Linear Speed Control for Multi-Machine system Using Fuzzy-Sliding Mode

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Abstract:
In this contribution, a control scheme based on multi input multi output Fuzzy Sliding Mode control (MIMO-FSMC) for linear speed regulation of multi-motors system is proposed. Once the decoupled model of the multi-motors system is obtained, a smooth control function with a threshold was chosen to indicate how far the state from to the sliding surface is. However, the magnitude of this control function depends closely on the upper bound of uncertainties, and this generates chattering. So, this magnitude has to be chosen with great care to obtain high performances. Usually the upper bound of uncertainties is difficult to known before motor operation, so, a Fuzzy Sliding Mode controller is investigated to solve this difficulty; a simple Fuzzy inference mechanism is used to reduce the chattering phenomenon by simple adjustments. A simulation study is carried out and shows that the proposed controller has great potential for use as an alternative to the conventional sliding mode contro.

Keywords*: multi-motors system, fuzzy logic, sliding mode control, MIMO*

1. Introduction

The systems handling web material such as textile, paper, polymer or metal are very common in the industry. The modelling and the control of multi-motors systems have been studied already for several decades [1]. The increasing requirement on control performance, however, and the handling of thinner web material led us to search for more sophisticated control strategies. One of the objectives in such systems is to increase web velocity as much as possible, while controlling web tension over the entire production line. This requires decoupling between web tension and speed, so that a constant tension can be maintained during speed changes [2, 3]. The decoupled adaptive fuzzy Sliding Mode Control (SMC) for robotic manipulators. This controller is proposed for a class of Multiple-Input Multiple-Output (MIMO) systems with unknown non-linear dynamics. Indeed, an online fuzzy adaptation scheme is suggested to approximate unknown non-linear functions to design SMC [4]. The stable adaptive fuzzy sliding-mode controller is developed in [5] for nonlinear multivariable systems with unavailable states. When the system states are not available, the estimated states from a semi high gain observer are used to construct the output feedback fuzzy controller by incorporating the dynamic sliding mode. It is proved that uniformly asymptotic output feedback stabilization can be achieved with the tracking error approaching to zero. The design and application of an adaptive fuzzy total sliding-mode controller (AFTSC) are addressed in [6]. The proposed control scheme comprises a special fuzzy sliding-mode controller and an adaptive tuner. The former is a main controller, which is designed without reaching phase to retain the merits of a total sliding-mode control approach. In this work the design of fuzzy sliding-mode (FSMC) to control a multi-motors system are proposed in order to improve the performances of the control system, which are coupled mechanically, and synthesis of the robust control and their application to synchronize the five sequences and to maintain a constant mechanical tension between the rollers of the system [7]. In this contribution, based on fuzzy variable structure control concept, the authors introduced a control scheme for the design and the tuning of fuzzy logic controllers with an application to winding system. To show the benefits of the MIMO-FSMC, simulation results comparing the performance of the proposed controller with that of Single-Input Single-Output Sliding Mode Controller (SISO-SMC) and with that of the conventional Multi-Input Multi-Output Proportional and Integral (MIMO-PI) controller are presented. The results obtained confirm that the proposed control structure improves the performance and the robustness of the drive system.

The model of the winding system and in particular the model of the mechanical coupling are developed and presented in Section II. Section III shows the development of sliding mode controllers design for winding system. The proposed MIMO fuzzy sliding mode control is given in the section IV. Section V shows the Simulation results using Matlab Simulink of different studied cases. Finally, the conclusion is drawn in Section VI.

2. System model's

In this system, the motor M1 carries out unreeling, M3 drives the fabric by friction and M5 is used to carry out winding, each one of the motors M2 and M4 drives two rollers *via* gears "to grip" the band (Fig.1). Each one of M2 and M4 could be replaced by two motors, which each one would drive a roller of the stages of pinching off. The elements of control of pressure between the rollers are not represented and not even considered in the study. The stage of pinching off can make it possible to isolate two zones and to create a buffer zone [8, 9]. The objective of these systems is to maintain the tape speed constant and to control the tension in the band.

The used motors are three phase induction motors type which each one is supplied by an inverter voltage controlled with Pulse Modulation Width (PWM) techniques.

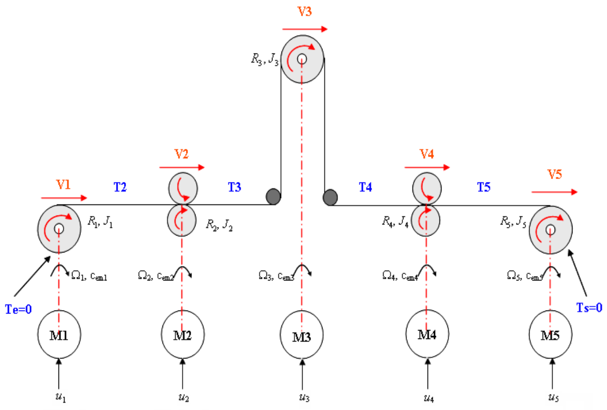

Fig. 1. Five motors web transport system

A model based on circuit equivalent equations is generally sufficient in order to make control synthesis. The electrical dynamic model of three-phase Y-connected induction motor can be expressed in the d-q synchronously rotating frame as [13]:

$$\left\{\begin{array}{l} \dfrac{di_{ds}}{dt} = \dfrac{1}{\sigma \cdot L_s}\left(-\left(R_s + \left(\dfrac{L_m}{L_r}\right)^2 \cdot R_r\right)\cdot i_{ds} + \sigma L_s \omega_e i_{qs} + \cdots \right. \\ \qquad \left. \dfrac{L_m \cdot R_r}{L_r^2}\cdot \varphi_{dr} + \dfrac{L_m}{L_r}\cdot \varphi_{qr}\cdot \omega_r + V_{ds}\right) \\ \dfrac{di_{qs}}{dt} = \dfrac{1}{\sigma \cdot L_s}\left(-\sigma L_s \omega_e i_{ds} - \left(R_s + \left(\dfrac{L_m}{L_r}\right)^2 \cdot R_r\right)\cdot i_{qs} - \cdots \right. \\ \qquad \left. \dfrac{L_m}{L_r}\cdot \varphi_{dr}\cdot \omega_r + \dfrac{L_m \cdot R_r}{L_r^2}\cdot \varphi_{qr} + V_{qs}\right) \\ \dfrac{d\varphi_{dr}}{dt} = \dfrac{L_m \cdot R_r}{L_r}\cdot i_{ds} - \dfrac{R_r}{L_r}\cdot \varphi_{dr} + \left(\omega_e - \omega_r\right)\cdot \varphi_{dr} \\ \dfrac{d\varphi_{qr}}{dt} = \dfrac{L_m \cdot R_r}{L_r}\cdot i_{qs} - \left(\omega_e - \omega_r\right)\cdot \varphi_{dr} - \dfrac{R_r}{L_r}\cdot \varphi_{qr} \\ \dfrac{d\omega_r}{dt} = \dfrac{P^2 . L_m}{L_r . J}.\left(i_{qs}.\varphi_{dr} - i_{ds}.\varphi_{qr}\right) - \dfrac{f_c}{J}.\omega_r - \dfrac{P}{J}.T_l \end{array}\right. \tag{1}$$

Where σ is the coefficient of dispersion and is given by:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{2}$$

By using of Hooke's law, Coulomb's law, mass conservation law and the laws of motion for each rotating roll the mechanical part model of the system is given by the two following parts equations [8, 9]:

Part 1: Tension model between two consecutive rolls

$$\left\{\begin{array}{l} L_1 \dfrac{dT_2}{dt} = ES(V_2 - V_1) - T_2 V_2 \\ L_2 \dfrac{dT_3}{dt} = ES(V_3 - V_2) + T_2 V_2 - T_3 V_3 \\ L_3 \dfrac{dT_4}{dt} = ES(V_4 - V_3) + T_3 V_3 - T_4 V_4 \\ L_4 \dfrac{dT_5}{dt} = ES(V_5 - V_4) + T_4 V_4 - T_5 V_5 \end{array}\right. \tag{3}$$

Part 2 :Roll velocity model

$$\left\{\begin{array}{l} \dfrac{d(J_1(t)\Omega_1)}{dt} = R_1(t)T_2 + C_{em1} - f_1(t)\Omega_1 \\ \dfrac{d(J_2(t)\Omega_2)}{dt} = R_2(t)(T_3 - T_2) + C_{em2} - f_2(t)\Omega_2 \\ \dfrac{d(J_3(t)\Omega_3)}{dt} = R_3(t)(T_4 - T_3) + C_{em3} - f_3(t)\Omega_3 \\ \dfrac{d(J_4(t)\Omega_4)}{dt} = R_4(t)(T_5 - T_4) + C_{em4} - f_4(t)\Omega_4 \\ \dfrac{d(J_5(t)\Omega_5)}{dt} = R_5(t)(-T_5) + C_{em5} - f_5(t)\Omega_5 \end{array}\right. \tag{4}$$

$k = 2, 3, 4, 5.$
Lk−1 is the web length between roll k−1 and roll k;
Tk is the tension on the web between roll k−1 and roll k;
Vk is the linear velocity of the web on roll k;
$\Omega_k = \omega_k \cdot P$: The rotational speed of roll k;
Rk is the radius of roll k;
E is the Young modulus;
S is the web section;
$C_{emk} = \left(i_{qs}^k.\varphi_{dr}^k - i_{ds}^k.\varphi_{qr}^k\right)$ is the k-th motor torque,
f_k is the friction torque of k-th motor torque.

3. Sliding mode control

The sliding mode control consists in moving the state trajectory of the system toward a predetermined surface called sliding or switching surface and in maintaining it around this latter with an appropriate switching logic. In the case of the nth-order system, the sliding surface could be defined as [12]:

$$S(x) = \left(\frac{\partial}{\partial t} + \lambda\right)^{n-1} \cdot e(x) \tag{5}$$

Where $\lambda > 0$

The control law is divided into two parts, the equivalent control Ueq and the attractivity or reachability control Un. The equivalent control is determined off-line with a model that represents the plant as accurately as possible. If the plant is exactly identical to the model used for determining Ueq and there are no disturbances, there would be no need to apply an additional control Un. However, in practice there are a lot of differences between the model and the actual plant. Therefore, the control component Un is necessary which will always guarantee that the state is attracted to the switching surface by satisfying the condition [12]:

$$\dot{S}(x) \cdot S(x) < 0$$

Therefore, the basic switching law is of the form:

$$U = U_{eq} + U_n \tag{6}$$

With $U_n = -M(\cdot) \cdot \mathrm{sgn}(S(\cdot))$

M(S): the magnitude of the attractivity control law Un, and sgn is the sign function

In a conventional variable structure control, Un generates a high control activity. It was first taken as constant, a relay function, which is very harmful to the actuators and may excite the unmodeled dynamics of the System. This is known as a chattering phenomenon. Ideally, to reach the sliding surface, the chattering phenomenon should be eliminated [12, 13]. However, in practice, chattering can only be reduced.

4. MIMO fuzzy sliding mode control (MIMO-FSMC)

Consider the class of nonlinear time varying systems described by the equations:

$$x_j^{(n)} = f_j(X_1,\cdots,X_m) + b_j(X_1,\cdots,X_m)u_j + d_j(t) \quad (7)$$

$$y_j = x_j \quad (8)$$

$X_j = \left[x_j, \dot{x}_j, \cdots, x_j^{(n-1)}\right]^T$: the j-th components of the state vector.

$$X = [X_1, \ldots.., X_m]^T$$

u_j is the j-th control input and y_j is the j-th system output

In (7) the function fj , the control gain bj, and the disturbance dj are assumed to be unknown.

The dynamics of (7) describe a large number of nonlinear systems encountered in practice, including a vast class of controllable nonlinear systems that could be converted into (7) by using appropriate transformations.

Then we can write a state space representation of (7) in terms of $e_j = x_j^* - x_j$ ($x_j^* = \text{constant}$), and its derivatives:

$$\begin{cases} \dot{e}_{j1} = e_{j2} \\ \dot{e}_{j2} = e_{j3} \\ \vdots \\ \dot{e}_{jn-1} = e_{jn} \\ \dot{e}_{jn} = -f_j(X) - b_j(X)\ u_j - d_j(t) \end{cases} \quad (9)$$

Where: $e_{j1} = \dot{e}_j, \ldots, e_{jn} = e_j^{(n-1)}$ and $x_{j1} = \dot{x}_j, \ldots, x_{jn} = x_j^{(n-1)}$

The fuzzy system rule base for control bandwidths λ_i is defined as follows

Rule 1: IF $e_i \in R_i^1$ THEN $\lambda_i = \lambda_i^1$
Rule2: IF $e_i \in R_i^2$ THEN $\lambda_i = \lambda_i^2$ (10)
$\vdots$
Rule j: IF $e_i \in R_i^j$ THEN $\lambda_i = \lambda_i^j$

Where $j = 1, \ldots, r_i$

Where e_i is the traking error for the i th system variable, and r_i is the total number of rules for the i th system variable. In (10), R_i^j is the j th fuzzy set on the i th universe of discourse, Characterized by membership function $u_i^j(e_i)$.

Therefore, each tracking error e_i , a fuzzy system is built such that each rule j has a specific control bandwidth in the consequent part. The aggregate control bandwidth λ_{i_f} is obtained by center average defuzzification and can be viewed as a nonlinear interpolation between linear mappings:

$$\lambda_{i\_f} = \frac{\sum_{j=1}^{r_i} u_i^j \lambda_i^j}{\sum_{j=1}^{r_i} u_i^j} \quad (11)$$

Based on the result from (11), the resulting sliding surface is represented as:

$$S_{i\_f} = \dot{e} + \lambda_{i\_f} . e_i$$

Finally the proposed MIMO Fuzzy Sliding Mode control (MIMO-FSMC) law is

$$U = U_{eq} + U_{n-f} \quad (12)$$

$$U_{eq}(x,t) = -D(t,x)^{-1} \cdot F(t,x)$$

$$U_{n-f}(x,t) = -\alpha_i \left[sat\left(\frac{S_{1\_f}}{\varphi_1} \ \cdots \ \frac{S_{i\_f}}{\varphi_i} \ \cdots \ \frac{S_{n\_f}}{\varphi_5} \right) \right] \quad (13)$$

The Fig. 2 shows the SMC control strategy scheme for each induction motor

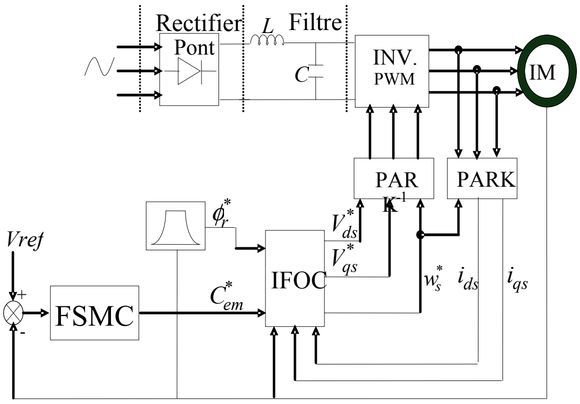

Fig. 2. Block diagram for each motor with FSMC control

5. Simulation results

The winding system we modeled is simulated using MATLAB SIMULINK software and the simulation is carried out on 10s.

To evaluate system performance we carried out numerical simulations under the following conditions:

Start with the linear velocity of the web of 5m / s.

The motor M1 has the role of Unwinder a roll radius R1 (R1 = 2.25 m).

The motors M2, M3, M4 are the role is to pinch the tape.

The motor M5 has the role of winding a roll of radius R5. The aims of the STOP block is to stop at the same time the different motors of the system when a radius adjust to a desired value (for example R5 = 0.8 m), by injecting a reference speed zero.

The comparison between the two controllers SISO-FSMC and MIMO-FSMC is achieved in the two cases:

Comparison of the control performances: it has been made by the comparison of the average speeds of the five motors Vavg, for each controller this average is expressed by the equation (14).

Comparison of synchronism between the speeds of the five motors: in this point one makes a comparison between the deviation standard of speeds of five motors Vstd, for each controller this average is expressed by the equation (15).

$$V_{avg} = \frac{1}{n}\sum_{i=1}^{n} V_i \quad (14)$$

$$V_{std} = \left(\frac{1}{n}\sum_{i=1}^{n}(V_i - V_{avg})^2\right)^{\frac{1}{2}} \quad (15)$$

As shown in Figs. (3-5). An improvement of the linear speed is registered, and has follows the reference speed for both PI controller and FSMC control, but in case of

PI controller, the overshoot in linear speed of Unwinder is 25%. Fig (4) and Fig (5) show that with the MIMO-FSMC controller the system follows the reference speed after 0.3 sec, in all motors, however, in the SISO-FSMC and PI controller the system follows after 1.3 sec and 2 sec, respectively.

From the Figures (3-5), we can say that: the effect of the disturbance is neglected in the case of the MIMO-FSMC controller. It appears clearly that the classical control with PI controller is easy to apply. However, the control with MIMO-FSMC offers better performances in both of the overshoot control and the tracking error.

Fig. 6 and Fig. 7 show the comparison between the MIMO-FSMC controller, the SISO-FSMC controller and the MIMO-PI controller. After this comparison we can judge that the MIMO-FSMC controller presents a clean improvement to the level of the performances of control, compared to the MIMO-PI controller, the synchronism between the five motors is improved with MIMO-FSMC controller compared to SISO-FSMC controller.

6. Conclusion

The sliding mode control of the field oriented induction motor was proposed. To show the effectiveness and performances of the developed control scheme, simulation study was carried out. Good results were obtained despite the simplicity of the chosen sliding surfaces. The robustness and the tracking qualities of the proposed control system using sliding mode controllers appear clearly.

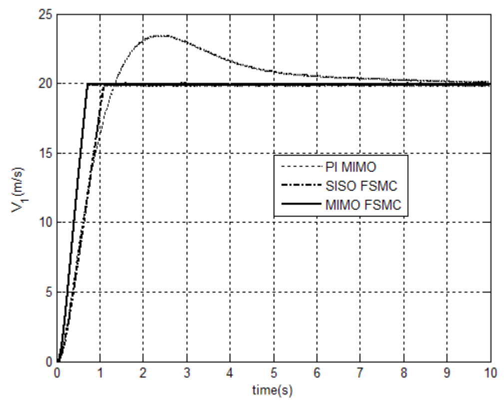

Fig. 3. The linear speed of unwinder M1

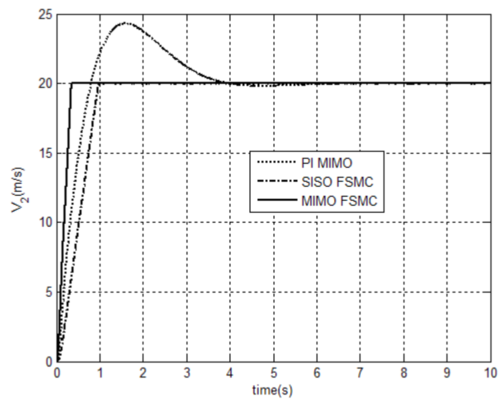

Fig 4. The linear speed of motor M2

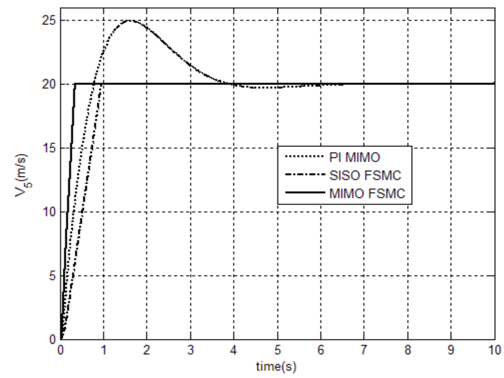

Fig. 5. The linear speed of winder M5

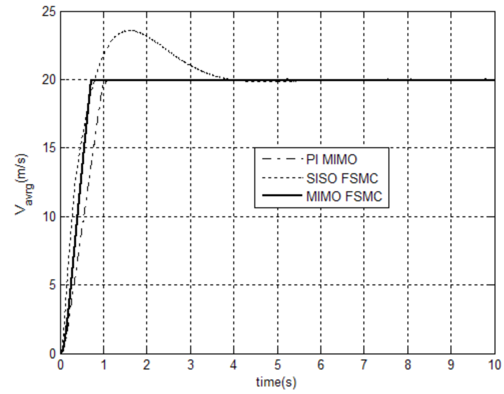

Fig. 6. comparison between the MIMO-FSMC, SISO-FSMC and PI MIMO with average speeds of five motors

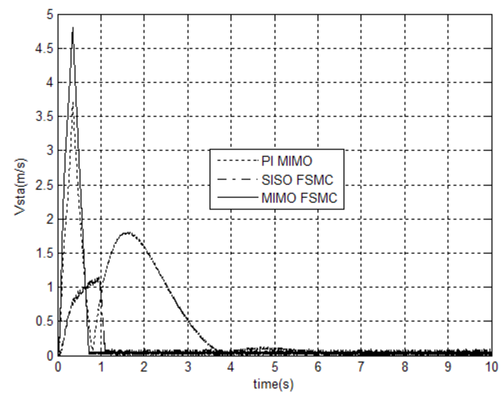

Fig. 7. Comparison between the MIMO-FSMC, SISO-FSMC and PI MIMO with the deviation standard of speeds of five motors

Furthermore, in order to reduce the chattering, due to the discontinuous nature of the controller, fuzzy logic controllers were added to the sliding mode controllers.

These gave good results as well and simplicity with regards to the adjustment of parameters.

The simulations results show the efficiency of the FSMC-MIMO controller technique, however the strategy of FSMC-MIMO Controller brings good performances, and she is more efficient than the FSMC-SISO controller and classical PI-MIMO controller.

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References:

1. Christian Thiffault Pierre Sicard Alain Bouscayrol, "Tension Control Loop Using A Linear Actuator Based On The Energetic Macroscopic Representation", CCECE 2004–CCGEI 2004, Niagara Falls, May 2004.
2. S. Charlemagne, A. Bouscayrol, Slama Belkhodja, J.P. Hautier, "Flatness based control of non-linear textile multimachine process". In: *Proc. of EPE'03*, CD-ROM, Toulouse (France), September 2003.
3. Adlane Benlatreche Dominique Knittel "State Feedback Control with Full or Partial Integral Action for Large Scale Winding Systems". In: *Industry Applications Conference*, Oct. 2005, vol. 2, pp. 973-978.
4. Hanène Medhaffar, Nabil Derbel ,Tarak Damak "A decoupled fuzzy indirect adaptive sliding mode controller with application to robot manipulator", *Int. J. Modelling, Identification and Control*, vol. 1, no. 1, 2006.
5. Shaocheng Tong and Han-Xiong Li "Fuzzy Adaptive Sliding-Mode Control for MIMO Nonlinear Systems", *IEEE Transactions on Fuzzy Systems*, vol. 11, no. 3, June 2003, pp. 354-360.
6. Chung-Chun Kung, Kuo-Ho Su and Lun-Ping Hung "Adaptive Fuzzy Total Sliding-Mode Controller Design and Its Application to Tension Control of a Winding process". In: *2006 IEEE International Conference on Systems, Man, and Cybernetics,* 8th–11th October, 2006, Taipei, Taiwan, pp. 3659-3664.
7. Rahmi Guclu "Sliding mode and PID control of a structural system against earthquake", *Mathematical and Computer Modeling*, vol. 44, issues 1–2, 2006, pp. 210-217.
8. Hakan Koç, Dominique Knittel, Michel de Mathelin, and Gabriel Abba, "Modeling and Robust Control of Winding Systems for Elastic Webs", *IEEE Transactions on Control Systems Technology*, vol. 10, no. 2, March 2002, pp. 197-208.
9. H. Koc, "Modélisation et commande robuste d'un system d'entrainement de bande flexible", Ph.D. thesis, Université Louis Pasteur (Strasbourg I University), 2000.
10. Zhongze Chen Changhong Shan Huiling Zhu "Adaptive Fuzzy Sliding Mode Control Algorithm for a Non-Affine Nonlinear System ", *IEEE Transactions on Energy Conversion*, vol. 19, issue 2, 2004 , pp. 362-368.
11. Yujie Zhao, Qingli Wang, Jinxue Xu, Chengyuan Wang, "A Fuzzy Sliding Mode Control Based on Model Reference Adaptive Control for Permanent Magnet Synchronous Linear Motor". In: *2nd IEEE Conference on Industrial Electronics and Applications – ICIEA 2007*, pp. 980-984.
12. Chien-An Chen, Huann-Keng Chiang, Chih-Huang Tseng, "The Novel Fuzzy Sliding Mode Control of Synchronous Reluctance Motor". In: *8th International Conference on Intelligent Systems Design and Applications – ISDA'08*, vol. 1, 2008, pp. 576-581.