Proceedings of

The 6th International Conference on Mechatronics Technology

ICMT2002

New Progress of Mechatronics Technology from the Birthplace

September 29 - October 3, 2002

Kitakyushu Science and Research Park, Kitakyushu, JAPAN

Organized by

Tokyo Institute of Technology　**Kyushu Institute of Technology**

CONFERENCE PROGRAM & CONTENTS

Conference Center, Kitakyushu Science and Research Park

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Modelling and Control of Electric Vehicle Dynamics Accounting for Skid Phenomena

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Abstract

In this paper we propose a model for the description of slip phenomena by using a case study based on electric triplex greens mowers. Such electric vehicles (EVs) are treated here as electromechanical systems, and their dynamics is described effectively with differential-algebraic models. We have implemented general types of nonlinear dependencies of the traction force on the slip ratio into our models, obtained torque-speed profiles of electric vehicle performance for different surface conditions, and implemented a slip ratio control strategy.

1. Introduction

Important trends in today's car industry include the development of advanced diagnostic systems and the finding of efficient alternatives to the conventional internal combustion engine (ICE) vehicles. Both tasks rely heavily on the achievements of *mechatronics*, and in this paper we focus on the development of new models for the dynamics of such advanced mechatronic products as electric vehicles.

Firstly, since conventional ICE vehicles are known to be one of the major source of urban pollution, electric vehicles represent a viable alternative. Secondly, in the class of alternatives to the ICE vehicles that exists in today's market, electric vehicles are evaluated very favourably due to their efficient control, which is, for example, is more efficient compared to hydraulic vehicles. Indeed, torque generation is very quick and accurate in most driving situations, and since a motor can be attached to each wheel, the EV can be handled easier with individual torque of every driven wheel controlled independently. Thirdly, the ideas developed for EVs can be often applied to other alternative-energy-source vehicles such as solar-electric vehicles.

The efficiency of electric vehicles is determined at large by the motor torque, and therefore torque-speed profiles of EVs become one of the most important characteristics helping to improve the performance of EVs.

In this paper we consider three-wheel electric vehicles. On the one hand, there is evidence to suggest that such vehicles are becoming popular in both the urban environment and in using them for specialized purposes [4]. On the other hand, we have had a specific case study in hand, namely electric triplex greens mowers of the Ransomes E-Plex II type. Although our major attention in this paper is given to off-road EVs, the methodology we have developed here can be applied to other types of electric vehicles. The model we have developed describes the dynamics of electric vehicles allowing modelling the nonlinear slip phenomena of a wheel. The model is based on a system of differential-algebraic equations and couples together the vehicle velocity, the wheel rotating velocity, the slip ratio, the traction force, and the torque. Therefore, in what follows we describe the EV as a *coupled electromechanical system*, account for slip phenomena in its dynamics, and propose an efficient control of the system.

2. EV dynamics: coupling mechanical and electrical parts of the system

We start from the mechanical part. The motion of the vehicle we are interested in can be described in terms of its longitudinal speed

$$I_v \frac{dV}{dt} = \bar{F}_d(t,\lambda) - \bar{F}_a - \bar{F}_g - \bar{F}_r, \qquad (1)$$

where I_v is the vehicle inertia, V is the vehicle velocity, and forces in the right hand side of (1) denote the traction, aerodynamic, gravity, and rolling forces, respectively. We note that the aerodynamic resistance is small for off-road vehicles as long as they operate under 48 km/h (e.g., [5]) which is the case for the electric vehicles considered here. Further, the gravity and rolling resistance forces are defined as

$$\bar{F}_g = M\sin\alpha,\ \bar{F}_r = M(\mu\cos\alpha + \tilde{\mu}V), \qquad (2)$$

where M is the mass of the vehicle, α is the road/surface angle, μ is a normalized traction force variable, often referred to as the friction coefficient (between the wheel and the road/surface), and $\tilde{\mu}$ is the wheel mechanism friction coefficient. Note also that the rotational inertia of the wheel and the electric motor is taken into account by using the effective mass of the vehicle as follows

$$I_v = \frac{M}{g} + f(n_w, r_w, I_w, I_m), \qquad (3)$$

where g is the gravitational constant, and f is a function of the number of wheels, n_w, radius of the wheels, r_w, rotational inertia of the wheels, I_w, and intertia of the electric motor, I_m. The key characteristic that we will pay a special attention to is μ which is in our model dependent on the slip ratio in a nonlinear manner. This function determines the nonlinear character of the traction force

$$F_d = \mu(\lambda)N,\ 0 \le \lambda \le 1, \qquad (4)$$

where N is the normalized traction force (on the flat surface $N = Mg$), and the slip ratio, λ, is defined via the velocity of the vehicle and the velocity of the wheel, V_w, in the following manner

$$\lambda = 1 - \frac{V}{V_w},\ V_w \ge V;\ \ \lambda = \frac{V_w}{V} - 1,\ V \ge V_{w,}, \qquad (5)$$

where $V_w = r\omega$ (r is the radius of the wheel and ω is its angular velocity). Finally, we note that in the context of electric mowers operating on flat grass surfaces the above model is reducible to

$$M\frac{dV}{dt} = F_d(t,\lambda), \qquad (6)$$

where the key to understanding of the vehicle dynamics is kept by F_d. Since λ is the function of both the vehicle velocity and the wheel velocity, we need the equation for the wheel dynamics. This can be written in the following form

$$I_w\frac{dV_w}{dt} = K_g K_T(\delta - K_g\varphi) - B_w V_w - F_d(t,\lambda), \qquad (7)$$

where K_T is the torsional stiffness of the transmission which provides coupling between the motor and the wheel by the gear ratio K_g, δ is the motor shaft position, φ is the wheel position, and B_w accounts for for the speed-dependent forces against the wheel shaft motion, so that in the most general setting we have one additional equation connecting the evolution of the motor shaft position with other characteristics [2]. However, considering electric mowers it is appropriate to sumarise the action of the first two forces in (7) by the motor torque, F_m, so that the above equation is reduced to

$$M_w\frac{dV_w}{dt} = F_m - F_d(t,\lambda), \qquad (8)$$

where M_w is the wheel mass. It is by this force F_m, generated by engine, the coupling between the mechanical part of the system described so far, and the electrical part is realized. In particular, for the electric vehicles considered in this paper the motor torque is determined from the relationship connecting the power P and the wheel velocity

$$F_m = \frac{T_w}{r},\ where\ T_w = \frac{P}{\omega},\ \omega = \frac{V_w}{r}, \qquad (9)$$

with the wheel torque denoted here by T_w. Further, for the electric mower we consider here the power is supplied by a 48V battery, and therefore, the input power to the mower is a function of current i that can be written in the following way

$$P = k\omega i = k\frac{V_w}{r}i, \qquad (10)$$

where the torque constant, k, was set to 1 in all computational experiments reported here.

3. Nonlinear models for slip phenomena

The problem of the slip ratio estimation is known to be a very difficult task for both high-performance cars and for off-road vehicles. Moreover, it is generally agreed that with the increase of the IT component in vehicle design this problem, known also in a more general setting as the tire-road friction estimation (TRFE), becomes one of the most important research areas in this field. There are several key technologies, currently under intensive studies, that allow addressing this problem effectively. Amongst them are those based on

- installation of optical sensors in the car front;
- installation of tire-noise analyzing acoustic sensors;
- installation of stress/strain sensors at the tire thread.

All the above technologies are typically applied to road vehicles, in particular high performance vehicles, while for off-road vehicles, operation of which is based on traction force, the wheel-slip methodology seems to be the most appropriate. Note also that this methodology gains more and more popularity for high performance vehicles as well [1]. There are different variants of this technique, but in all cases the velocities of individual wheels are required to be estimated. In what follows we consider a one-wheel model [3] concentrating on the traction force evaluation which is dependent critically on the surface conditions, and hence on the so-called $\mu - \lambda$ curves.

The often-used basis for such curves construction lies with the assumption that the slip slope (sometimes called the longitudinal stiffness) is a sufficient characteristic to provide an accurate estimate for the friction μ. The important thing to realize is that linear approximations of such curves (e.g., [1,5]) may fail to predict correctly torque-speed profiles. Moreover, it is also well known that some nonlinear approximations such as

$$\mu = \frac{k\lambda}{a\lambda^2 + b\lambda + 1} \qquad (11)$$

might not be always appropriate either since the slip computed from them might give a significant offset [1]. In this paper we use the following fully nonlinear approximation valid on the whole interval $\lambda \in [0,1]$

$$\mu = \mu_0 \sin\{\mu_1 \arctan[\mu_2((1-\mu_3)\lambda + \frac{\mu_3}{\mu_2}\arctan(\mu_2\lambda))]\}, \qquad (12)$$

e.g. [1]. This dependency reproduces very well all surface conditions that we have dealt so far. In particular, based on the Sauer-Danfoss data we found that for grass surfaces $\mu_1 = 22, \mu_3 = 1$. Coefficients μ_0 and μ_2 should be chosen differently for different grass conditions, e.g. for the dry grass conditions

$\mu_0 = 0.5,\ \ \mu_2 = 13.0965,$ while for the wet grass conditions a good approximation of the $\mu(\lambda)$ curve is obtained with $\mu_0 = 0.015,\ \ \mu_2 = 13.6.$ The plot of the $\mu(\lambda)$ curves in these particular situations are given in Fig. 1.

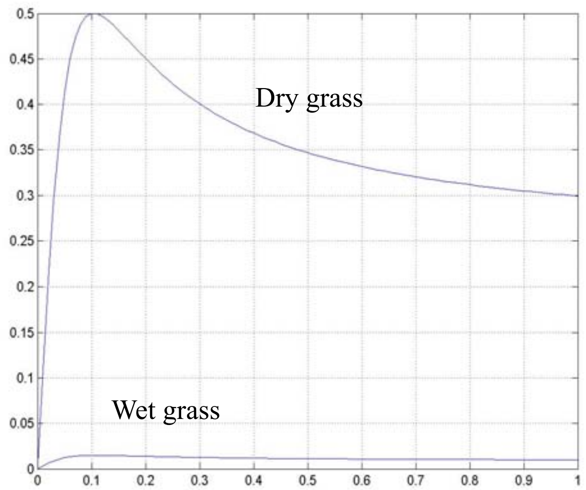

Fig. 1: Friction as a function of the slip ratio.

Now we are in a position to formulate the complete model for the electric vehicle dynamics based on a system of differential-algebraic equations discussed above. The system couples together mechanical and electrical parts of the EV and accounts for the general nonlinear slip phenomena. Note also that the procedure developed in the next section remains practically the same if other than (12) algebraic equations are used to approximate $\mu(\lambda)$ curves.

4. Differential-algebraic models for electric vehicle dynamics

The motion of the electric vehicles is considered here with due regard to the electromechanical coupling. This fact would allow us to achieve an efficient control of the system. In order to describe the basic principles of the model construction and its numerical solution, firstly we consider the motion of an electric vehicle on a flat surface. The system developed in the previous section can be re-written in this case in several different forms. We write the resulting system in terms of the following variables

$$y_1 \equiv V_{w},\ y_2 \equiv V,\ y_3 \equiv \lambda,\ y_4 \equiv \mu,\ y_5 = P, \tag{13}$$

as follows

$$\frac{dy_1}{dt} = \frac{1}{M_w}\left(\frac{y_5}{y_1} - y_4 Mg\right), \tag{14}$$

$$\frac{dy_2}{dt} = \frac{1}{M} y_4 g M_w, \tag{15}$$

$$0 = -y_3 + \min\left(|1 - \frac{y_2}{y_1}|, |1 - \frac{y_1}{y_2}|\right), \tag{16}$$

$$0 = -y_4 + \mu_0 \sin\{\mu_1 \arctan[\mu_2((1-\mu_3)y_3 + \frac{\mu_3}{\mu_2}\arctan(\mu_2 y_3))]\}, \tag{17}$$

$$0 = -y_5 + \frac{y_1}{r} i_{a.} \tag{18}$$

This is a differential-algebraic system, and the degree of its singularity in the most general case is expressed in terms of nipoltency of the associated matrix pencils. Recall that if differential and algebraic components of such systems are included in one vector $y^T = [x^T, z^T]$, then the typical scenarios we have to deal with for such problems are

$$F(y, y', t) = 0,\ Ay' + f(y,t) = 0, \tag{19}$$

$$x' = f(x,z,t)\ \ and\ \ g(x,z,t) = 0, \tag{20}$$

giving general representations for the fully implicit, linear implicit, and semi-explicit models. The system (14)—(18) is semi-explicit, in which case the degree of singularity can be characterized by the notion of index. The numerical solution of system (14)—(18) has been performed by the Gear backward differentiation methodology as well as by the Rosenbrook method, available in MATLAB-6. An iterative scheme for the solution of (14)—(18) has been also developed, and the analysis of its convergence has been conducted.

5. Computational results: flat surface cases

The electric vehicle motor has to be able to produce a high torque in the low-speed region and to be able to work in a wide-speed range of practically constant power in the high-speed region. The basic insight into the problem can be obtained by recalling that torque-speed profiles for electric motors have constant-rate torques up to the so-called base angular velocity (in the case of our electric mower it is $\omega_{base} = 7.685[rad/s]$) at which the motor reaches its power limit (in our case $P_{\max} = 1300[W]$). Then the motor is still operational, but with practically constant power, until the maximum angular velocity is reached (in our case $\omega_{\max} = 15.37[rad/s]$). The maximum torque of the motor we use in our investigations is $T_{\max} = 169.2[Nm]$ (under the assumptions made this is equal to the wheel torque). The other parameters of interest, not mentioned otherwise, are the mass of the wheel $M_w = 11.65[kg]$, the mass of the vehicle $M = 221.3[kg]$ (taken at 1/3 of the total mass of the mower unit), the rotational speed of the motor at maximum power $n_{\max} = 146.78[rev/s]$ and the radius of the wheel $r = 0.254[m]$. In the computations reported here we take $g = 9.82[m/s^2]$ and $k = 1[Nm/A]$.

In what follows we report some computational experiments performed for an electric triplex greens mower of the RANSOME E-PLEX type. We start from modeling vehicle dynamics for different surface conditions (e.g., dry or wet grass) and with pre-defined time-dependent currents. Firstly, we consider the acceleration of the mower on dry grass. In this case the first two algebraic equations in system (14)—(18) are simplified to

$$\lambda = 1 - V / V_w, \qquad (21)$$

$$\mu = \mu_0 \sin(\arctan(\mu_3 / \mu_2 \arctan(\mu_2 \lambda))). \qquad (22)$$

The results of computations are presented in a unified manner, where from left-to-right and then from top-to-bottom the following functions are given (a) current as a function of time, (b) power as a function of time, (c) vehicle and wheel velocities as functions of time, (d) slip ratio as a function of time, (e) friction as a function of time, and (f) friction as a function of the slip ratio.

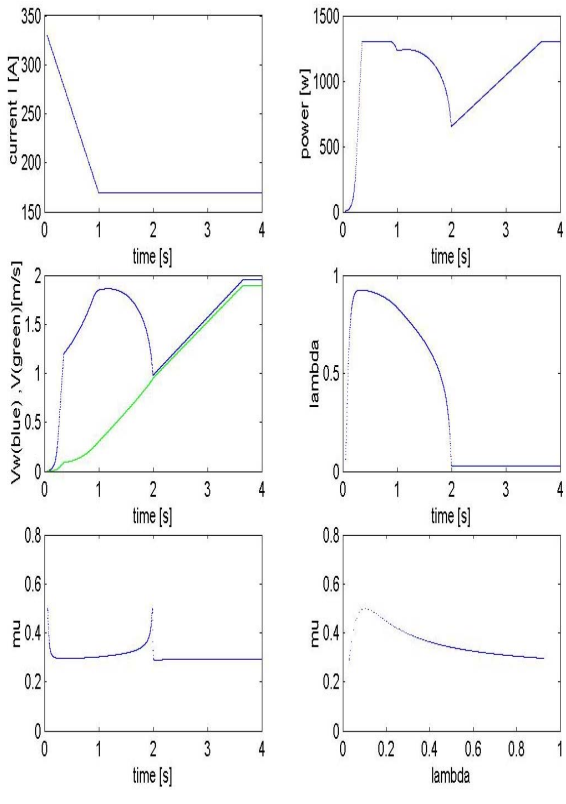

Fig. 2: Simulations for the flat, dry grass surface.

In Fig.2 simulation results of the mower performance on dry grass are given. While we have to deal with a quite large slip ratio during the first two seconds of the mower operation, after this period the wheel and vehicle velocities are maintained practically the same under very small slip ratio. This cannot be achieved under the same conditions on wet grass without adjusting the current.

A more difficult case deals with changing surface conditions (within a single experiment) for different current dynamics. Our first computational experiment dealing with such situations is the mower motion from dry to wet grass. Consider the situation where the mower starts on wet grass but after the first two seconds it moves to the wet grass area. The difficulty in dealing with such situations can be clearly seen from the dynamics of slip ratio (see Fig.3).

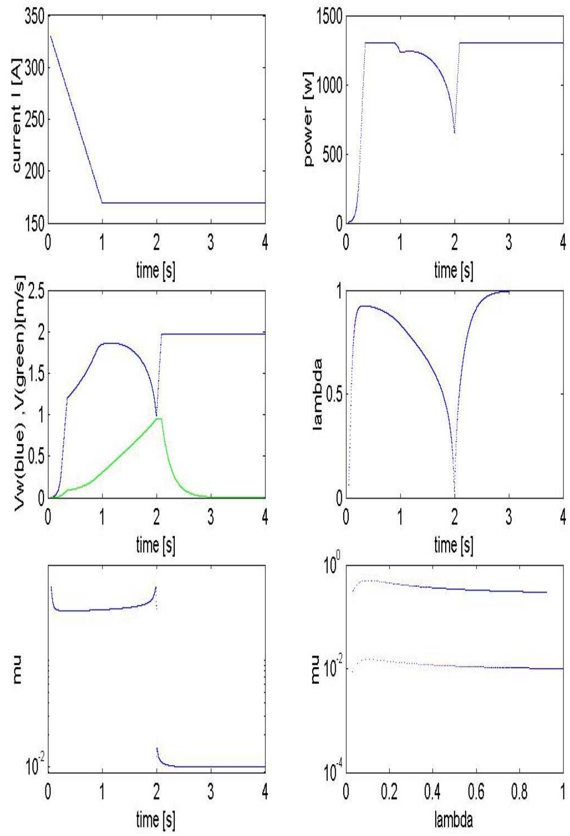

Fig. 3: Changing surface properties.

Indeed, after starting its decreasing path on the dry grass, the slip ratio increases again quickly as soon as the mower enters the wet grass area. In such situations what is needed is the appropriate choice of the current.

6. Computational experiments with changing topography of the surface

Even on golf courses, where the electric triplex greens mower we are dealing with is frequently used, one has to deal with changing topography, and therefore the model used in the previous section has to be modified accordingly to account for possibilities of changing inclinations of the surface. Typically, the maximum angle of inclination of a hilly surface of golf courses does not exceed 25^0. If topography changes are to be taken into account, the sign of the vehicle gravitational force component should be adapted according to these changes so that the traction force is defined now as

$$F_d = \begin{cases} F_r - F_{inc}, \; \textit{for uphill situations}, \\ F_r + F_{inc}, \; \textit{for downhill situations}, \end{cases} \quad (23)$$

where $F_{inc} = Mg\sin\theta$, and the friction force is now $F_r = \mu Mg\cos\theta$ with θ being the angle of inclination. In both cases the algebraic equations of the model remain unchanged, while the differential equations should account for the additional force F_d defined by (23), and therefore they can be re-written as

$$\frac{dV_w}{dt} = \frac{1}{M_w}\left(\frac{P}{V_w} - \left(\mu Mg\cos\theta - Mg\sin\theta\right)\right), \quad (24)$$

$$\frac{dV}{dt} = \mu g\cos\theta - g\sin\theta. \quad (25)$$

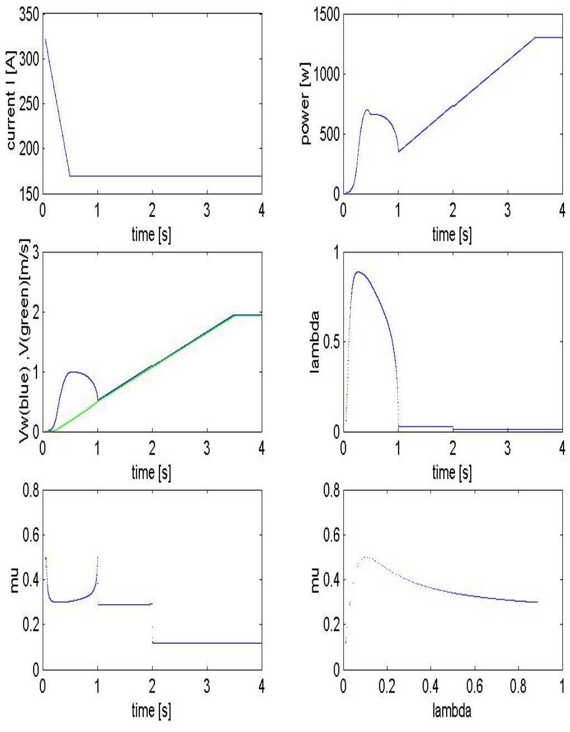

Fig. 4: Downhill on the dry grass surface.

For relatively small angles (e.g., we have considered the case of $\theta = 10^0$ on dry grass surfaces), after an initial increase in slip ratio, there are no problems in maintaining the wheel velocity at the same level as the vehicle velocity for the same definition of current as considered in the previous examples. As for downhill cases, system (24)—(25) needs to be slightly modified

$$\frac{dV_w}{dt} = \frac{1}{M_w}\left(\frac{P}{V_w} - \left(\mu Mg\cos\theta + Mg\sin\theta\right)\right), \quad (26)$$

$$\frac{dV}{dt} = \mu g\cos\theta + g\sin\theta. \quad (27)$$

This simple modification, required from the physics of the problem, leads to a qualitatively different situation. Indeed, since the traction force becomes smaller in the uphill situation compared to the flat-surface case, one would expect that the problems related to slip phenomena become more severe in that situation which has been observed in our computational experiments. However, in the downhill situation, the positive sign of F_{inc} will offset severity of the slip phenomena when and if they happen. This is demonstrated by Fig. 4 where the results of computations for $\theta = -10^0$ for the dry grass conditions are presented.

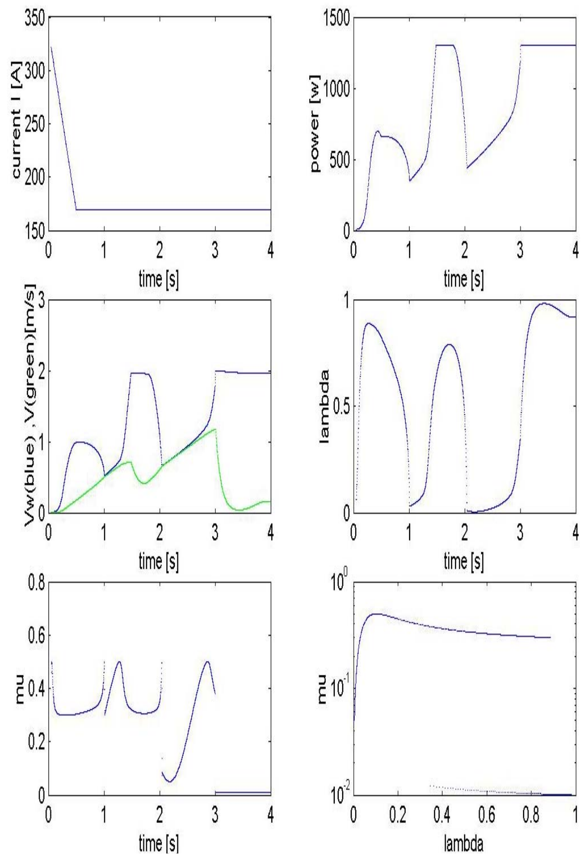

Fig. 5: Changing surface properties and topography.

After these considerations a general case of electric vehicle performance on different surfaces and over varying topographies can be considered. For example, different combinations of the situations considered above can be modeled with θ being a function of time. The situation becomes quite difficult if the surface conditions change. Indeed, if, for example, for the first second the mower operates on the dry flat surface ($\theta = 0^0$) and then topography changes as $\theta = 14\sin(4(t-1))$, and, in addition, after three seconds of operation on the dry grass the mower enters the wet grass area, the mower cannot be effectively operated under the predefined current as discussed above. Fig. 5 demonstrates clearly difficulties in the situations like this. Note also that these difficulties do not arise under dry surface conditions (see Fig. 6).

Finally, we demonstrate that the implementation of a PI controller can deal effectively with the most difficult situations considered so far. The implementation of the controller is based on controlling the current in this electromechanical system. Our final result is given for different surface conditions and for different topographies (see Fig. 7). As it is seen, with the controller implementation it is easy to maintain the velocity of the wheel at the vehicle velocity level, and therefore prevent slip phenomena.

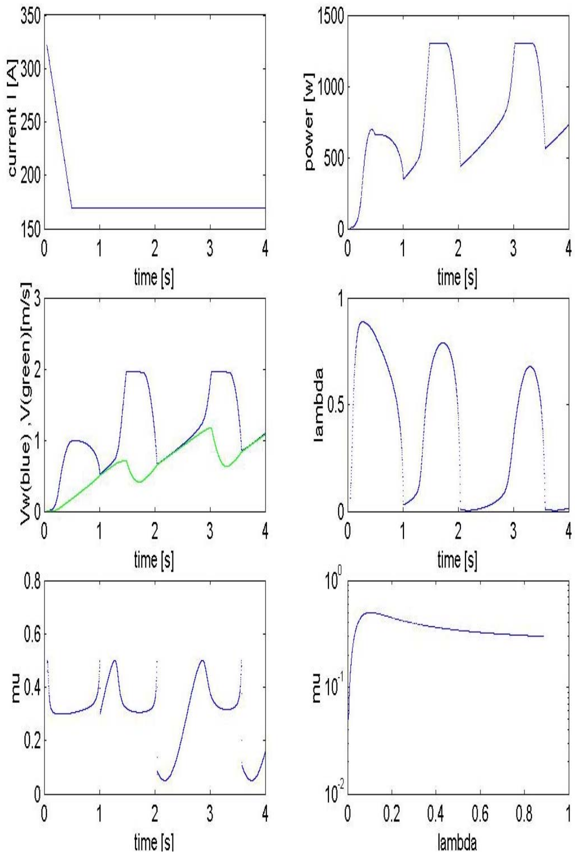

Fig. 6: Changing topography of the dry grass surface.

7. Concluding remarks

In this paper electric vehicles have been considered as fully coupled electromechanical systems, and their dynamics has been studied with due account for slip phenomena. The problem has been formulated as a system of differential-algebraic equations coupling electric and mechanical parts of the system, and the nonlinear dependency of the normalized traction force on the slip ratio has been implemented into the model in such a way that discrepancies of linear models have been eliminated. The analysis of the resulting system has been carried out by using three algorithms, the Gear backward differentiation formula, a modified Rosenbrock formula of order two, and an in-house developed iterative scheme. In the analysis of EVs performance the system has been solved for different situations of interest, giving the possibility of controlling the slip by the current of the in-wheel electric motor. In particular, we have investigated in detail the dynamics of electric mowers with in-wheel drive systems in typical situations, including practically important cases of changing topography of the surface and changing the surface conditions.

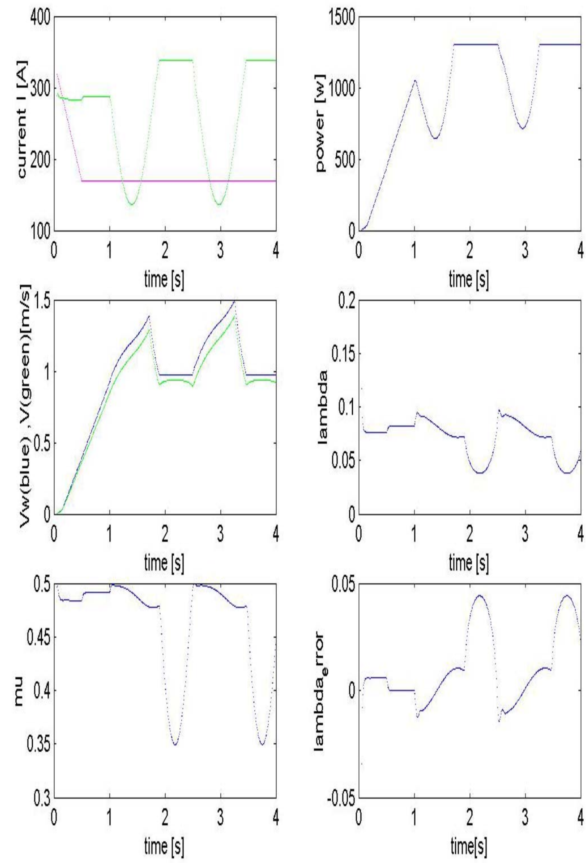

Fig. 7: Mower control for different topographical surfaces with varying properties.

References

[1] Gustafsson, F., Slip-based tire-road friction estimation, Automatica, 33(1997), pp.1087—1099.
[2] Haskara, I., Ozguner, U., and Winkelman, J., "Wheel slip control for antispin acceleration via dynamic spark advance", Control Eng. Practice, Vol.8 (2000), pp.1135—1148.
[3] Sakai, S., Hori, Y., Advanced motion control of EV with fast minor feedback loopes: basic experiments using the 4-wheel motored EV "UOT Electric March II", JSAE Review, Vol. 22(2001), pp.527—536.
[4] Solero, L. et al, Nonconventional three-wheel EV for urban mobility, IEEE Trans. On Vehicular Technology, Vol. 50(2001), pp.1085—1091.
[5] Wang, J.Y., Theory of Ground Vehicles, 3rd Ed., John Wiley Wiley & Sons, 2001.

6th International Conference on Mechatronics Technology

September 29-October 3, 2002
Kitakyushu Science and Research Park
Kitakyushu, Fukuoka, JAPAN

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ICMT2002
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MITSUBISHI CHEMICAL CORPORATION
700MB CD-R
Proceedings of
6th International Conference on Mechatronics Technology
September 29 - October 3, 2002
Kitakyushu, JAPAN
MITSUBISHI