Power Quality and Electromagnetic Interference in a Trolleybus Traction System

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Abstract—This paper presents an analysis of the power quality impact and electromagnetic interference in a trolleybus traction system. As test subject it is used a 180 kW induction motor supplied by a three phased inverter with field oriented control. A fast Fourier transform was used in a simulation process, to determine the power quality and electromagnetic interference processes of the current supplied to the motor.

Keywords—trolleybus, traction system, fast Fourier transform, computer aided analysis, harmonics.

I. INTRODUCTION

Electric traction is an ever-growing trend in today’s society. It is generally much more efficient than fuel-powered traction, but also demands a complex approach in the traction motor as well as control devices [1].

In the ex-USSR region, a transitional period has been happening since 1991. The legacy in electric public traction was DC traction for trolleybuses and electric trams. For this type of transportation, the contact line (CL) derived was also DC. For trolleybuses the contact line provided a supply voltage of 600 V. Up until this point the source for loss of power quality was either the non-linearity of the motor and the transient processes of the electromagnetic switches [8,9].

After the fall of the USSR, incrementally, the DC traction systems were upgraded with electronic traction systems, and new AC systems were entering the market [2, 3]. Due to unstable and low-quality supply power the electronics on the new trolleybuses are frequently failing if not accounted for. During testing and exploitation, it was discovered that the power converters had a significant impact on EMC and power quality of the line [10]. The mechanical characteristic of the traction load does not function in a steady state for long, and the effects on power quality and EMC must be studied separately for an ample functioning.

The most common analysis of harmonic distortions for electric signals is the Fourier transform analysis [4], though the Wavelet transform is being used to analyze more complex electric and power system [5].

This paper focuses on the induction motor traction system for a trolleybus concerning power quality and electromagnetic interference that appear, based on harmonic decomposition. The fast Fourier transform (FFT) [4] was used to decompose the stator current of a typical 180 kW induction motor supplied by an inverter (Fig. 1), at transient process of acceleration in a simulated environment [11].

II. THE INDUCTION MOTOR TRACTION SYSTEM

The selected traction motor for analysis is the Induction motor. A viable traction system for Induction motors in trolleybuses is rated at 180 kW power. Besides the traction control, a trolleybus control system has a series of other functions, such as system diagnostic, protection and peripheral control (Fig.2).

![Fig. 1. A power converter installed on the roof of an trolleybus](image1)

![Fig. 2. A complex traction system structure. 1- power converter, 2- Induction motor, 3 – computer connection box, 4 – LCD human-machine interface, 5- video registration devices, 6 - speakers](image2)
The power converter (position 1 from Fig. 2) is an inverter, based on IGBT discrete modules. The common inverter topology can be modified to allow regenerative brakes for the trolleybus, and also increase safety and system reliability with the VT7, VT9, VT 10 and VT 11 transistors, as well as an extra varistor (Fig. 3).

For further analysis, we considered a 180 kW induction motor with field oriented control (FOC) [7], currently used in trolleybuses, the TAD-3. The characteristics of the motor are presented in Table 1.

| Name                  | Symbol | unit | TAD-3 |
|-----------------------|--------|------|-------|
| Rated power           | $P_N$  | kW   | 180   |
| Rated Supply phase voltage | $U_{IN}$ | V   | 400   |
| Rated phase current   | $I_{IN}$ | A   | 300   |
| Rated slip            | $s_N$  | -    | 0.015 |
| Rated velocity        | $n_N$  | rot/min | 1480 |
| Rated torque          | $T_N$  | Nm   | 780   |
| Rated efficiency      | $\eta_N$ | $\eta$, % | 93   |
| Power factor          | $\cos \varphi$ | - | 0.9   |
| Pairs of poles        | $p$    | -    | 2     |
| Friction coefficient  | $k_f$  | -    | 0.02  |
| Rotor inertia         | $J$    | kg·m² | 32    |
| Stator resistance     | $R_s$  | $\Omega$ | 0.00953 |
| Rotor resistance      | $R_r$  | $\Omega$ | 0.021 |
| Stator leakage inductance | $L_s$  | H   | 0.000235 |
| Rotor leakage inductance | $L_r$  | H   | 0.000235 |
| Mutual inductance     | $L_m$  | H   | 0.00095 |

The adapted control mechanism for the inverter is the rotor FOC, whose advantages and mathematical models are long documented [7, 8]. The current control algorithm is focused on current control, via pulse width modulation (PWM) of the IGBT. The basic control algorithm is described by (1) and the reference axis is oriented by the rotor field as shown in Fig. 4.

$$u_s = R_s i_s (1 + s \cdot T_s) - \omega_r \sigma \Psi_s + \Phi_s$$

$$u_r = R_r i_r (1 + s \cdot T_r) + \omega_r \sigma \Psi_r + \Phi_r L_m$$

Where $u_s$, $u_r$ – stator voltage projection on x and y axis respectively of the rotational reference axis; $i_s$, $i_r$ – stator current projection on x and y axis respectively of the rotational reference axis; $R_s$ – stator resistance; $L_s$, $L_r$, $L_m$ – stator, rotor and mutual inductances; $s$ – rotor slip; $T_s$, $T_r$ – stator time constant; $\omega_r$ – reference axis rotational speed; $\sigma$ – dispersion constant

The algorithm of vector control of the traction asynchronous motor is realized by a separate 32-bit microprocessor (Fig. 5). The peripheral and diagnostic control of traction systems are ensured by a separate processor. The dual-processor system allows fast reaction of motor control, which also does not encumber the diagnostics and peripheral reaction times.

The vector control method adds to serious advantages of induction motors, compared to the DC motors, in industry, as well as traction. On the other hand, the growing number of electric converters comes with a scarcely researched question of impact on the power quality, and correct response to the power quality impact.

### III. POWER QUALITY ANALYSIS OF A TRACTION SYSTEM WITH INDUCTION MOTOR

As an inheritance from the soviet system, the power systems engineers were never focused on the quality of electrical energy. Electric energy was abundant and the designed equipment was robust, at the cost of efficiency and material.

As a first attempt to analyze power quality in trolleybus traction system with induction motor and inverter, it is common to begin with the FFT, which develops on the discrete Fourier transform (2), for signal decomposition, $i$ being harmonic order, $A$ – amplitude, $\omega$ – pulsation and $t$ - time.

$$f(t) = \sum_{i=0}^{N} A_i \left[ \cos(i\omega t) - \sin(i\omega t) \right]$$
Due to previous familiarity, and the possibilities, we used the Matlab’s Simscape Electrical module to model the FOC electric drive (Fig. 6), specifically to analyze the harmonics of the motor’s current and contact line voltage with the FFT. The traction usage of electric drives is focused on transient processes of the vehicle, such as start and stop of the trolleybuses at stations, and along the prescribed route [11].

The simulation hypothesis is testing a FOC induction motor with speed control. The rotor speed varies in steps (Fig. 9): 1st step is 500 rpm at 0.5 s, 2nd - 1000 rpm at 1.5 s, and 3rd - 1480 rpm at 2.5 s. The torque for this hypothesis is considered constant.

The fundamental frequency for FFT analysis is 50 Hz, as is the motor’s rated frequency. It was also considered when analyzing the noise on the DC bus, provoked by either the transient processes in the chopper or by the power inverter for motor control. At transient processes the total harmonic deformation becomes irrelevant of the fundamental 50 Hz frequency.

The transient results current, speed, torque and DC bus voltage are presented in (Fig.9). A first observation is the form variation of stator current; whose frequency varies visibly at each new speed step. A second observation is that the bus voltage takes dips at each step, leading to the conclusion that a higher load on the motor takes a toll on the DC contact line, as shown more expletively (Fig. 7). A multiplication for a public transport contact line, for 2 or 3 hundred trolleybuses, will show a necessary voltage control system that would allow more current at the rectifier and transformer phases of supply. Expanding with FFT analysis on the supply voltage, it can be observed that the harmonics appear notably up to 5 Hz, and combine for a 3.05 % THD of the DC component (Fig. 8).
Further analysis was focused on the harmonic analysis of the current through FFT. Because these transient processes are hard to be concluded on, with FFT for the whole period, the Fourier decomposition was made for each speed step.

The first step (fig.10) shows a conglomeration of harmonics around the fundamental frequency, and also around the harmonic order 90. Zooming on the area of harmonic order 90 (fig. 11) it can be observed that most impact is provided by the harmonics of order 89 and 90, which can raise up to 60% of the fundamental. Further to delve into the current decomposition, the emphasis was made on the first part of the harmonic distribution, up to 50 Hz, which is considered the fundamental frequency (fig.12). A natural conclusion is that the highest magnitude frequency is not the fundamental, but rather 15 and 20 Hz, which also leads to a high total harmonic distortion factor. This can also be observed in fig.12 – that the frequency of the current at first speed step is much smaller than that of the last step, which is closest to rated. Here the fundamental frequency of the sine wave, provided by the inverter, may be considered 20 Hz, which is 2.5 times smaller than the rated frequency of the motor.

The second step (fig.13) shows again a conglomeration of harmonics around the fundamental frequency, and also around the harmonic order 90. Zooming on the area of harmonic order 90 (fig. 14) it can be observed that most impact is provided by the harmonics of order 88, 89 and 90, which can raise up to 40% of the fundamental 50 Hz. This is a decrease of 20 % of magnitude of high frequency harmonics, compared to the first step. When the emphasis is put on the fundamental harmonic (fig.15), it can be observed that the highest magnitude frequency is still not the 50 Hz, but 34 and 35 Hz. This relates to Fig.12, as the frequency tends to be proportional to motor speed.

The third step (Fig. 16) shows again a conglomeration of harmonics around the fundamental frequency, and also around the harmonic order 90. Zooming on the area of harmonic order 90 (fig. 17) it can be observed that the high frequency harmonics are more distributed at this range, and the maximum magnitude of these harmonics reach only 1% of the fundamental. This is a vast decrease of magnitude of high frequency harmonics, compared to the first step (where it reaches 60%) (Fig.11) and second step (where it reaches 40%) (Fig. 14). When the emphasis is put on the fundamental harmonic (Fig.18), it can be observed that the highest magnitude frequency is 50 Hz, with very small percentages of sub harmonics. This relates to Fig.9, as the frequency tends to reach the rated value for the motor, and the motor tends to reach the rated speed. The third step has the minimum of harmonics and deformations, as it commands a current frequency closest to the rated one.
The total harmonic distortion (THD) varies greatly at the three speed steps, if we consider the fundamental 50 Hz, thus it is not a tangible value for this analysis. The THD value for the 3rd step reaches 43%. Meaning the third step of speed is the least distortive in FOC, and the most preferable one. On the other hand, the frequency of the current is varied to vary speed, thus a more correct approach to harmonic distortion would be to analyze the THD relative to the frequency of the current at given speed. In this case a clearer image of harmonic deformation will appear, rather than consider a change of current frequency as deformation.

As the set speed becomes closer to the rated rotor speed, the bulk of high frequency harmonics (of level 80 and beyond) move towards the fundamental. At 2.5 s, when the rotor speed is set almost to the rated, it can be observed the most of the higher-level harmonics, are negligible entirely.

IV. CONCLUSIONS

During the FFT analysis it was discovered that the harmonic THD of the stator current of the motor varies greatly at low motor speeds. The frequency of the current varies as the FOC dictates, and the fundamental frequency provided by the inverter changes, but not that of the motor. A more thorough approach to harmonic deformations would be to analyze the THD relative to the frequency of the current at given speed.

Considering that vehicles have a constantly dynamic functioning, almost never being in a steady state, we can conclude that the effects of harmonic distortion are considerable, and that more action needs to be undertaken to mitigate these effects.

Due to the dynamic nature of electric traction it would be impossible to negate completely all the currents distortions, thus a more thorough analysis of harmonic evolution should be undertaken to identify the most impactful harmonics. The high harmonic orders will determine electromagnetic interferences with other electric equipment from the driving system of trolleybus, or with the supplying line. These interferences will require mitigation measures such as presented in [12].

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