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Library of Samples for E-Vehicle Propulsion Drive Tuning

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***Abstract* – The majority of testing cycles for the vehicle comparison is the long-term cycles and could not be used for the short-term transient mode imitations. Also, all the used nowadays testing cycles were designed for internal combustion engine vehicles and take into account not only energy and mechanical aspects, but also pollution and internal combustion engine characteristics. The paper presents a collection of sample signals developed to explore and simulate multiple system impacts to emulate different reference and load conditions. The study describes the major driving modes, such as the constant-speed cruising, speeding up and braking, typical parking regimes, uphill and downhill motion, and taking a turn. The developed testing equipment and software are described. Responses of the battery vehicle drives to the changeable controls and disturbances were studied in the laboratory test bench. The set of test cycles prepared in the frame of the ABB control arrangement was applied to the system evaluation and assessment. The developed methodology can be recommended to adjust the electric drives for different kinds of testing equipment. Experimental validation of the described approach has demonstrated the broad possibilities for the steady-state and transient modes of vehicle quality evaluation. It suits for recommendations that can be made with regard to the tuning of the drive regulators, control looping, sensor allocation, and feedback arrangements.**

***Keywords* – Automotive applications; Electric vehicles; Test equipment; Variable speed drives.**

I. INTRODUCTION

There is no order of merit or checklists of essential requirements appropriate to every electric drive or even to most of them. Such demands are very diverse for a broad range of driving applications. Also, the relative weighting of importance of various features should alternate among particular areas. As the drive use differs according to the field, such properties as the steady-state and transient accuracy, speed range, surge resistance capability, weight, or size are often decisive properties. In this connection, the problem can be considered from two points of view. The former deals with rational economic and technical judgments whereas the latter involves specific electromechanical and adjustment estimations. This paper studies the electric drive of automotive applications, particularly hybrid electric vehicles and electric vehicles (HEV/EV) for which a specific test bench has been designed.

According to a recent literature review concerning the HEV/EV drives, drive quality is mostly estimated from the viewpoint of economic and technical efficiency. In [1], [2], [3] the first feature of propulsion quality is the capital cost. The major problem in [4] is the drive power density resulting from the system size and weight. The third integral mark strongly associated with the capital cost of HEV/EV is the drive reliability. For this reason, the squirrel-cage induction motors and the permanent magnet reluctance motors are recommended in [5] – [8] as more reliable and required less maintenance than any other machine. Moreover, many studies, for instance [9] – [15], discuss the efficiency as the significant factor of the HEV/EV drive quality. In order to validate most of these indicators in the test benches the New European Driving Cycle (NEDC) is commonly used ([4], [5], [16], [17]).

Conversely, effective control considerations have not found proper attention in literature. Nevertheless, the control quality above all affects the vehicle mobility, driving suitability and ease, parking accuracy, and cruising stability. Therefore, focus in this paper is mostly on the requirements related to control restrictions and tuning possibilities of the HEV/EV propulsion drives. The goal is to propose a methodology for adjusting the electric drives under the test cycles different from the standard NEDC. By estimating the drive responses, the discussed methodology helps to measure the steady-state and transient vehicle quality and to recommend approaches to the drive regulator tuning, control looping, sensor allocation, and feedback arrangements.

Firstly, the set of specific HEV/EV motor drive estimations is specified. Next, some conventional drive control signals are described and their implementation in the scope of the ABB arrangement is proposed. Finally, some examples of the developed methodology are shown and recommendations are given about the use of the described approach for the drive designers and consumers.

II. QUALITY ESTIMATIONS OF THE HEV/EV DRIVES

To qualify the HEV/EV drives, different indicators have been proposed. In terms of controllability, a drive must have acceptable performance with regard to both the steady-state operation and the transient responses [18]. The steady-state operation is concerned with the accuracy of control and how closely the vehicle follows slow excursions of the control signal.

Important steady-state estimation is the rate of the system response to rapid input and load changes [19]. In power converters, the overload capacity is restricted by their heat dissipation features. Typically, for the semiconductor devices it is relatively small, but for the electrical machines this value is significant enough. The rated overload capacity of motors represents the ratio of their maximal and rated torques indicated in the datasheets whereas the practically reachable value depends on the actual control possibilities of the particular drive design. The torque rise time of the open-loop systems is about 10 ms whereas this parameter for the closed-loop drives is within 1 ms. The speed rise time is usually by an order greater. When determining the transient responses, the physical properties of the drive subsystems are of primary importance.

A speed range is another important index showing the ratio of the maximal motor speed to its minimally accessible level over the full area of disturbances [20]. In particular, to measure the speed adjustment range, the drift of the load torque should be within the expected maximal and minimal levels.

Speed regulation is also a specific feature of the drive operation. It deals with the fractional reduction of speed upon the variable load torque [21]. Nearby the zero speed regulation can be realized by the use of frequency-controlled synchronous motors or with the help of induction motors in the closed-loop control systems with a tachometric negative feedback. A rigorous specification for speed regulation may be refused in an acceptance of loss of efficiency or loss of power/weight ratio.

For various HEV/EV vehicles, the dynamometer test cycles are employed in type-approval tests for emission certification. Such test cycles are as follows: the NEDC used in Europe, JC08 applied in Japan, the UDDS (FTP-75) used in the United States. The NEDC cycle includes four urban driving cycle (ECE R-15) segments characterized by the low vehicle speed and low engine load, followed by one extra-urban segment to account for more aggressive and higher speed driving [22]. The urban driving cycle ECE-R15 is used to evaluate the tuning quality of the HEV/EV. The cycle has been designed to represent typical driving conditions of busy European cities, with a maximum speed of 50 km/h.

Fig. 1 shows the timing diagram of the test bench with open-loop drive system and applied ECE R-15 cycle. The speed reference signal is shown here with the dot-line and the measured speed with the continuous blue line. The main benefit of ECE R-15 is that it is easy to apply and repeat.

In using the ECE-15R driving cycle for the propulsion drive system tuning, some problems could be found. First, the tuning is possible only from the side of speed reference control. Second, the ECE R-15 has many constant speed cuts that are very rare in the urban driving, but can be used for steady-state mode tuning of the propulsion drive system. In the steady-state mode at the constant parameters, the drive could be tuned to achieve the best drive performance, but in the case of variable load, the drive control parameters have to be retuned according to load variation.

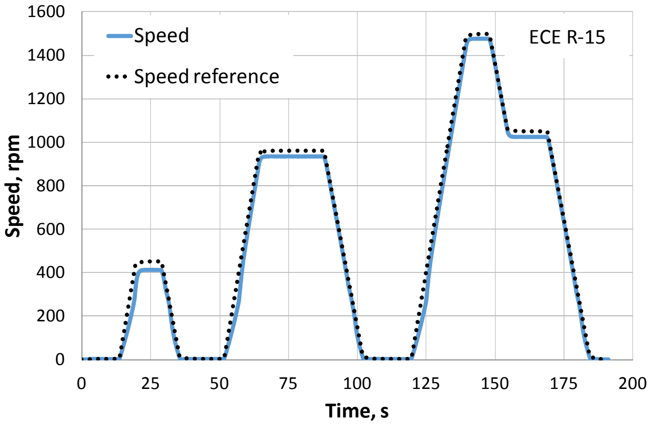

Fig. 1. Speed profile of ECE-15R driving cycle applied to the experimental setup.

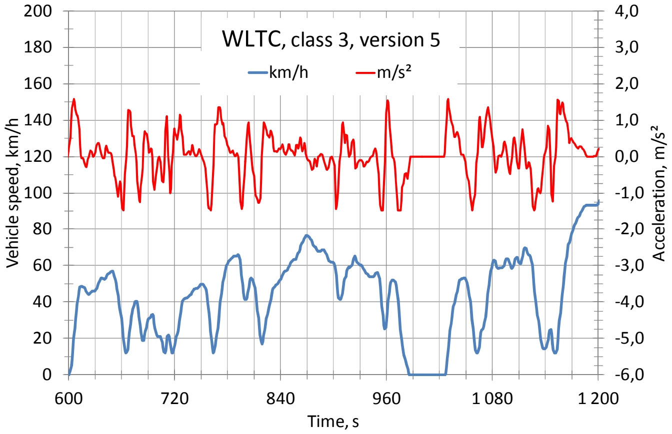

Fig. 2. Speed and acceleration profiles of WLTC.

There are some different standardization projects forwarded to develop the World-wide harmonized Light duty driving Test Cycle (WLTC), to represent typical driving characteristics around the world, and to obtain the basis for a legislative worldwide harmonized type certification test. One of the programs was launched by the World Forum for the Harmonization of Vehicle Regulations of the United Nations Economic Commission for Europe (UN-ECE) to evaluate pollution and energy consumption [22]. One cut of WLTC is presented in Fig. 2.

WLTC has some advantages in comparing with ECE R-15. Firstly, WLTC has less steady-state mode cuts during the test cycle making it more suitable for the transient analysis. Moreover, as it is shown in Fig. 2, WLTC has an acceleration function, which means the transient processes could be described more carefully and the drive load forces could be taking into account by using the dynamic torque T_{dyn},

$$T_{dyn} = J\frac{d\varpi}{dt}, \qquad (1)$$

where J is moment of inertia of the drive system and $d\varpi/dt$ is an acceleration. In spite of all WLTC benefits, it is still in development stage and cannot represent testing cycles for many typical driving characteristics. Tuning of the vehicle propulsion drive requires more careful and deep study of the processes inside the systems.

III. TESTING SOFTWARE

To estimate the abovementioned indicators, specific test cycles were designed. The library presents the family of simple tests that can be adopted to simulate multiple mechanics, thus allowing the study of different parameters and load conditions for testing and tuning of the open-ended and closed-loop drive systems. Fig. 3 shows the developed test.

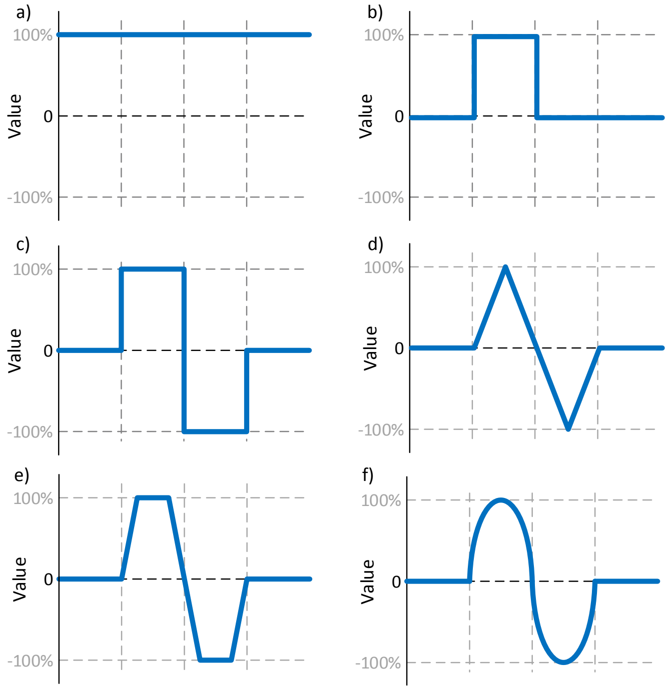

Fig. 3. Test cycles: a) constant; b) pulse; c) meander; d) triangle; e) trapeze; f) sinusoidal.

These test cycles could be adopted for both the references and the loading models of the HEV/EV traction.

A constant set-point shown in Fig. 3(a) is simulated by the step signal y^* of the required level k:

$$y^* = k\,. \tag{2}$$

Using as the speed reference, it imitates a constant-speed vehicle motion, particularly the stable cruising control mode. Using as the load reference, it imitates a constant-load vehicle motion during the highway cruising.

A rectangle pulse reference cycle given in Fig. 3(b) is represented by the permanent input k within the time slot $t \in \{0;\ t_1\}$, $t_1 < \tau$, where τ is the signal period. Within the remaining part of the period a delay is assumed:

$$\begin{cases} y^* = k, & t \in \{0;\ t_1\} \\ y^* = 0, & t \in \{t_1;\ \tau\} \end{cases}. \tag{3}$$

Using as the speed reference, is imitates the speed-up and brake modes of the vehicle travelling at self-adjusted acceleration and deceleration. In this way, some typical parking regimes are provided. As the load reference, this cycle is typical for constant-rate acceleration and deceleration.

A meander speed reference cycle presented in Fig. 3(c) corresponds to some specific parking regimes, where the drive requires fast reversing. It is simulated by the permanent signal k within the time slot $t_1 < \tau$. Within the remaining part of the period the set-point changes its sign:

$$\begin{cases} y^* = k, & t \in \{0;\ t_1\} \\ y^* = -k, & t \in \{t_1;\ \tau\} \end{cases}. \tag{4}$$

As the load reference cycle, it is typical for some variable speed driving modes.

In a triangle reference cycle, the set-point temporary rises within the first quarter of the period as shown in Fig. 3(d). Next, it drops until the last quarter of the period. Finally, it rises again:

$$\begin{cases} y^* = kt, & t \in \left\{0;\ \frac{\tau}{4}\right\} \\ y^* = y^*_{\frac{\tau}{4}} - k\left(t - \frac{\tau}{4}\right), & t \in \left\{\frac{\tau}{4};\ \frac{3\tau}{4}\right\} \\ y^* = -y^*_{\frac{\tau}{4}} + k\left(t - \frac{3\tau}{4}\right), & t \in \left\{\frac{3\tau}{4};\ \tau\right\} \end{cases}. \tag{5}$$

As a speed reference, this cycle simulates different driving modes, such as uphill and downhill vehicle operation, overtaking, and even the city-cruising between traffic lights. As a load reference, it imitates the vehicle load during overtaking, with desired acceleration.

A trapezoidal reference cycle, Fig. 3(e), is a composition of the triangle and meander reference cycles:

$$\begin{cases} y^* = kt, & t \in \{0;\ t_1\} \\ y^* = y^*_{t_1}, & t \in \{t_1;\ t_2\} \\ y^* = y^*_{t_1} - k(t_3 - t_2), & t \in \{t_2;\ t_3\} \\ y^* = -y^*_{t_3}, & t \in \{t_3;\ t_4\} \\ y^* = -y^*_{t_3} + k(\tau - t_4), & t \in \{t_4;\ \tau\} \end{cases}. \tag{6}$$

This speed reference imitates the most conventional city cruising, particularly between the traffic-lights.

Finally, a sinusoidal reference cycle, presented in Fig. 3(f), of an amplitude k_1 changes relatively the constant level k at the required frequency $\omega = 2\pi/\tau$ as follows:

$$y^* = k + k_1 \sin(\omega t), \quad t \in \{0;\ \tau\}. \tag{7}$$

Using this signal, accurate travelling up the gradient and taking a turn can be effectively simulated using the speed-reference and load-reference tests.

According to vehicle mechanics [23], the vehicle velocity, acceleration, the road slope angle, and the rolling friction mainly affect the vehicle load. This means that during manoeuvres, such as acceleration and deceleration, turning, overtaking, and the road type changing (turning from highway to country road) the load of propulsion drive is changing. During crossing the interferences on the road, like puddles or areas partially covered with ice or sand, the load could suddenly be changed for short time. Using the developed cycles, these regimes can be effectively simulated with the load-reference tests.

IV. LABORATORY STUDY OF THE HEV/EV DRIVE TUNING

The test bench developed in the Electrical Drives Laboratory of Tallinn University of Technology is based on the induction machines. Induction machines, especially the squirrel cage motors, have high reliability and low manufacturing cost, though their efficiency and torque density are not adequate. The test bench incorporates two motor drives. The testing system is based on the ABB ACS800 with the M3AA112M GAA 112022-ADC squirrel-cage induction motor (1455 rpm, 400 V, 50 Hz, 4 kW). The loading system is built on the ABB ACS611 electric drive, with an induction motor M3AA132SB 3GAA 138110-ADC (2820 rpm, 400 V, 50 Hz, 4.7 kW). To imitate the mechanical chain of a HEV/EV, the transmission shaft was used. The remaining installation equipment such as remote control buttons and measurement devices was mounted within a specially manufactured cabinet where interconnections were made through the cabling equipment. The ABB toolbox DriveWindow provides the remote control of the tested and loading drives, their tuning, monitoring, graphical trending, and registration of the drive parameters. The output data from the DriveWindow software can be presented and saved in graphical and numerical forms for the following analysis [24].

To implement the laws (2)–(7), the ABB adaptive programming methodology and the DriveAP toolkit were used [25]. The obtained results are presented in Fig. 4 to 13.

TABLE I. ANALYSIS OF DIFFERENT SPEED PROFILES OF THE TESTED DRIVE.

	Speed errors		Energy, kWh	Current, A	Control mode
	Max, %	Mean, %			
Pulse	-0.50	0.12	1.75E-04	5.69	DTC
	-1.06	0.98	2.06E-04	5.47	SCALAR
Meander	-0.49	0.11	1.49E-03	5.72	DTC
	-0.55	0.58	1.69E-03	5.42	SCALAR
Triangle	-0.97	0.05	1.42E-03	5.64	DTC
	-1.47	0.94	1.69E-03	5.41	SCALAR
Trapeze	-0.73	0.11	1.44E-03	5.66	DTC
	-1.13	0.99	1.72E-03	5.42	SCALAR
Sinusoidal	-0.49	0.04	1.38E-03	5.64	DTC
	-1.08	0.96	1.67E-03	5.40	SCALAR

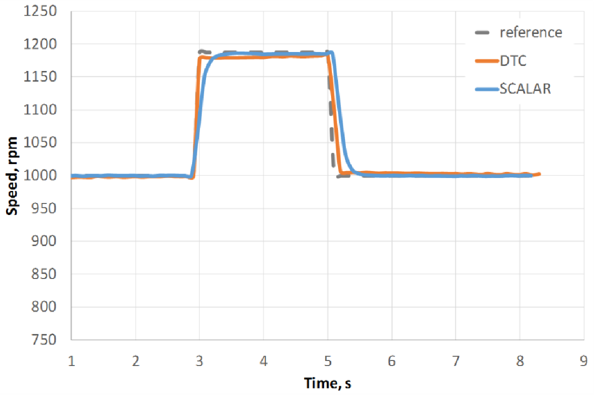

Fig. 4. Drive speed response profile around 1000 rpm at pulse test cycle.

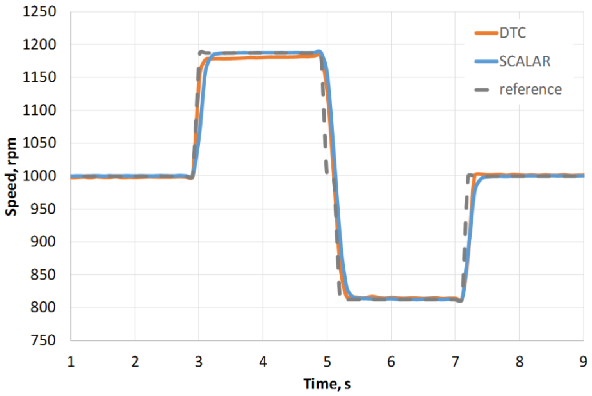

Fig. 5. Drive speed response profile around 1000 rpm at meander test cycle.

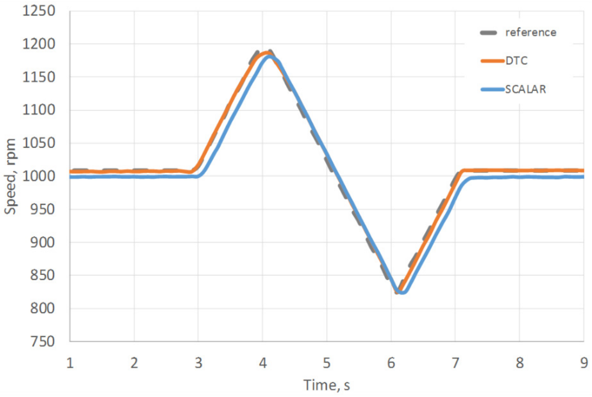

Fig. 6. Drive speed response profile around 1000 rpm at triangle test cycle.

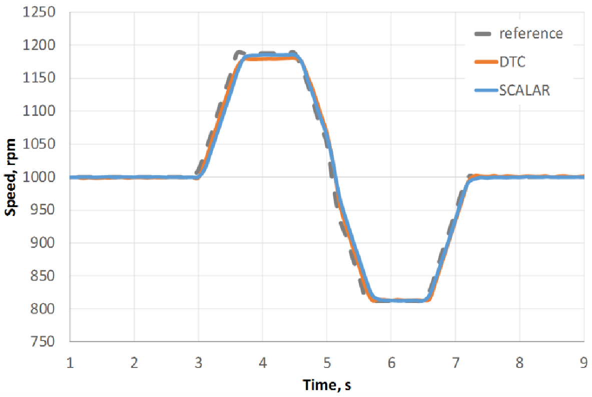

Fig. 7. Drive speed response profile around 1000 rpm at trapeze test cycle.

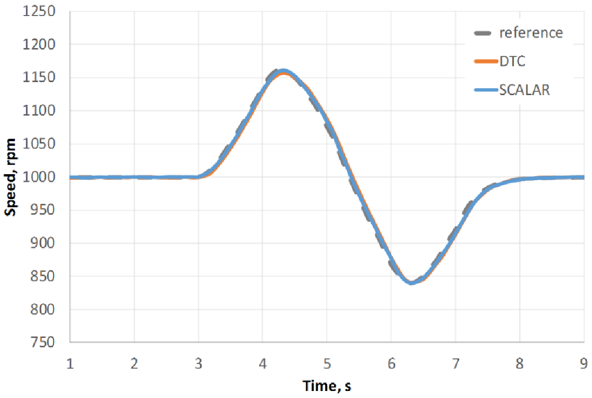

Fig. 8. Drive speed response profile around 1000 rpm at sinusoidal test cycle.

All the tests were conducted in both the sensorless closed-loop (DTC) and the open-ended (SCALAR) control modes of the testing drive running at different speeds and loads. The trials were initially performed in the closed-loop system under the proportional gain of 10 and integral gain of 0.3 without the derivative gain. The 400 ms time constant of the speed active filter was assigned. Then, the drive was tested at the SCALAR control mode with compensated slip; the load frequency value was raised to achieve revolution speed of 1000 rpm.

Fig. 4 to 8 show the traces of the drive speed responses at 1000 rpm. As it can be seen from the traces, the both systems, closed-loop and open-ended, are properly tuned. All the testing cycles are correctly executed. As a result of such tuning, good controllability of the HEV/EV propulsion drive could be achieved.

Table I compares the results of the response analysis. The Max speed error represents maximal difference between the speed reference and the real speed response in percent. The Mean speed error represents the average difference between the speed reference and the real speed response during the testing cycle; all values are shown in percent. In the Energy column, the energy consumption of testing drive was evaluated. Because of the small power of the testing drive (4 kW), differences between energy consumption in different control modes are noticeable. As there were no current spikes marked during the tests, the average values of consumed currents are presented in in the Current column.

TABLE II. ANALYSIS OF TESTED DRIVE RESPONSE ON VARIABLE LOAD PROFILES.

	Speed errors		Energy, kWh	Current, A	Control mode
	Max, %	Mean, %			
Pulse	3.67	0.0097	5.73E-04	6.42	DTC
	5.06	-0.0004	5.90E-04	7.00	SCALAR
Meander	5.13	0.0006	6.17E-04	6.34	DTC
	3.63	-0.0012	7.77E-04	5.86	SCALAR
Triangle	4.46	0.0000	5.27E-04	6.35	DTC
	2.62	0.0003	5.18E-04	5.89	SCALAR
Trapeze	4.83	0.0005	5.80E-04	6.31	DTC
	3.21	-0.0008	5.28E-04	5.87	SCALAR
Sinusoidal	3.79	-0.0001	7.05E-04	6.29	DTC
	2.39	-0.0003	5.64E-04	5.87	SCALAR

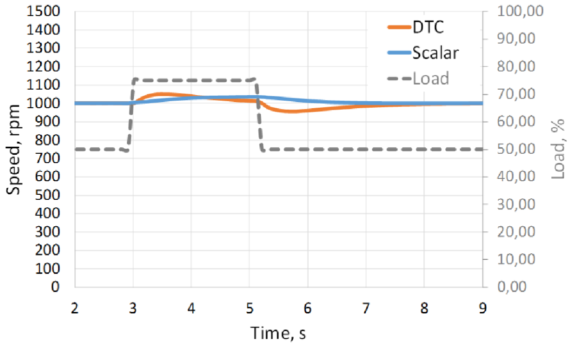

Fig. 9. Drive speed response on variable load of pulse profile.

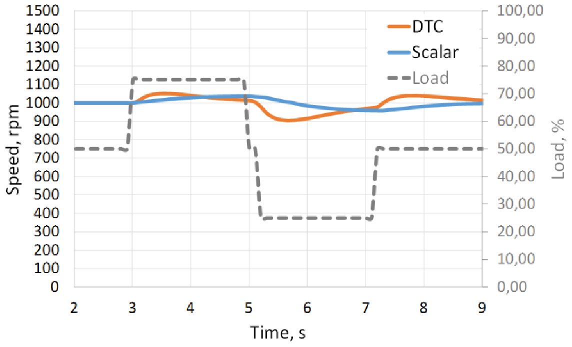

Fig. 10. Drive speed response on variable load of meander profile.

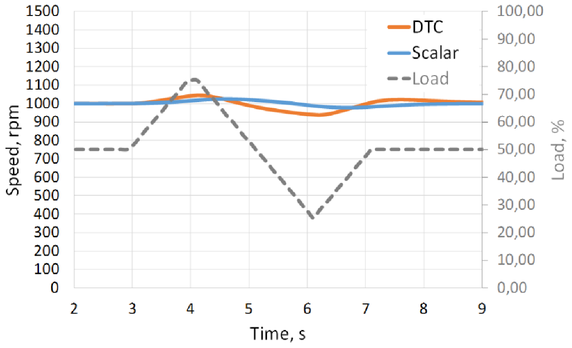

Fig. 11. Drive speed response on variable load of triangle profile.

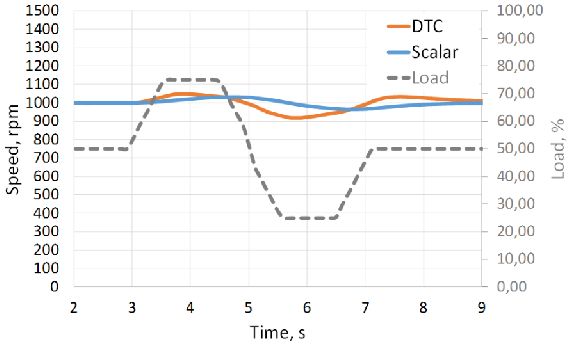

Fig. 12. Drive speed response on variable load of trapeze profile.

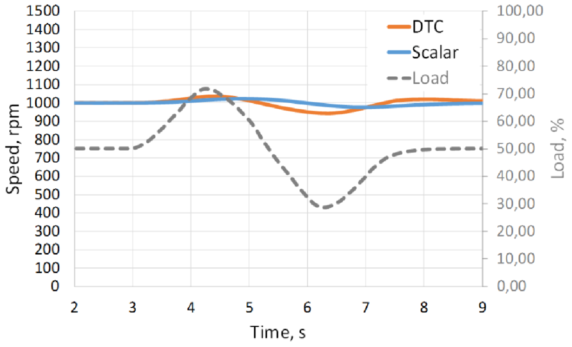

Fig. 13. Drive speed response on variable load of sinusoidal profile.

Our analysis of the speed responses under the desired test cycles shows that in the majority of typical driving situations, the closed-loop control is preferable. At proper tuning, it results in the minimal steady state errors, thus providing better controllability, faster rate of the system response, broader speed range, and higher speed regulation.

Fig. 9 to 13 show the traces of the drive speed responses at different load cycles under DTC and SCALAR control modes. As it can be seen from the traces, the open-ended system has some delay and it makes speed response on different load smoother, while closed-loop system has some speed spikes. In Table II the same parameters of the testing drive demonstrates like it is in Table I. As analyses show, at the variable load the open-ended system shows better performance. Speed errors of the SCALAR control mode are mostly some lower than in the DTC control mode. Moreover, the consumed energy and average current are less under the open-ended control mode.

The open-ended control could be preferable for load response driving modes. It is totally clear that the load of the propulsion system of the HEV/EV could not be predicted with a high accuracy, but it is possible to tune the system for the specific driving modes and to give a possibility to the vehicle controller in selection the driving mode for the vehicle depending on the driving terms (e.g. parking, city cruising, highway cruising, off-road driving etc.).

V. CONCLUSIONS

Literature review shows that tuning of the propulsion drive of HEV/EV is mostly estimated from the viewpoint of economical and technical efficiency. The majority of testing cycles for the vehicle comparison is the long-term cycles and could not be used for the short-term transient mode imitations. Also, all the used nowadays testing cycles were designed for internal combustion engine vehicles and take into account not only energy and mechanical aspects, but also pollution and internal combustion engine characteristics.

An effective methodology was proposed to explore the drive responses under changeable control and disturbance signals. Using the laboratory test bench, multiple conventional modes of the vehicle motion were studied. Analysis of test results shows that the closed-loop control systems are preferable for speed variable working modes because of smaller speed response errors and better energy performance. Under changeable load conditions, the open-ended control systems could be recommended because of smaller energy consumption under SCALAR control mode of the propulsion drive.

The developed methodology can be recommended to adjust the electric drives for different kinds of testing equipment. Experimental validation of the described approach has demonstrated the broad possibilities for the steady-state and transient modes of vehicle quality evaluation. It suits for recommendations that can be made with regard to the tuning of the drive regulators, control looping, sensor allocation, and feedback arrangements.

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