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DETERMINANT OF THE VARIABILITY OF THE LOAD CYCLE OF A MULTI-SOURCE HYDROSTATIC DRIVE SYSTEM

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Abstract: *This article, by determining the mathematical relationship called the determinant of the WZ duty cycle variability and the procedure presented therein, gives an engineer who is not a specialist in the field of multi-source drives a tool to assess the impact of a possible modernization of a single-source system to any multi-source system (hydrostatic, electrical or mechanical). Knowing the value of the WZ determinant, the engineer can quickly estimate potential savings in any selected areas (energy or ecological). In this work, the author presented a method for estimating the potential benefits in the energy area resulting from the reduction of fuel consumption after replacing a single-source drive system with a multi-source system used for a selected load cycle.*

Keywords: *Multisource drive system, hydrostatic transmission, modelling and simulation, load cycle, control*

1. Introduction

Nowadays market of machines and devices is regulated by rigorous standards regarding energy consumption, environmental pollution, noise, safety, ergonomics, recycling, etc. The people responsible for implementing the provisions and rules contained in the standards are mainly engineers-designers and constructors. The multitude of regulations, new, more sophisticated technologies and a greater number of physical phenomena considered in machines mean that more is demanded from engineers. For designers and constructors, designing a machine or device with even greater efficiency, lower emissions of harmful or hazardous compounds, faster in operation, more reliable, safer, less noisy or easier to use without additional support in the form of a person (expert), procedure or expert support system them in areas in which they are not specialists is becoming increasingly difficult.
Work is underway in many global research centers to increase the efficiency of drive systems used in machines operating in rapidly changing, repeatable work cycles. One of the reasons for this interest is the possibility of recovering part of the energy usually dissipated in the braking process, by collecting it and storing it in batteries, and then reusing it in the most energy-intensive phases of the machine's work cycle. The use of drive systems with energy accumulation, instead of classic drive systems, is therefore an interesting and promising way to increase the efficiency of the drive system - up to 30%. However, the wide scope of knowledge, the complexity of the issues and the costs associated with the design and construction of this type of drive systems mean that work on them is carried out only in a few, specialized research and development centers.
The paper presents a method for determining the coefficient of variation (WZ) by means of which the designer-engineer, after determining only a few parameters that can be determined on the basis of the machine's operating cycle, can estimate the potential benefits associated with the use of a multi-source drive system instead of a single-source (classic) one to implement a given duty cycle.

2. General information about multi-source drive systems (MDS)

Seven important issues regarding the construction and design of multi-source drive systems is presented in Table 1.

Table 1: Seven important issues regarding the construction and design of multi-source drive systems

No	Description of the issue	State
1	How to assess the matching of energy and ecological characteristics in drive systems for spectral forms of loads (stochastic)?	There are proposed assessment methods for selected types of drive systems.
2	Ways to increase the efficiency of individual components and the entire drive system.	Constant progress related to the development of technique and technology. The work is still ongoing.
3	Appropriate, mutual adjustment of the operating areas of high-performance drive system components.	The issue has been solved in many areas of technology. Work is ongoing on optimal solutions in multi-source systems.
4	When to use multi-source (hybrid) drive systems, which enable limiting the operating characteristics of the primary energy source to the most favorable areas and recovering part of the kinetic or potential energy that is usually lost?	Problem solved. There are many commonly used solutions (mechanical, electrical, hydraulic, etc.).
5	Quantitative assessment of energy efficiency of various variants of drive system solutions operating under the same load conditions.	There are many theories and assessment methods in this area.
6	Answer the question: When is the expansion of a single-source propulsion system to a multi-source one justified?	There are general considerations, but there is no method for estimating the potential benefits before deciding whether to expand the system.
7	Solving control issues, in particular solving control system synthesis problems (on-line or off-line control).	There are solutions in some areas. Work on autonomous systems (FL, NN, AI) is ongoing.

2.1 Research subject

During the analysis of the results of the research conducted by the author, it was found that it is possible to determine the potential benefits resulting from the use of a multi-source drive system instead of a single-source one at the initial stage of design work. But how to do it? The considerations will be presented on the example of the drive system below (fig. 1).

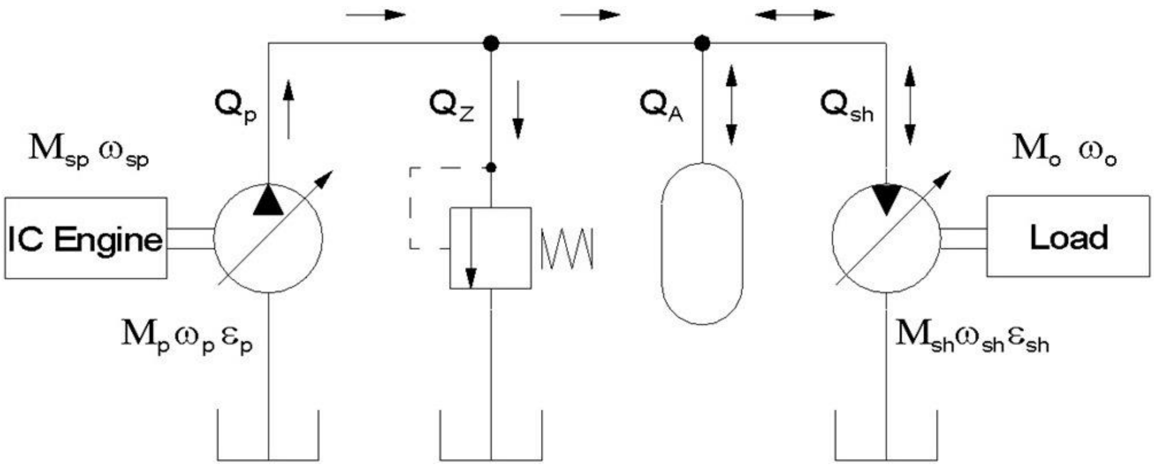

Fig. 1. Schematic diagram of hydrostatic transmission (M: torque; ω: angular velocity; Q: flow ratio; ε: hydrostatic unit control; indexes: sp: IC engine; p: hydrostatic pump; sh: hydrostatic motor; 0: load; z: flow through overflow valve) [1]

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2.2 Basic data analysis

The basis for all analyzes of multi-source systems is the machine's work cycle (fig. 2), resulting mainly from the task for which it was built [2], [3], [4], [5].

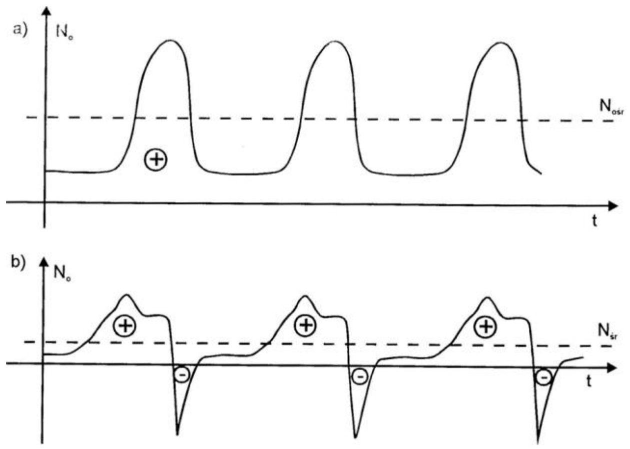

Fig. 2. Variability of energy demand in cyclically operating drives: a) possibility of stabilizing the energy source, b) possibility of stabilization and energy recovery [6], [7]

Most often, when describing the operation of a machine or drive system, the speed is measured and then, based on the energy balance of the working system, a cyclorama of force and power is developed (fig. 3) [8], [9], [10], [11].

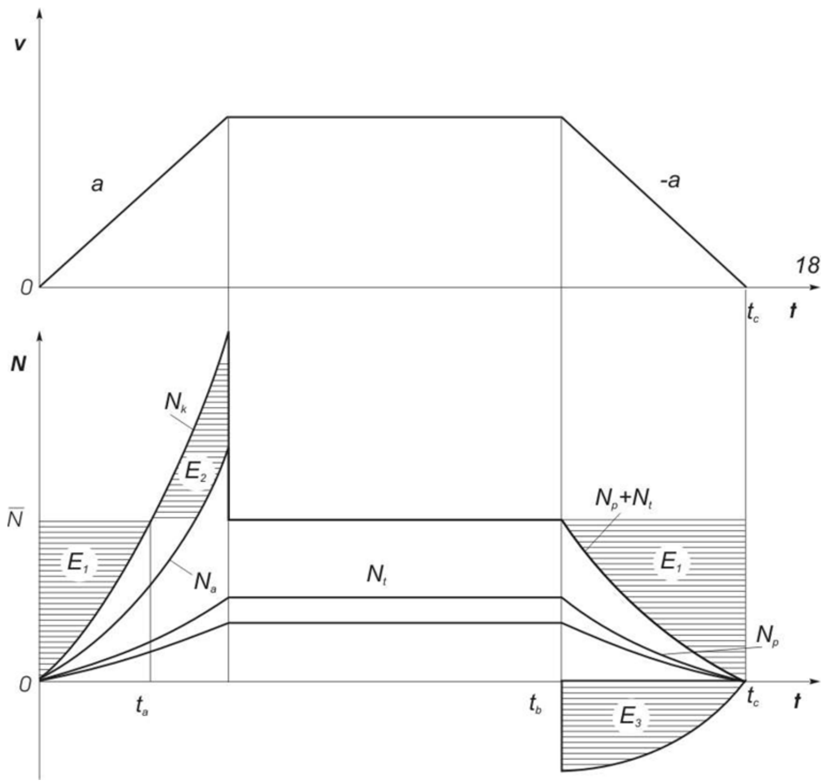

Fig. 3. An example of a simple work cycle [8]

In most working machines and vehicles, changes in the load state are a random process and can be presented in the form of a two-dimensional random variable moment Mo (force F) and angular velocity ωo (linear velocity v) (fig. 4) [12].

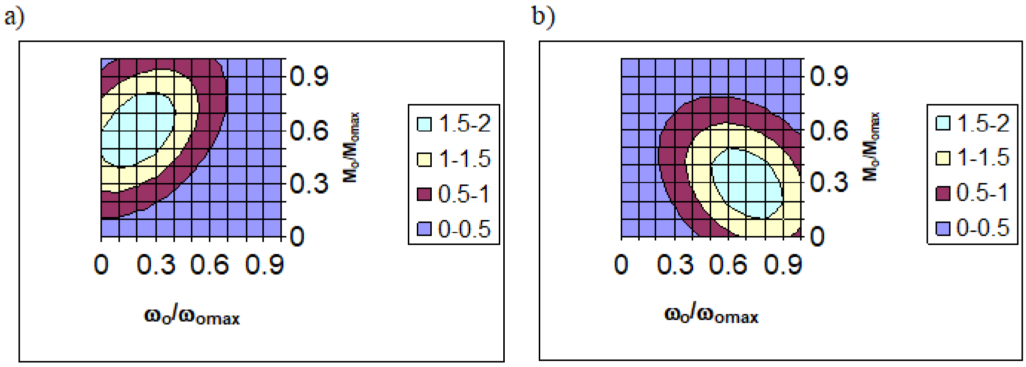

Fig. 4. Examples of load density functions for a bus operating on a) urban and b) intercity routes [12], [13]

3. Determinant of the variability of the load cycle of a multi-source hydrostatic drive system WZ

Discussed in the monograph [14]:
- kinetostatic method,
- method of estimating fuel consumption in a single- and multi-source system (attachment),
- simulation verification of the results obtained using the kinetostatic method,
- proprietary software for determining the settings of drive system components,
- and proprietary software for digitizing universal characteristics,

were used to develop a tool (expert system) on the basis of which an engineer, even if he is not a specialist in the field of multi-source drives, will be able to estimate the difference in energy consumption by a drive system implementing a given duty cycle in the structure of a single-source drive system and its multi-source equivalent. With these estimates, the engineer's decision to upgrade a single-source propulsion system to an equivalent multi-source system will be faster and with less error.
Research and analyzes of single- and multi-source drive systems operating in variable and repeatable work cycles, characteristic of work machines, buses, transport trolleys, etc., resulted in the development of a mathematical formula constituting the basis for the decision to expand the single-source drive system to its multi-source equivalent. Its final form was adopted in the form of relationship (1). It was called the determinant of duty cycle variability - WZ:

$$WZ = \frac{N_{sr\_br}}{N_{sr\_r}} * \frac{1}{n}\sum_{i=1}^{n}\frac{t_{di}}{t_{ci}} \qquad (1)$$

wherein:
WZ - determinant of work cycle variability [-],
N_{sr_br} - average power in the work cycle without considering the energy that can be recovered in the recuperation process [W],
N_{sr_r} - average power in the work cycle considering the energy that can be recovered in the recuperation process [W],
t_d - time of energy supply to the drive system in the work cycle (No > 0) [s],
t_c - total duration of the work cycle [s],
n - number of changes in the energy demand in the work cycle from energy supplied to the drive system No > 0 to energy recoverable in the recuperation process No < 0 [-].
The above formula considers only five characteristic parameters. It is the result of a compromise between the quality of the estimate of the potential reduction in fuel consumption ΔG_e in a given work cycle and the time needed to perform this estimate. The WZ determinant in the proposed form will allow for a quick assessment of the potential benefits resulting from replacing a single-

source drive system with a multi-source system, based on the characteristics of the machine's work cycle, presented in the form of the course of the effort variable M_o, current ω_o and load power N_o.

3.1 Procedure for determining the fuel consumption difference ΔG_e

To determine the difference in fuel consumption ΔG_e between a single-source drive system and its multi-source equivalent operating in the same duty cycle, follow the procedure presented below (fig. 5) [15]:

The most important elements of the method are:

- Knowledge of the machine's work cycle - the highest priority.
- Analysis and assessment of basic parameters of the machine's work cycle.
- Concluding the continuation of the procedure based on the recuperation coefficient χ20.
- Calculation of the WZ variability determinant for a given work cycle.
- Using the designated determinant function and determining potential benefits.

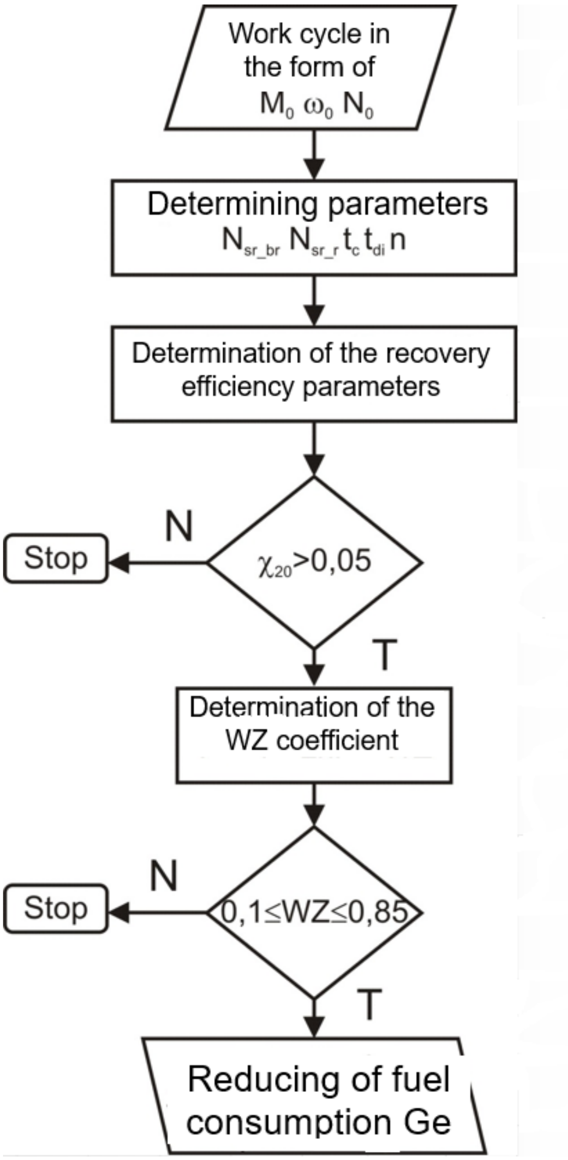

Fig. 5. Scheme of the procedure for determining the WZ duty cycle variability determinant

A description of the procedure is provided below.

- Presentation of the machine's work cycle in the form of waveforms of torque M_o, angular speed ω_o and energy demand (power) N_o during the cycle.
- Determining the parameters of the selected work cycle:

a) N_{sr_br} - average power in the work cycle without considering the energy that can be recovered in the recuperation process,

b) N_{sr_r} - average power in the work cycle, considering the energy that can be recovered in the recuperation process,

c) t_c - duration of the work cycle,

d) t_d - time of energy supply to the drive system in the duty cycle ($N_o>0$),

e) n - number of changes in energy demand in the work cycle from energy supplied (E_d) to the drive system to energy recoverable in the recuperation process (E_o).

- Determination of the heat recovery efficiency factor χ_{20} - eq. (6)
- If the condition $\chi_{20}>0.05$ is met, the next point is passed, otherwise the procedure is interrupted (this method cannot be used).
- Introducing the parameters specified earlier into the relationship describing the coefficient of variation of the WZ duty cycle - eq. (1).
- If the condition 0.1 ≤WZ≤0.85 is met, proceed to the next point of the procedure, i.e. determining the reduction in fuel consumption ΔG_e, otherwise the procedure is interrupted (this method cannot be used).
- Reading from the chart the estimated value of reducing fuel consumption ΔG_e by an internal combustion engine performing a given duty cycle in the structure of a multi-source propulsion system in relation to a single-source propulsion system.

3.2 Determinant of the variability of the load cycle of a multi-source hydrostatic drive system

The WZ determinant. They are calculated using equations (2) to (6). Their graphical interpretations for load are shown in Fig. 6.

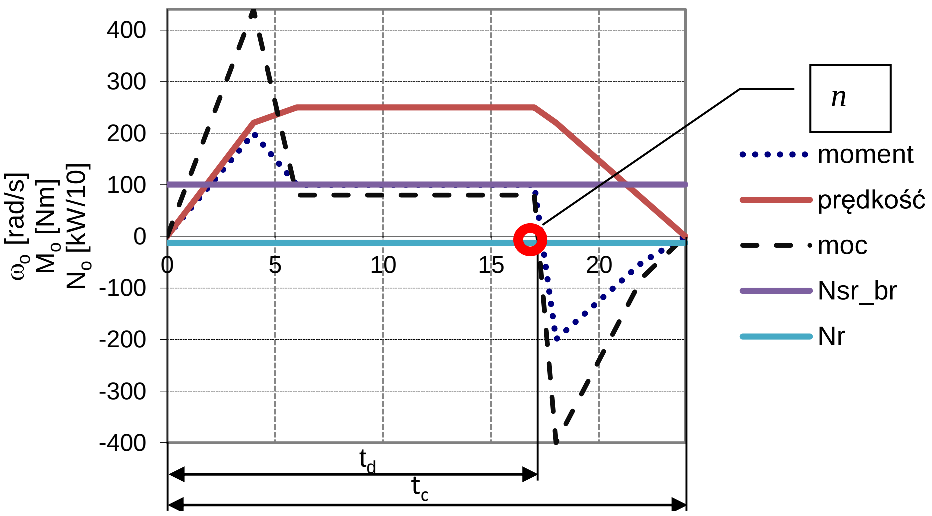

Fig. 6. Graphical interpretation of the parameters used to calculate the WZ determinant for load

Parameters: N_{sr_br} - average power in the work cycle without taking into account the energy that can be recovered in the recuperation process, N_r - average power in the work cycle that can be recovered in the recuperation process and N_{sr_r} - average power in the work cycle including the energy that can be recovered recovery in the recuperation process, were determined from equations (2) to (4):

$$N_{sr\_br} = \frac{1}{t_c}\int_0^{t_c} N_o(t)\,dt \text{ dla } N_o(t) \geq 0 \tag{1}$$

$$N_r = \frac{1}{t_c}\int_0^{t_c} N_o(t)\,dt \text{ dla } N_o(t) < 0 \tag{2}$$

$$N_{sr\_r} = \frac{1}{t_c}\int_0^{t_c} N_o(t)\,dt \tag{3}$$

where:

$$N_{sr\_r} = N_{sr\_br} - N_r \tag{4}$$

The condition that initially verifies the possibility of using the WZ determinant is the heat recovery efficiency coefficient. Knowing the values of the parameters and, the coefficient can be determined from the following relationship (6):

$$\chi_{20} = \frac{N_r}{N_{sr\_br}} \tag{5}$$

For duty cycles for which the indicator χ_{20} reaches values below 0.05 (χ_{20} < 0.05), estimation of the difference in fuel consumption ΔG_e is not possible using this method.
The next parameter is the duration of the work cycle t_c. This is the time from the start to the end of the cycle. Parameter t_d – this is the time of energy supply to the drive system in the work cycle (N_o>0).
The last parameter to be determined in this step of the procedure is the n coefficient. This is a number that determines (for a given duty cycle) the number of transitions of the cyclorama from power No > 0 to power No < 0 - which can be recovered in the recuperation process. For load III shown in Figure 6, the number n is 1 (the location is marked with a circle in Figure 6).

A graphical representation of the value of the WZ determinant as a function of the fuel consumption reduction ΔG_e is shown in Figure 7. To determine the reduction in fuel consumption ΔG_e for any duty cycle after replacing the single-source propulsion system with a multi-source one, the obtained value of the WZ determinant should be compared with the function determined on the basis of the approximation of the results obtained in Table 2. The formula of the function in the range of applicability of the method shows the relationship (7) [10]:

$$\Delta \mathrm{G_e} = 4.05 \cdot \mathrm{WZ}^2 + 18.35 \cdot \mathrm{WZ} + 16.57 \quad \text{dla} \quad 0.1 \leq WZ \leq 0.85 \tag{6}$$

where:

ΔG_e - change in fuel consumption,

WZ - coefficient of variation of the duty cycle.

Table 2: List of WZ parameters for the analyzed work cycles

Load	$N_{śr\_br}$ [kW]	N_r [kW]	$N_{śr\_r}$[kW]	ΔG_e[%]	n	t_d / t_c [s]	χ	**WZ**
Load III	10.02	1.25	8.77	34.3	1	0.72	0.13	**0.82**
Load IV	5.91	0.69	5.22	25.32	3	0.17	0.12	**0.19**
Load V	11.05	0.75	10.30	16.19	4	0.12	0.07	**0.13**
Load VI	3.15	0.76	2.39	22.09	2	0.27	0.24	**0.35**
Load VII	5.01	0.90	4.11	19.56	4	0.18	0.18	**0.21**

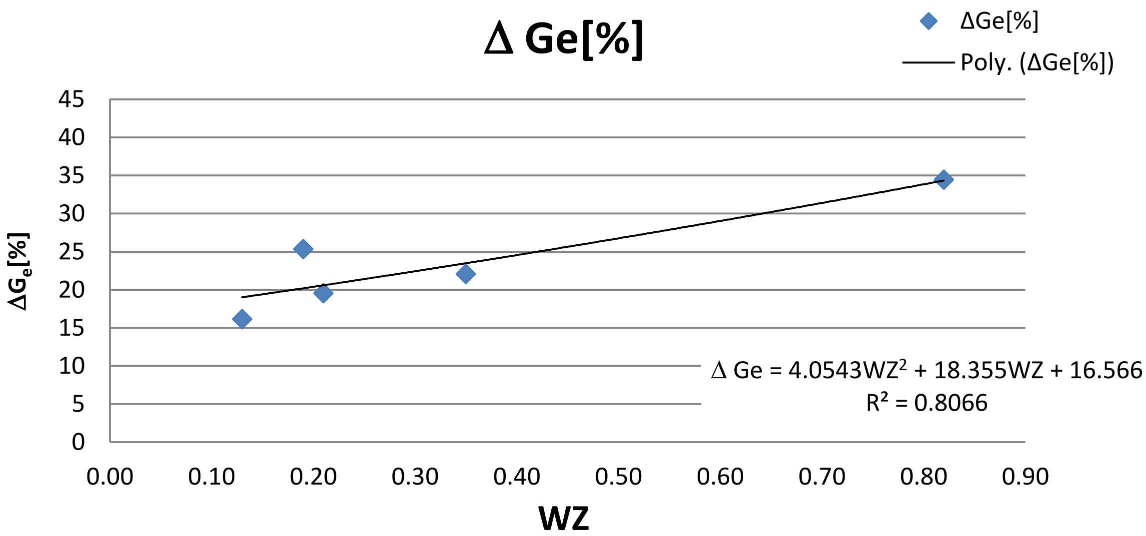

Fig. 7. Determinant of the variability of the WZ duty cycle as a function of the reduction in fuel consumption ΔG_e, approximation with a second-order polynomial

4. Conclusions

The paper, by determining the mathematical relationship called the determinant of the WZ duty cycle variability and the procedure presented therein, gives an engineer who is not a specialist in the field of multi-source drives a tool to assess the impact of a possible modernization of a single-source system to any multi-source system (hydrostatic, electrical or mechanical). Knowing the value of the WZ determinant, the engineer can quickly estimate potential savings in any selected areas (energy or ecological). In this work, the author presented a method for estimating the potential benefits in the energy area resulting from the reduction of fuel consumption after replacing a single-source drive system with a multi-source system used for a selected load cycle.

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