Some Design Aspects of the Commutator Series Motor Operating in Both Direct Current and Single-Phase Electric Traction
Part 1- Commutation Analysis and Transformer E.M.F.

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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. Thus, based on author's experience on railway electric traction in the areas of training, motor rolling stock maintenance, design and research on traction motors, this paper presents a developed analysis concerning motor commutation, as well as an original derivation related to the transformer e.m.f. formula. It should be noted that in railway electric traction standards, on the basis of motor armature current waveforms the chopper-driven dc commutator motor is called as "undulating current traction motor", and at same way the single-phase ac/dc converter-driven dc commutator motor is named as "rectified current traction motor".

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

1 Introduction. Motor commutation analysis

As well known, in commutator motors the large current due to a current-rush may have to be commutated under unfavorable conditions, i.e. the commutating flux may not follow instantaneously the rapid changes in the armature current, or flux distortion may occur due to weak field. Under these conditions sparking may occur at the brushes, but the operation of the traction motor may be considered as satisfactory provided that this sparking does not cause a flash-over. To produce a flash-over, sufficient voltage must exist between adjacent commutator segments so that an arc, once formed between a brush and a segment, will be maintained and extended from segment to segment as the commutator rotates.

On the other hand, there is no exact definition of successful commutation, especially in traction motors due to severe variations in the armature current. Hence, the commutation can be considered good even if sparking occurs provided that it does not result in excessive maintenance, both commutator and brush lives are as longer as possible. According to the Westinghouse's degree of sparking guide, the best commutation is "black with no visible sparking" (degree 1). However, for traction motors the 1 ¼ degree ("light intermittent sparking") can be considered successful commutation [1,2,3,4,5].

In the particular case of traction motors, the brush life is evaluated by means the "wear rate factor", expressed as the "wear in mm per 1000 km". This factor should be intended as a relative indicator because depends on several operational conditions:

- type of motor and duty cycle,
- atmospheric conditions,
- commutator conditions such as film, runout, quality,
- brush assembly design which includes brush grade, holder design and spring pressure,
- quality of motor design, operation and maintenance.

Based on service experience, an estimate of 0.08 to 0.10 mm per 1000 km brush wear could be considered normal for both undulating current and rectified current dc traction motors [1,5].

As well known, the sparking depends on electrical and mechanical causes. The electric are related to the airgap flux distribution, voltage between adjacent segments in the vicinity of the brushes, armature reaction, and e.m.f.'s induced in the coils undergoing commutation, whereas the mechanical are the inadequated choice of brush grade, friction, commutator film, vibrations, high micas, high brush spring pressure, and commutator rugosity. In addition, maintenance of the commutator has progressively decreased due to improvements in construction, better ventilation and the choice of a suitable brush grade having high contact resistance and good polishing qualities.

The commutating conditions in both undulating and rectified current traction motors are considerably more complicated than those in a direct current straight traction motor, as, in addition to the e.m.f. induced in the commutated coils by the reversal of the armature current (reactance voltage), there is a static e.m.f., called the "transformer e.m.f.", which is induced in these coils by the alternations of the main flux. Then the overheating of certain armature coils and the vicious sparking at the brushes are due to the relatively large circulating currents which are induced by the alternations of main flux in the coils short-circuited by the brushes, these coils and the main field coils acting respectively as the secondary and primary windings of a transformer [1,2,3].

In practice, since the amplitude of the transformer e.m.f. is proportional to the alternations of main flux, i.e. to the alternations of main field winding current, its largest values occur at heavy loads. Therefore, under these conditions severe sparking is liable to occur, as the coils undergoing commutation have the circulating currents due to the transformer e.m.f. superimposed upon the current which is being commutated.

The circulating currents, however, produce other effects which are detrimental to the desirable performance of the motor. Thus, since the coils occupying the neutral zone are in the position of maximum mutual inductance with respect to the main field winding, and the circulating currents are produced by induction, the magnetic field set up by the short-circuited coils act in opposition to the magnetic field producing the main flux, resulting this reaction in a weakening of the main flux as well as in a reduction of torque [1,5].

Because the "reactance voltage of commutation" is neutralized by means of commutating poles, the magnitude of the circulating currents is proportional to "transformer e.m.f. per coil × number of coils short-circuited by a brush / resistance of path of circulating currents". This path includes the contact surface of the brushes, the appropriate armature coils and their connections to the commutator segments. On the other hand, the transformer e.m.f. can be limited by the use of a smoothing coil to reduce the motor current alternating component, together with a non-inductive shunt resistor connected in parallel with the main field winding. The shunt resistance must be higher than that of the main field winding. Then, the alternating component of the motor current is carried through the shunt resistor, whereas the steady component is carried through the field winding. Note that both undulating and rectified currents may be resolved into a steady component and an alternating component.

In addition, split or sandwich brushes (in which two brushes, each of half the thickness of a solid brush, are cemented together with insulating cement) are also used due to a reduction in the magnitude of the circulating currents, as the path includes the double length of the brush as well as the increased contact resistance.

Considerations of the permissible sparking at continuous rating limit the residual transformer e.m.f. in adjacent commutator segments to a maximum of 0.5 volts [1,2,3]. On the other hand, the traction motors are designed for using electrographitic brush grades with the following resistivity ranges:

- straight direct current traction motors: 1200μΩ.cm to 3650μΩ.cm,
- straight single-phase alternating current traction motors: 3900μΩ.cm to 6800μΩ.cm,
- undulating current and rectified current traction motors: 3900μΩ.cm to 6600μΩ.cm.

As a standard in electric traction, straight direct current motor denotes a purely dc motor directly supplied from the dc overhead catenary or conductor third rail by means a classic rheostatic control, and the straight single-phase alternating current motor is a commutator series motor designed in order to operate under sinusoidal alternating voltage and current, being directly supplied from the ac overhead catenary by means a transformer and a tap- changer switch. It is also important to emphasize that the construction of traction motors differs in many aspects from that of general purpose industrial motors due to the following factors:

- necessity of minimum weight associated with adequate mechanical strength and robustness, in consequence of which a gear transmission is necessary to obtain a sufficiently high speed for the motor armature,
- location of the motor under the motor coach or locomotive floor, which position very severely restricts the overall dimensions to definite limiting values determined by the diameter of the driving wheels and the track gauge,
- large centrifugal forces to which the rotating parts are subjected at the maximum speed of the motor rolling stock.

In addition, concerning armature winding both wave (two-circuit) and lap (multiple-circuit) windings are employed in traction motors, the choice depending on several design factors. Wave windings would be employed for all tramway, trolleybus and motor coach small motors with rheostatic control, whereas lap windings would be employed for the larger railway motors and in cases where the number of commutator segments for a wave winding with single-turn coils would result in too high a value for the average voltage across adjacent segments. As much as possible single-turn coils are employed to obtain good commutation and freedom from flash overs. At present, modern commutator motors are the chopper-driven and rectifier-driven, operating respectively under dc and ac motor rolling stock. As can be seen later, in order to obtain a good commutation lap winding with single-turn coils is employed.

On the other hand, taking into account that the duty cycle of traction motors consists of irregular cycles of variable output, for commutator motors two standard ratings are adopted by the railway constructors, being defined as follows [4,5]:

- continuous rating: the output at the motor shaft for an unlimited period at normal voltage which produces temperature rises not exceeding the limits specified in insulation class,
- one-hour rating: the output at the motor shaft for one hour period at normal voltage which produces temperature rises not exceeding the limits specified in insulation class.

Figs. 1 and 2 shows the schematic configuration of locomotives equipped respectively with chopper-driven dc traction motors and single-phase ac/dc rectifier-driven dc traction motors. In addition for both drives the dc voltage and current waveforms are also shown. As can be seen in Figs. 1 and 2 the dc traction motor is rigorously the same, the only difference concerns the resistance of the non--inductive shunt resistor as well as the inductance of the smoothing reactor. Note that the motor is named “undulating current traction motor” or “rectified current traction motor” on the basis solely of the current waveforms, that is as a function solely of the type of electric drive. On the other hand, the principal data related several locomotives operating with these two types of dc traction drives are presented respectively in Tables 1 and 2. Concerning the Austrian locomotive BoBo 1044 (Table 2) it is important to emphasize the number of units, the output power and, in particular, its specific power (61 kW/t), the highest of ever for motor rolling stock equipped with commutator traction motors [1,2,3,4].

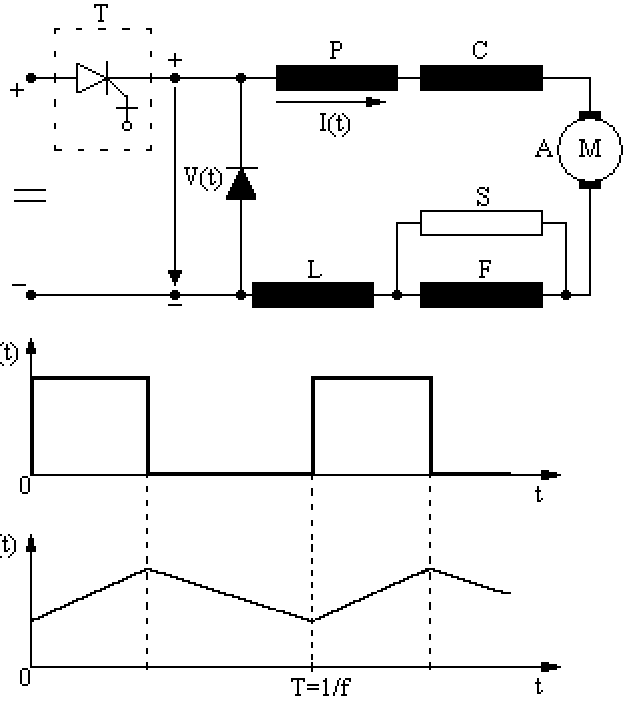

Fig.1 Schematic arrangement of a locomotive equipped with chopper-driven dc traction motors (undulating current motors). T - chopper, F - main field winding, P - commutating pole winding, C - compensating winding, A - armature winding, S - non-inductive shunt resistor, L - smoothing coil.

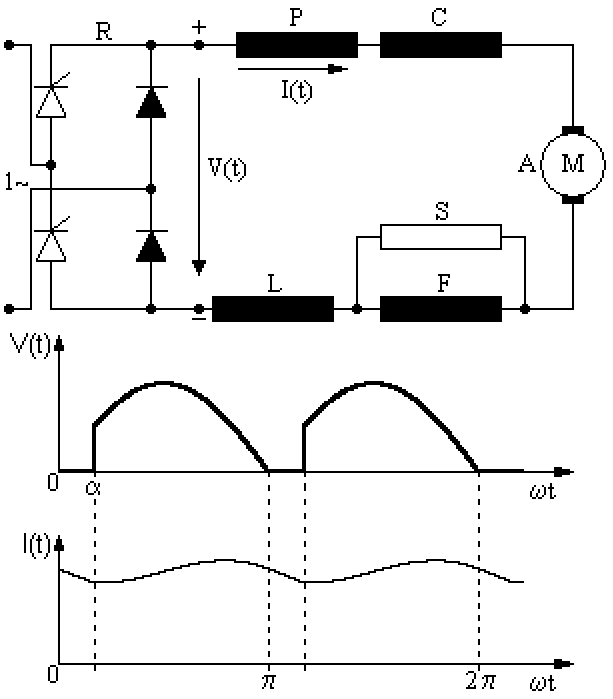

Fig.2 Schematic arrangement of a locomotive equipped with single-phase rectifier-driven dc traction motors (rectified current motors). R - rectifier, F - main field winding, P - commutating pole winding, C - compensating winding, A - armature winding, S - non-inductive shunt resistor, L - smoothing coil.

2 Transformer e.m.f.

Theoretically speaking, that is for ideal motor commutation conditions, the parallel "main field winding – non-inductive shunt resistor" as shown in Fig.3, presents the following characteristics:

- the resistance of the non-inductive shunt resistor is equal to infinite,
- the resistance of the main field winding is equal to zero,
- the reactance of the non-inductive shunt resistor is equal to zero,
- the reactance of the main field winding is equal to infinite.

Therefore, for ideal commutation one can assume that:

- the steady component of armature current flowing through the shunt resistor is equal to zero,
- the total steady component of the armature current flows through the field winding,

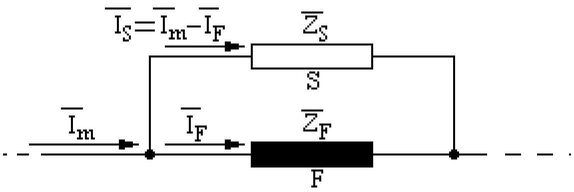

Fig.3 "Main field winding - non-inductive shunt resistor" parallel.

- the total alternating component of the armature current flows through the shunt resistor,
- the alternating component of the armature current flowing through the field winding is equal to zero, then the main flux should be resolved into only a steady component and, consequently, the transformer e.m.f. should be equal to zero.

However, in practice neither the shunt resistance nor the field winding reactances are both equal to infinite. In addition the field winding resistance must be lower than that of the shunt but not equal to zero.

Table 1 Principal data of main line electric locomotives equipped with choppers and undulating current traction motors.

locomotive	traction system	explorer and year	number of units	track gauge (mm)	continuous output power (kW)	maximum speed (km/h)	mass (ton)	kW/t
BB 7200	1500 V	SNCF 1976-85	210	1435	3830	180	90	43
BBB E633	3000 V	FS 1979-89	151	1435	4330	130	106	41
BoBo GDe4/4	840 V	MOB 1983	4	1000	1016	100	48.5	21
CC S250.6	3000 V	RENFE 1987	5	1668	4600	160	123	37

SNCF-Société National des Chemins de Fer Français (French Railways); FS-Ferrovie dello Stato (Italy Railways); MOB-Montreux-Oberland Bernois (Private Switzerland Railway); RENFE-Red Nacional de los Ferrocarriles Españoles (Spain Railways).

Table 2 Principal data of main line electric locomotives equipped with single-phase half-controlled rectifiers and rectified current traction motors.

locomotive	traction system	explorer and year	number of units	track gauge (mm)	continuous output power (kW)	maximum speed (km/h)	mass (ton)	kW/t
BB 15000	25 kV 50 Hz	SNCF 1971-78	65	1435	4000	180	90	44
BoBo 1044	15 kV 16 2/3 Hz	ÖBB 1974-92	216	1435	5148	160	84	61
BoBo Rc4	15 kV 16 2/3 Hz	SJ 1975-83	128	1435	3600	135	78	46
CoCo 9E	50 kV 50 Hz	SAR 1978-83	31	1067	3780	90	168	23
CoCo EL1	25 kV 50 Hz	NRZ 1983-84	30	1067	2490	110	114	22
BoBo HGe4/4 II	15 kV 16 2/3 Hz	CFF 1989	8	1000	1836	100	63	29

ÖBB-Österreichische Bundesbahn (Austrian Railways); SJ-Svenska Statens Järnvägar (Sweden Railways); SAR-South African Railway; NRZ-National Railway of Zimbabwe; CFF-Chemins de Fer Fédéraux Suisses (Switzerland Railways).

As a consequence, about 10 % of the steady component of the armature current flows through the shunt resistor, whereas a residual alternating component of the armature current flows through the field winding. Therefore there is a "residual transformer e.m.f." induced in the commutated coils by the residual alternating component of the main flux.

Different derivations concerning particular transformer e.m.f. relationships for all commutator series traction motors were presented in previous works [1,2,3,5]. However, a generalized relationship related to the transformer e.m.f. in order to be used in both undulating and rectified current motors can be derived, as proposed in this paper.

Since the current flowing through the main field winding is pulsating (or undulating), the main flux is also pulsating and may be resolved into a steady component, equal to Φ_{av} (mean value), and a residual alternating component having a rms value Φ_{res} and an electrical angular frequency ω, that is

$$\Phi(t) = \Phi_{av} + \sqrt{2}\,\Phi_{res}\sin\omega t \qquad (1)$$

Hence, by application of the Faraday's law the instantaneous value of the residual transformer e.m.f. induced by the residual alternating component of main flux in the coils short-circuited by the brushes is as follows

$$E_{trB}(t) = -n_s\frac{d\,\Phi(t)}{d\,t} = \sqrt{2}\,\omega\, n_s \Phi_{res}\sin(\,\omega t - \pi/2\,) \qquad (2)$$

where n_S is the number of turns per armature coil. Its rms value is then given by

$$E_{trB} = \omega\, n_s \Phi_{res} \qquad (3)$$

On the other hand, taking into account the parallel "shunt resistor – main field winding", as can be seen in Fig. 3, one can write the following phasor relationship related to the alternating components

$$\bar{I}_F = \frac{\bar{Z}_S}{\bar{Z}_S + \bar{Z}_F}\bar{I}_m \qquad (4)$$

where Z_S and Z_F are the impedances of the shunt and the winding respectively, I_F the rms value of the residual alternating component of the current flowing through the main field winding, and I_m the rms value of the alternating component of the motor armature current, all referred to the frequency ω of the ac component of the current.

Since the shunt resistor is non-inductive and its resistance is higher than that of the winding, by simplifying one can write

$$\bar{Z}_S \approx R_S \qquad (5)$$

$$\bar{Z}_S + \bar{Z}_F \approx jX_F \qquad (6)$$

where R_S is the shunt resistance and X_F the field winding reactance referred to the frequency ω. On the basis of the equivalent circuit for the motor, the voltage phasor relationship referred to the frequency ω is as follows:

$$\bar{V}_m = \bar{E}_m + \bar{Z}_m(\sqrt{2}\,\bar{I}_m) \qquad (7)$$

where V_m denotes the amplitude of the alternating component of the motor voltage, E_m the amplitude of the static internal e.m.f. induced in the armature winding by the residual alternating component of the main flux, and Z_m the total impedance of the motor equivalent circuit. Taking Figs. 1 and 2 into account, it should be noted that Z_m includes the following series-connected impedances: armature winding, compensating winding, commutating pole winding, shunt resistor – main field winding parallel, and smoothing coil. Since the steady component of the main flux Φ_{av} is higher than the rms value of the residual alternating component Φ_{res}, and the resistance of the motor equivalent circuit R_m is lower than its reactance X_m, one can write:

$$\bar{E}_m \approx 0 \qquad (8)$$

$$\bar{Z}_m \approx jX_m \qquad (9)$$

Therefore, (7) can be rewritten as follows:

$$\bar{I}_m \approx \frac{1}{\sqrt{2}}\frac{\bar{V}_m}{jX_m} \qquad (10)$$

Thus taking (5), (6) and (10) into account, from (4) one obtains the rms value of the residual alternating component of the current flowing through the main field winding:

$$I_F = \frac{1}{\sqrt{2}}\frac{R_S}{X_F}\frac{V_m}{X_m} \qquad (11)$$

In the case of a purely unsaturated magnetic circuit the flux is directly proportional to the current, that is

$$\Phi_{res} = k_\Phi\, I_F = \frac{k_\Phi}{\sqrt{2}}\frac{R_S}{X_F}\frac{V_m}{X_m} \qquad (12)$$

where k_Φ is a constant of proportionality. On the other hand, as well known

$$X_F = \omega\, L_F \qquad (13)$$

where L_F is the inductance of the main field winding given by the following equation:

$$L_F = \frac{\Psi_F}{I_F} = \frac{n_F\,\Phi_{res}}{I_F} \qquad (14)$$

being n_F the total number of turns in the main field winding and Ψ_F its linkage flux. By combining (12), (13) and (14), (13) can be rewritten as follows:

$$X_F = \omega\, n_F\, k_\Phi \qquad (15)$$

Finally, taking (3), (12) and (15) into account one obtains

$$E_{trB} = \frac{\sqrt{2}}{2}\frac{n_S}{n_F}\frac{V_m}{X_m} R_S \qquad (16)$$

In practice, the sparking at the brushes is due to the residual transformer e.m.f. induced between two adjacent commutator segments E_{tr}. According to an original derivation proposed in [5], one obtains the following fundamental relationship between rms residual transformer e.m.f.'s E_{tr} and E_{trB},

$$E_{tr} = \frac{p}{a} E_{trB} \qquad (17)$$

where p is the number of pole pairs and a the number of pairs of parallel circuits in the armature winding. Then, effecting the substitution of (16) into (17) one obtains

$$E_{tr} = \frac{\sqrt{2}}{2}\frac{p}{a}\frac{n_S}{n_F}\frac{V_m}{X_m} R_S \qquad (18)$$

3 Conclusions

As shown in this paper, for both chopper-driven and ac/dc converter-driven traction motors the simplest method of obtaining a good commutation conditions consists to connect a smoothing coil in series with the motor as well as to provide a shunting of the main field winding with a non-inductive resistor. As a support for optimized design of these two equipments an original generalized formula concerning the commutation transformer e.m.f. is also proposed.

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