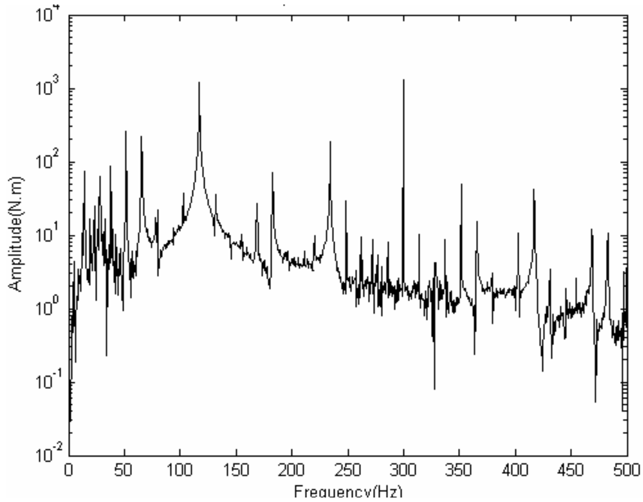


Figure 5: Frequency spectra of the electromagnetic torque without inductance L.

Table 3: Frequencies and amplitudes of electromagnetic torque.

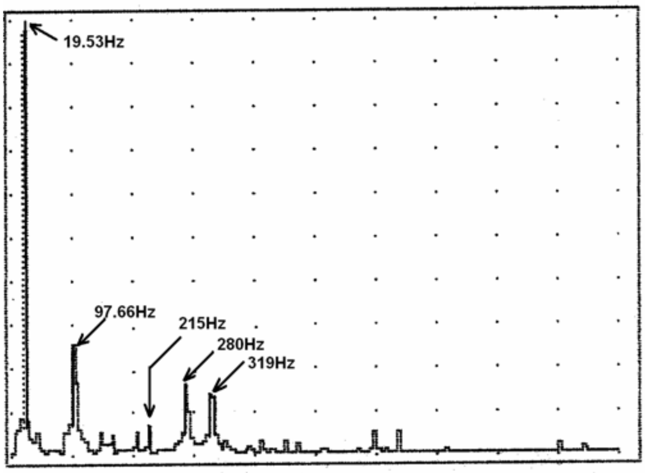
Frequency Modulus (Hz)	Amplitude of torque components (N.m)			
	without L	with L=1mH	with L=5mH	with L=10mH
0	5294	5292	5281	5193
14	75.16	4883-	68.56	-
28	62.05	-	-	-
37.5	87.64	44.07	12.26	-
51.5	254.2	91.21	18	25.5
65.5	218.7	74.72	-	7.3
79.5	21.73	-	-	-
117	1223	804.3	504	513.4
169	23.52	14.29	-	-
183	70.12	34.8	13.5	10.12
234.5	186.1	165.8	200	160.6
248.5	29.46	-	-	-
300	1287	775.7	300	156.4
351.5	50.26	66.99	85.86	75.28
365	15.56	-	-	-
417	41.75	22.72	-	4.5
468.5	-	17.12	29.82	26

4. EXPERIMENTAL RESULTS

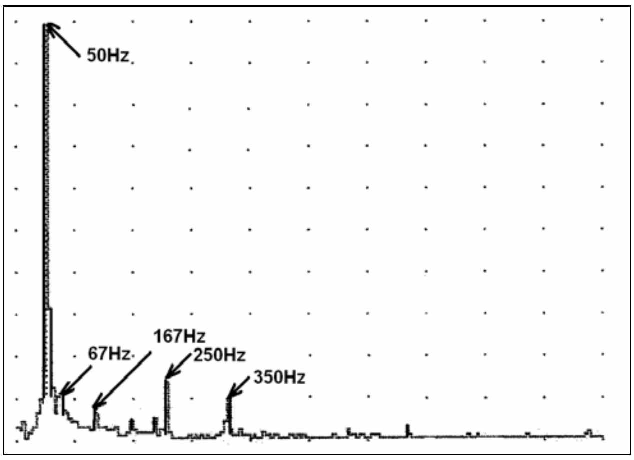
Figure 6 and Figure 7 show the spectrum of the rotor current and the stator current for a slip equal to 0.3906, respectively.

In Figure 6, the fundamental frequency of 19.53Hz (100%) is present. The harmonics of 5th, 7th and 11th orders of the rotor are also present in the spectrum. They correspond to the 97.66Hz (26.8%), 136.71Hz and 214.83Hz, respectively.

Component harmonics, due to the six-pulse inverter that appear on the DC currents at frequencies multiples of 300Hz, appear in the rotor currents with two side-bands, 280.47Hz and 319.53Hz frequencies.
In Figure 7, the 50Hz fundamental frequency (100%) is present and the effects of the 5th and 7th harmonics of the rotor-current appear also at frequencies of +67.19Hz and +167.18Hz, the 11th harmonic of the rotor-current appears in the stator at frequencies of +184.36Hz. The large peaks of the stator frequency of 250Hz and 350Hz correspond to the rotating fields established by the rotor frequencies of 280.47Hz and 319.53Hz.



X Scale: 97.7 Hz/div, Y Scale: 10 %/div,
X Resol: 20 # /div, YResol: 25 # /div, X size: 200
Figure 6: Frequency spectra of the rotor current for slip=0.3906.



X Scale: 97.5 Hz/div, Y Scale: 10 %/div,
X Resol: 20 # /div, Y Resol: 25 # /div, X size: 200
Figure 7: Frequency spectra of the stator current for slip=0.3906.

5. CONCLUSIONS

This paper presents the study of the influence of the DC link inductance on the harmonics of the rotor current, the stator current and the electromagnetic torque of a slip energy recovery system (SERS). A brief explanation of the circuit configuration was made. To perform the harmonic study, a special Matlab code program was developed, with several special features.
The oscillations of the electromagnetic torque were explained considering the interaction between the stator and the rotor fundamental and harmonic currents.
The simulation results show a strong disturbance in the electromagnetic torque in the steady state and the corresponding spectrum.
The non quality factor defined for the rotor current changes from 0.4628 without the DC coil, to 0.062 with a DC coil of 10 mH.
The experimental results obtained with no DC coil, are in accordance with the simulation ones for the same speed and value of inductance.

6. RERERENCES

[1] L. Refoufi and P. Pillay, "Harmonic analysis of energy recovery induction motor drives," IEEE Trans. on Energy Conversion, vol.9, Dec.1994.
[2] G.D. Marques and P. Verdelho, “A simple slip-power recovery system with a DC voltage intermediate circuit and reduced harmonics on the mains”. IEEE Trans. on Industrial Electronics. Vol.47, pp 123-132, February 2000.
[3] J. Faiz, H. Batari and E. Akpinar, “Harmonic analysis and performance improvement of slip energy recovery induction motor drives”. IEEE Trans. Power Electronics, vol 16, pp. 410-417, May 2001.
[4] N. Hoshi and al “A compact type slip-power recovery system with sinusoidal rotor current for large pump/fan drives”. IEEE Trans. Power Electronics, vol 16, pp. 410-417, May 2001.
[5] J. Chatelein, Machines Électriques Tome 1, Dunod (1983), pp.240.

7. AUTHORS

M.T. Outeiro, Instituto Superior de Engenharia de Coimbra, Rua Pedro Nunes - Quinta da Nora
3030-199 Coimbra, Portugal.
Email: touteiro@mail.isec.pt

Dr. E.S. Saraiva, Instituto de Telecomunicações, Pólo de Coimbra, Pólo II – Pinhal de Marrocos, P - 3030 - 290 Coimbra, Portugal.
Email: esaraiva@deec.uc.pt