Electrical Power and Energy Systems 57 (2014) 212–221

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Electric arc power collection system for electric traction vehicles

Adrian Pleşca *

Gheorghe Asachi Technical University of Iaşi, Romania Blvd. Dimitrie Mangeron, 21-23, Iaşi 700050, Romania

ARTICLE INFO

Article history:
Received 28 December 2012
Received in revised form 7 November 2013
Accepted 25 November 2013

Keywords:
Electric arc
Power collection
Electric traction vehicles

ABSTRACT

One of many problems in electric traction vehicles is supplying the necessary power to the vehicle. The main difficulty with a conventional overhead system is the maintenance of good contact between the sliding pantograph and the catenary system. As an alternative to the pantograph–catenary system for power collection by contact, there are some methods of power transfer to a moving vehicle without contact: capacitive coupling, electromagnetic-wave transmission, inductive coupling and through an arc plasma. This paper proposes an electric arc power collection system to be used at electric traction vehicles such as tramways and trains. Starting from Nottingham's equation on the approximation of volt-ampere characteristic of the direct current electric arc, a mathematical model which includes the variation of the electric arc length, depending on the moving electrode rotations speed, is being proposed. Next, the test bench, especially designed for the analysis of power transfer through the electric arc, between a fix and a moving electrode, is presented. Practically, a simulation of an electric traction system running was developed, in which the main dc motor is supplied from a source of continuous variable voltage from a dc generator by means of the electric arc developing between a copper disc and the graphite skate contact, the key element of a tramway pantograph built at a scale of 1:4. A longitudinal argon blow-out has been used to sustain the electric arc. The electric arc characteristics at various arc column lengths, various moving electrode rotations and various argon blowing speeds along the arc column, have been analyzed. Also, from experimental tests, the variation of the rotation velocity of the moving electrode against length of the arc column, has been obtained for different blowing speed of the argon gas. There is a good correlation between experimental data and computing results of electric arc characteristics for different rotation velocity of the moving electrode and different length of the arc column, in stationary conditions.

1. Introduction

The contactless power transfer represents an important aspect for many applications. A special domain is the power transfer between the pantograph and the contact line for the electric vehicles supplied from a catenary system, where the present-day contact is realized between two different materials [1,2]. The power requirement of a fast moving vehicle on the ground increases rapidly with speed. There are basically four methods of contactless power transfer: capacitive, electromagnetic, inductive, and through an arc plasma.

In the capacitive interface, the electric field is confined between conductive parallel plates, alleviating the need for magnetic flux guiding and shielding components that add bulk and cost to inductive solutions. The realizable amount of coupling capacitance is limited by the available area of the device. To reduce the necessary plate area to accessible sizes, the frequency of the voltage must be increased, but even so, the dimensions of the capacitor will be large. A low efficiency, safety problems and electromagnetic interferences are the major disadvantages of this method. The electromagnetic power transfer is made through the air or waveguides. The principle is to transform the energy into microwaves, to transmit this energy between two antenas and finally to convert the microwaves into electric energy at the receiver. A high efficiency imposes frequencies of about GHz to preserve the focalisation of the beam. In inductive coupling, the power transfer is based on the magnetic flux of an energized primary coil along the track being linked by a secondary coil on the moving vehicle. There are three basic types of inductive coupling methods: coupling without magnetic circuits, with a magnetic circuit on the vehicle only and with magnetic circuits on the vehicle and along the entire track. All the types of inductive power transfer are more efficient as the voltage and frequency increase. The main problem is the high electromagnetic interference.

Power collection may be achieved by conduction through an arc plasma which bridges the gap between a collector, attached to the fast moving vehicle, and a distributor, supported from the ground. In many applications involving electrical contacts between moving components (conducting materials) of any device, discharge

---

* Tel.: +40 723055173; fax: +40 232 237627.
E-mail address: matrix_total2000@yahoo.com

0142-0615/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijepes.2013.11.048

Nomenclature

l	length of the arc column
I	current through the arc column
U_a	arc column voltage
α_1	by definition $\alpha_1 = a_1 + c_1 l$
β_1	by definition $\beta_1 = b_1 + d_1 l$
a_1, b_1, c_1, d_1	constants
α	by definition $\alpha = a + cl$
β	by definition $\beta = b + dl$
a, b, c, d	constants
l_0	initial length of the arc column
l_m	maximum length of the arc column
n	rotation velocity of the moving electrode

effects, i.e., charge transfer between components, are expected. The very origin of these phenomena is due to controlled or uncontrolled switching off, leading to contact interruptions as observed in many applications of sliding contacts to trains propulsion or signal transfer in wind power plants. From a physical point of view, two main types of discharge have to be distinguished: the glow discharge and arcing plasma columns, differing by the physical conditions constraining the system. The physical conditions imposed to the electrodes as well as the conditions for arc sustainment depend strongly on the geometry and size of the air gap, the electrodes surface state and the atmospheric conditions.

Whatever the arcing conditions, the most significant damage caused to the components is rather well known and has been characterized for a long time [3–6]. The main reason of pantograph arcing is the varying gap due to the mechanical vibration between the pantograph and catenary, so it is important to study the electrical characteristics of pantograph arcing as the overvoltage, DC component and harmonic spectrum [7–9]. The arcing mechanism and corresponding asymmetry in the voltage and current waveforms are governed by line speed, current, supply voltage, load power factor and pantograph material [10,11]. In previous works, the harmonic spectrum of pantograph arc current was analyzed using a Mayr's model [12] for the arc behavior control and time-controlled switches for starting the pantograph detachment and reattachment events. Influences of different parameters on DC traction system, such as the supply voltage polarity, the relative motion between the pantograph and the overhead contact wire, the forward motion along the track and the lateral sliding motion of the pantograph are presented in [13]. The hazards of arc to the contact wire, pantograph skateboards, communication signals and power quality have been discussed in [14–16]. An experimental analysis of the arc root movement and influence of different parameters is presented in [17].

This study attempts to achieve and validate the possibility of energy transfer through the electric arc for a direct current traction system. The influence of the arc column length and rotation velocity of the moving electrode has been investigated. In order to improve the electric arc stability, a gas (argon) has been blown along the arc column.

2. Theoretical aspects

Characterizing the stationary electric arc may be done using plasma physics concepts (nature of the gas in which the discharge is achieved, its pressure, the charge carrier density, the electrons temperature, the positive ions temperature, the gas temperature, etc.), or more efficiently, by the volt – ampere characteristic, $U(I)$, corresponding to a “black box” type model, which, sometimes, enhances the influence of certain factors, as well. The rigorous analytic description of the arc discharge evolution has been the objective of numerous research studies worldwide [18], implemented in mathematical models of the electric arc, rather difficult to carry out, not only because of the multitude of influencing factors, but also because of the completely different behavior of the discharge zone, before and after the current crosses zero [19].

Though these tentative models might be divided into different families according to their main interest, they reflect faithfully the physical (macroscopic) structure of the plasma column [20,21]: the cathode (the electrodes), the space-charge region in its vicinity (sheath about a few 10^{-2} μm), the ionization zone (about a hundred μm) and the plasma itself. The cathode is characterized by its thermal and electrical conductivities and its work function (energy threshold for electron emission). In the space-charge region is maintained the high electric field required for accelerating the electrons injected from the cathode to the plasma or the ions recombining at the cathode. The ionization zone is a rather thick sheath dominated by collisions and necessary for sustaining the discharge. Some models are based on differential conservation equations on integral balances for mass, energy and momentum. Most of the arc models have been based on the simplifying assumption of local thermodynamic equilibrium, but there are deviations from local thermodynamic equilibrium in the AC arc when current passes zero [22]. Because of the arc instabilities it is difficult to compare numerical modeling results with measurements, another challenge in modeling being the co-existence of multiple arcs appearing in some conditions. A comprehensive understanding of the plasma-electrode interaction and electric arc models is offered by [23]. Models of the sliding contact were studied by [24].

In what follows, the most important characteristic of the electric arc, in stationary state, corresponding to the cylindrical model, in direct current, the volt-ampere characteristic will be analyzed, as it ensures the support for some useful comments on power transfer by electric arc. This characteristic under stationary regime, $U_a(I)$, may be written as:

$$U_a = C\,l\,I^{-m} \tag{1}$$

in good agreement with the experimental research which proposes such a relation for the electric arc that develops between the copper contact plates, when the material constant $C = 80$, l (cm) and the parameter $m = 0.5$. It is worth mentioning that relation (1), defining the volt – ampere characteristic of the dc electric arc under stationary regime, corresponding to the cylindrical model, neglects the electrode phenomena occurring on the contact plates. In order to take these phenomena into account, Nottingham proposed an approximating relation for the $U_a(I)$ characteristic, of the form:

$$U_a = \alpha_1 + \frac{\beta_1}{I^m}, \quad m < 1, \quad \alpha_1 = a_1 + c_1 l; \quad \beta_1 = b_1 + d_1 l \tag{2}$$

in which the influence of the arc column length l (cm) is emphasized, a_1 (V), b_1 (VA^m), c_1 (V/cm) and d_1 (VA^m/cm) being constants that depend mainly on the materials of the contact plates. For the technical calculus, Ayrton proposed a simpler expression:

$$U_a = \alpha + \frac{\beta}{I}, \quad \alpha = a + cl; \quad \beta = b + dl \tag{3}$$

where l (cm) is the arc column length and a (V), b (VA), c (V/cm), d (VA/cm) are constants that depend on the electrode shape and their