Some Design Aspects of the Commutator Series Motor Operating in Both Direct Current and Single-Phase Electric Traction. Part 2-Design of the Main Field Winding Shunt Resistor and Smoothing Coil

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Abstract: - As well known the commutator motors are yet used in a large-scale in both direct current and single-phase alternating current traction, powered respectively by choppers and single-phase thyristor half--controlled rectifiers. As a sequence of Part 1, this paper proposes an original and generalized methodology concerning design procedures for both main field winding shunt resistor and smoothing coil for purposes of a good commutation and motor design. To corroborate these proposed theoretical procedures, experimental results are also presented. Previously, another original derivation way for obtaining the generalized transformer e.m.f. formula is also proposed.

Key-Words: - Undulating current traction motor, rectified current traction motor, transformer e.m.f., smoothing coil, non-inductive shunt resistor.

1 Introduction. Transformer e.m.f.

As previously written in Part 1 of this work, the residual transformer e.m.f. is induced by the residual alternating component of main flux in the armature coils short-circuited by the brushes. As shown in Fig.1, each main pole coil with $n_F/2p$ turns and the n_S turn armature coils under commutation act as the primary and secondary windings of a transformer [1,2,3,4]. It will be noted that the armature coils under commutation, occupying the neutral zones where the brushes are placed, are traversed by the whole of the main flux.

Hence, the transformer ratio for that equivalent transformer is

$$\frac{\frac{V_F}{2p}}{E_{trB}} = \frac{\frac{n_F}{2p}}{n_S} \quad (1)$$

where V_F is the rms value of the alternating component of the voltage drop at the terminals of the parallel "shunt resistor – main field winding". Assuming that the alternating component of the motor armature current is totally carried through the shunt, one can write

$$V_F \approx R_S \; I_m \quad (2)$$

On the other hand, being

$$I_m \approx \frac{1}{\sqrt{2}} \frac{V_m}{X_m} \quad (3)$$

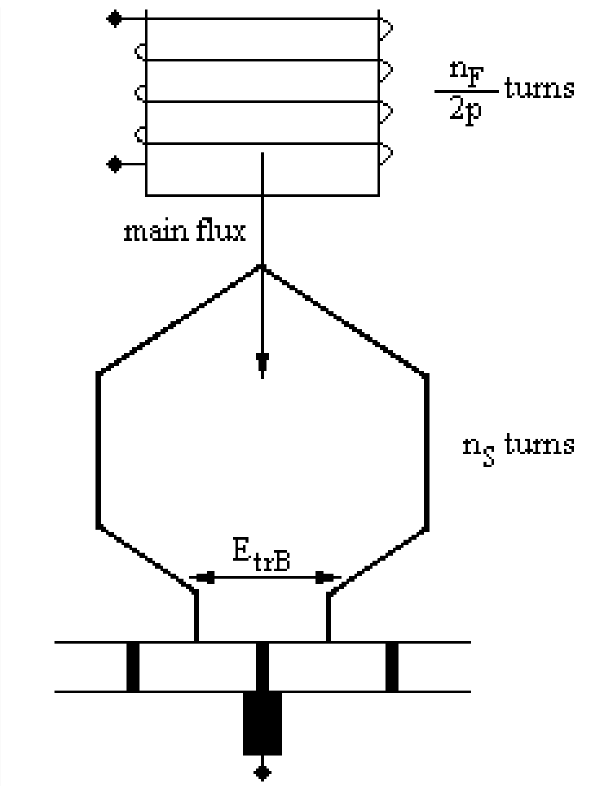

Fig.1 Diagram showing the transformer effect between main pole coil and armature coils under commutation.

$$E_{tr} = \frac{p}{a} E_{trB} \quad (4)$$

taking (1) into account, one obtains

$$E_{tr} = \frac{\sqrt{2}}{2}\frac{p}{a}\frac{n_S}{n_F}\frac{V_m}{X_m}R_S \tag{5}$$

As can be seen, although these two derivation methods (Part 1 and Part 2) being different, the final result is the same. Consequently, one concludes about the correctness of the procedures adopted for both derivation methodologies.

Therefore, that generalized relationship is a simplest method of calculating the residual transformer e.m.f. between adjacent commutator segments for all types of armature windings, due to the introducing of the factor *p*/*a* [4].

Then, it is now important to estimate the residual transformer e.m.f. induced between two adjacent commutator segments for booth chopper-driven and single-phase ac/dc converter-driven motors.

1.1 Chopper-driven motor

For this motor arrangement, taking into account that [1,2]

$$V_m = \frac{2V}{\pi}\sin k\pi \tag{6}$$

where V is the continuous mean value of the motor voltage, and k the chopper on-off ratio (or chopper duty cycle), by substituting (6) in (5) one obtains

$$E_{tr} = \frac{\sqrt{2}}{\pi}\frac{p}{a}\frac{n_S}{n_F}\frac{R_S}{X_m}V\sin k\pi \tag{7}$$

1.2 Single-phase ac/dc converter-driven motor

The amplitude of the alternating component of the motor voltage is given by [3]

$$V_m = V\frac{\sqrt{5\sin^2\alpha + 2\cos^2\alpha + 3\cos\alpha - \cos 3\alpha}}{3} \tag{8}$$

where V is the continuous mean value of the motor voltage, and α the delay angle of the half-controlled thyristor rectifier. Then, by substituting (8) in (5) one obtains:

$$E_{tr} = \frac{\sqrt{2}}{6}\frac{p}{a}\frac{n_S}{n_F}\frac{R_S}{X_m}V \sqrt{5\sin^2\alpha + 2\cos^2\alpha + 3\cos\alpha - \cos 3\alpha} \tag{9}$$

1.3 Comments

Therefore, from (7) and (9) one can conclude that simple lap winding (a=p) with single-turn coils (n_S =1) must be employed to minimize the residual transformer e.m.f..

2 Undulating Factor

As known [1,2,3,4], this factor is defined by means the following standard relationship

$$\mu = \frac{I_M - I_m}{2\,I} \tag{10}$$

where I_M, I_m and I are respectively the maximum, minimum and mean values of the motor current.

2.1 Chopper-driven motor

Taking into account that [1,2]

$$I_M - I_m = \frac{4\,V}{\pi\,X_m} \tag{11}$$

from (10) and introducing k = 0.5 the maximum value for the undulating factor is obtained by means the following equation:

$$\mu = \frac{2\,V}{\pi\,X_m I} \tag{12}$$

2.2 Single-phase ac/dc converter-driven motor

For this motor (10) can be rewritten as follows [3]

$$\mu = \frac{\sqrt{2}\,I_m}{I} \tag{13}$$

Thus, by combining (3) and (8) one obtains

$$\mu = \frac{\frac{1}{3}\frac{V}{X_m I}}{\sqrt{5\sin^2\alpha + 2\cos^2\alpha + 3\cos\alpha - \cos 3\alpha}} \tag{14}$$

For the continuous motor voltage it is α = 0. Thus, the undulating factor for the continuous rating is given by

$$\mu = \frac{2}{3}\frac{V}{X_m I} \tag{15}$$

It should be noted that in (12) and (15) V and I are the continuous mean values of the motor voltage and armature current respectively.

2.3 Comments

From a study of (12) and (15), for a given motor continuous rating (V and I constants) one concludes that the undulating factor is inversely proportional to the reactance of the motor equivalent circuit X_m, as expected.

Of course, for a high motor reactance the undulating of the armature current must be small, that is the higher the reactance the lower the undulating factor. Since the alternating component of the armature current is completely deviated from the main field winding for the shunt resistor, i.e. assuming that the impedance of the parallel "shunt resistor – main field winding" is approximately equal to the shunt resistance, the impedance of the main field winding can be considered equal to zero. However, this adverse effect upon the total internal motor impedance is compensated by the smoothing coil.

Thus, in these conditions the impedance of this coil must be higher than that for a motor with no shunt resistor. It should be noted that the impedance is practically equal to the reactance because this reactance is higher than the resistance.

3 Smoothing coil design

The inductance of this coil can then be theoretically calculated, for booth chopper-driven and single-phase ac/dc converter-driven motors, from (12) and (15) as follows.

3.1 Chopper-driven motor

For this motor, one can consider that the alternating component of the armature current has the same frequency of the chopper f. On the other hand, assuming that the smoothing coil reactance is higher than that of the motor windings, so that

$$X_m = 2\pi f L \qquad (16)$$

where L is the smoothing coil inductance. Then, by substituting (16) in (12) results

$$L = \frac{1}{\pi^2}\frac{1}{f}\frac{1}{\mu}\frac{V}{I} \qquad (17)$$

3.2 Single-phase ac/dc converter-driven motor

For this case, the alternating component of the armature current has a frequency double that of the supply current (catenary current wire) f, so that

$$X_m = 2\pi(2f)L \qquad (18)$$

Similarly, by substituting (18) in (15) results

$$L = \frac{1}{6\pi}\frac{1}{f}\frac{1}{\mu}\frac{V}{I} \qquad (19)$$

3.3 Comments

From a study of (17) and (19), for a given motor continuous rating (V, I and f constants) one concludes that the inductance of the smoothing coil is inversely proportional to the imposed value for the undulating factor, as expected, i.e. the lower the factor the bigger the smoothing coil.

4 Non-inductive shunt resistor design

The resistance of this shunt can be theoretically calculated from (7) and (9) as follows.

4.1 Chopper-driven motor

From (7) one can conclude that the residual transformer e.m.f. is maximum for k = 0.5. Hence, inserting this value in (7) and by combining (7) and (16) results for the shunt resistance the following equation

$$R_S = \sqrt{2}\,\pi^2 \frac{a}{p}\frac{n_F}{n_S} f L \frac{E_{tr}}{V} \qquad (20)$$

As usual in practice, assuming the motors with a simple lap armature winding ($a = p$) with single-turn coils (n_S = 1), and by substituting (17) in (20) one obtains

$$R_S = \sqrt{2}\, n_F \frac{1}{\mu}\frac{E_{tr}}{I} \qquad (21)$$

4.2 Single-phase ac/dc converter-driven motor

For the continuous rating of motor, the delay angle of the half-controlled rectifier is α=0. Hence, inserting this value in (9) and by combining (9) and (18) results for the shunt resistance

$$R_S = 6\sqrt{2}\,\pi \frac{a}{p}\frac{n_F}{n_S} f L \frac{E_{tr}}{V} \qquad (22)$$

Assuming $a = p$ and n_S = 1 and by substituting (19) in (22) one obtains

$$R_S = \sqrt{2}\, n_F \frac{1}{\mu}\frac{E_{tr}}{I} \qquad (23)$$

4.3 Comments

From a study of (21) and (23), for any given motor (n_F constant) and for a given continuous rating current (I constant) one concludes that the resistance of the non-inductive shunt resistor is inversely proportional to the imposed value for the undulating factor and directly proportional to the imposed value for the rms transformer e.m.f.. Hence, for a given undulating factor low values for the transformer e.m.f. correspond to low values for the shunt resistance and, as a consequence, the lower this resistance the better the bypass of the ac component of the armature current.

5 Conclusions

As shown in this paper, for both chopper-driven and ac/dc converter-driven traction motors, the series field winding must be shunted non-inductively to bypass the ac component of the armature current and thereby obtain a non-pulsating flux. In addition the motor must be designed with a simple lap armature winding with single-turn coils. On the other hand, instead of laboratory experimental optimizing of the most suitable smoothing coil and shunt resistor, it is more convenient for purposes of pre-design and comparison to calculate theoretically both values by means the design equations proposed in this work. It should be observed that for undulating factor and rms residual transformer e.m.f. their most advisable maximum values are of the order of 0.20 to 0.40 and 0.4 V to 0.5 V respectively [1,2,3].

Table 1 shows computed and experimental values (these later in bold and italic) of shunt resistance and smoothing coil inductance for some undulating and rectified current traction motors, and a close approximation can be observed. The slight discrepancies between calculated and actual values are due to the simplifications assumed in the theoretical derivation methodologies. It should be also noted the extremely small values obtained for the shunt resistance. However they are significantly higher than those for the resistance of the main field winding – as an example, for a motor with a continuous armature current of 1300 A, this resistance is of the order of $8 \times 10^{-4}\ \Omega$, while for a 300 A motor is approximately equal to $5 \times 10^{-2}\ \Omega$.

In last years the inverter-driven three-phase squirrel-cage induction motor has been adopted as standard for both dc and single-phase ac electric traction. However the series-connected commutator motor is yet used in a large scale, and in order to decrease maintenance costs and increase efficiency and availability is usual the substitution of classic control by modern systems – as example the using of chopper instead rheostatic control. Taking into account that the commutator motor is the same, it should be equipped with a smoothing coil and a non-inductive shunt resistor to provide a good commutation. Therefore, one can conclude that this work give guidance for a correct re-design of those external motor equipments in order to obtain a good commutation.

References:

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Table 1 Computed and experimentally obtained values of the non inductive shunt resistance and the smoothing coil inductance for several commutator traction motors.

traction motor characteristics				imposed parameters for continuous rating				undulating current motors		rectified current motors	
P (kW)	V (V)	I (A)	n_F	chopper frequency (Hz)	catenary frequency (Hz)	E_{tr} (V)	μ	R_S (Ω)	L (mH)	R_S (Ω)	L (mH)
1218	1070	1200	----	----	16 2/3	----	0.40	----	----	----	7.10 ***7.24***
415	775	290	----	----	50	----	0.35	----	----	----	6.50 ***7***
380	550	750	----	----	50	----	0.20	----	----	----	3.90 ***4.20***
254	750	360	40	440	-----	0.5	0.40	0.24 ***0.29***	1.48 ***1.70***	----	----
				-----	50	0.5	0.40	----	----	0.20 ***0.24***	5.53 ***6.50***
1400	1500	1000	48	250	-----	0.5	0.30	0.14 ***0.17***	2.50 ***2.95***	----	----
				-----	50	0.5	0.30	----	----	0.11 ***0.13***	5.31 ***6.30***

[3] C. P. Cabrita, On the Commutation and Design of Single-phase AC/DC Converter- Driven DC Motors for Electric Traction, *Electromotion Journal*, Vol. 7, No. 3, 2000, pp. 163-173.

[4] C. P. Cabrita, On the Commutation of Straight Single-Phase Commutator Traction Motor and Reasons of its Downfall at 50 Hz, *Electricidade Review*, No. 149, March 1980, pp. 122-130.