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AN ALGORITHM FOR THE DETERMINATION OF THE CONTROL PARAMETERS OF A MULTISOURCE DRIVE SYSTEM

ALGORYTM WYZNACZANIA PARAMETRÓW STEROWANIA DLA WIELOŹRÓDŁOWEGO UKŁADU NAPĘDOWEGO

Abstract

This article presents an application of the kinetostatic method. The kinetostatic method is a universal method for determining optimum control of unit components in a multisource drive system with regard to selected energetic or ecological criteria. The method's algorithm and mathematical models for components with descriptions are presented. Example results of this method when applied to a hydrostatic multisource drive system composed of hydrostatic transmission, gas-loaded accumulator and IC engine as the primary source of energy, are presented.

Keywords: multisource drive systems, kinetostatic method algorithm, hydrostatic drives, energy optimization, ecology

Streszczenie

W artykule przedstawiono zastosowanie metody kinetostatycznej. Metoda kinetostatyczna jest uniwersalną metodą wyznaczania optymalnego sterowania komponentami wieloźródłowego układu napędowego ze względu na wybrane kryteria: energetyczne lub ekologiczne. Przedstawiono algorytm metody oraz modele opisujące komponenty układu. Artykuł zawiera przykładowe wyniki działania metody wyznaczone dla hydrostatycznego wieloźródłowego układu napędowego zbudowanego z: przekładni hydrostatycznej, akumulatora gazowo- hydraulicznego oraz silnika spalinowego jako pierwotnego źródła energii.

Słowa kluczowe: wieloźródłowy układ napędowy, metoda kinetostatyczna, napęd hydrostatyczny, optymalizacja energetyczna, ekologia

1. Introduction

The kinetostatic method is a universal method applied for the purpose of determining the following parameters for a multisource drive system (Fig. 1). The system is created from components of known characteristics for a known load presented in the form of a machine operating cycle and has the criteria [1–3]:

- optimum work point for the primary source of energy;
- initial parameters for the secondary source of energy;
- control parameters for other components in the drive system.

The method assumes the following:

- for the full duration of machine operation, the primary source of energy will operate at one point;
- the energy level of the secondary source, at the beginning and at the end of the operating cycle, shall remain the same.

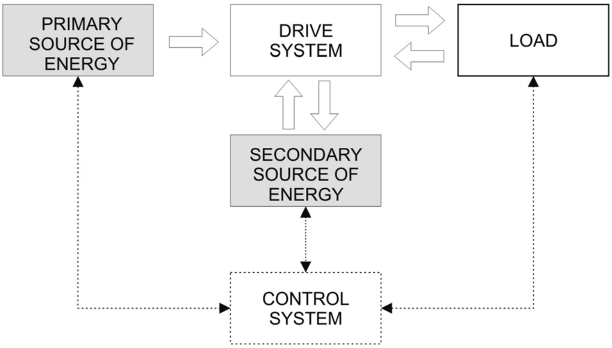

Fig. 1. Multisource drive system scheme

The result of using this method is a set of parameters for controlling the multisource drive system. The results obtained through the application of the kinetostatic method will be presented for the multisource hydrostatic drive system under investigation (Fig. 2) [1, 4].

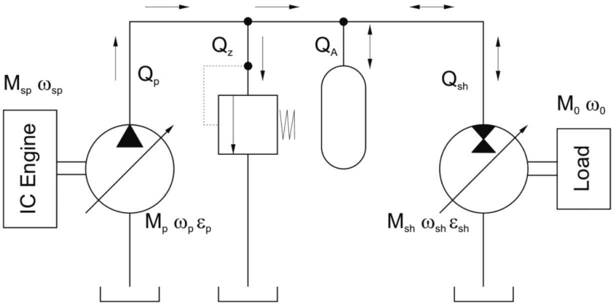

Fig. 2. Schematic of the structure of the multisource hydrostatic drive system

The multisource hydrostatic drive system covers:

- IC engine work point (M_{sp}, ω_{sp}) for the selected optimisation criteria, e.g. minimum fuel consumption in cycle G_e (Fig. 3d), minimum emission of nitrogen oxides NO_x in exhaust gases, DYM – smoke level, etc.;
- diagram of $\varepsilon_p(t)$ and $\varepsilon_{sh}(t)$ hydrostatic unit control in the operation cycle (Fig. 3c);
- initial pressure p_{a0} in the accumulator (in this case, 30.2 MPa);
- accumulator initial charge pressure, p_{gwst} (gas pressure in the accumulator is not connected to the hydraulic system – 25 MPa).

The figure below (Fig. 3) presents the control parameters of selected components of the multisource drive system [5].

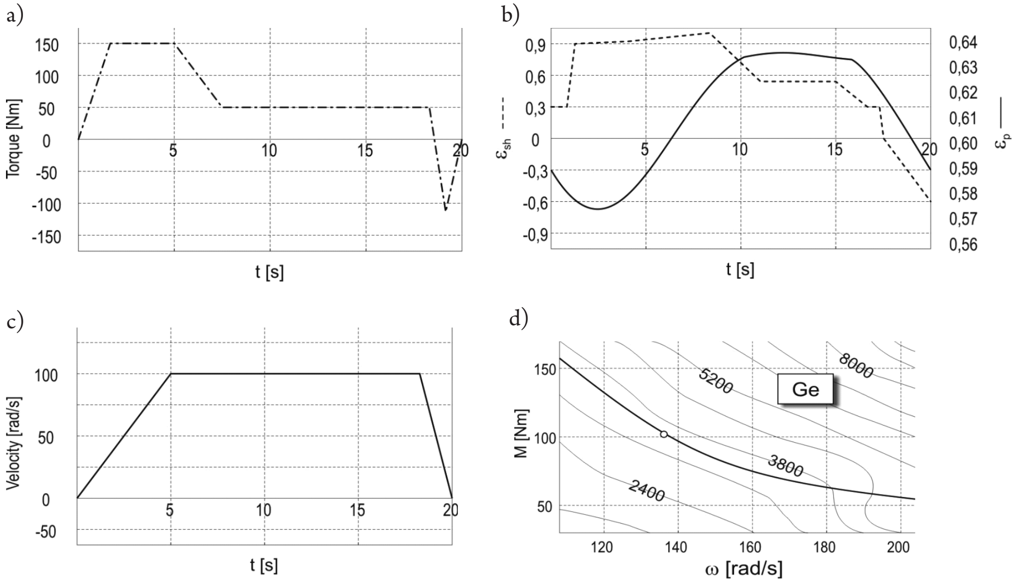

Fig. 3. An example of results obtained with the use of the kinetostatic method for Load I: a) M_o – load torque; b) ω_o – load angular velocity; c) hydrostatic units control; d) specified combustion engine work point

2. Algorithm for the determination of the control parameters of the multisource drive system (kinetostatic method)

The method for selecting the parameters of operation for the multisource drive system was based on the kinetostatic method [1, 2, 6]. Block diagrams (Figs. 4, 5) present the algorithm of performance while calculating the settings for the hydrostatic units, pump – ε_p, engine – ε_{sh}, M_{sp} IC engine work point, and ω_{sp} and p_{gwst} parameters of the initial accumulator load.

The following assumptions were made:

- real characteristics of the hydrostatic units were taken into account by means of applying regression equations;

- the engine work point (M_{sp}, ω_{sp}) is constant during the whole working cycle;
- M_{sp} torque and ω_{sp} angular velocity of the IC engine will reduce to M_p torque and ω_p angular velocity on the hydrostatic pump shaft;
- torque (M_o) and angular velocity (ω_o) of the load in GROSS form will reduce to torque (M_{sh}) and angular velocity (ω_{sh}) on the hydrostatic engine shaft;
- the universal characteristics of the combustion engine were presented in the form of discrete points with criteria values assigned;
- the gas and hydraulic accumulator were presented in the form of BWR model;
- self-locking phenomena of the hydrostatic unit operating as a hydrostatic engine takes place within the range of swash plate angle $0 < \varepsilon_{sh} < 0.3$;
- the impact of temperature on the operation of the hydrostatic unit was neglected;
- the impact of fluid compressibility was neglected;
- there were no leaks in the hydraulic system.

Step l. The allowable possible working area is determined depending on the characteristic features of the engine. Based on the above, the set of analysed engine work points M_{sp}, ω_{sp}, G_{cj}, CO, NO_X, DYM (smokiness) are specified.

Step 2. The machine load characteristics in the working cycle within duration time T are presented in the form of a table or in analytical form – it involves the dependencies of load torque (power) $M_o(t_j)$ and angular velocity (linear) $\omega_o(t_j)$. In this step, it is also necessary to assume the values of time increments Δt. The parameters of the accumulator are selected: capacity and initial determination of the accumulator charge status $E_a(t_i = 0)$ (equations from 1–4).

Table 1. Dependencies describing the energy either supplied to or taken from the accumulator for different movement phases [1]

Movement phase	Energy flowing via the wheels' points of contact with the pavement	Energy supplied to or taken from the accumulator	Equation number
1. Acceleration	$\lvert E_{1k}\rvert = \sum_i \int_0^{S_{1i}} N_{i1}(t)dt$	$E_{1a} = \sum_i \int_0^{S_{1i}} \left(\frac{-N_{1i}(t)}{\eta_{a1i}(t)\cdot\eta_{S1i}(t)\cdot\eta_{M1i}(t)\cdot\eta_{p1i}(t)} + \overline{N}_z \right)\cdot$ $\cdot\eta_{a1i}(t)\cdot\eta_{s1i}(t)\cdot dt$	(1)
2. Steady flow	$\lvert E_{2k}\rvert = \sum_i N_{2i}s_{2i}$	$E_{2a} = \sum_i \left(\frac{-N_{2i}s_{2i}}{\overline{\eta}_{a2i}\cdot\overline{\eta}_{St2i}\cdot\overline{\eta}_{M2i}\cdot\overline{\eta}_{p2i}} + \overline{N}_z s_{2i} \right)\cdot\overline{\eta}_{st2i}\overline{\eta}_{a2i}$	(2)
3. Locking (braking)	$\lvert E_{3k}\rvert = \sum_i \int_0^{S_{3i}} N_{3i}(t)dt$	$E_{3a} = \sum_i \int_0^{S_{3i}} \left(-N_{3i}(t)\eta_{p3i}(t)\eta_{M3i}(t) + \overline{N}_z \right)\cdot\eta_{st3i}(t)\eta_{a3i}(t)dt$	(3)
4. Active stoppage	$\lvert E_{4k}\rvert = 0$	$E_{4a} = \overline{N}_z \overline{\eta}_{st4} \overline{\eta}_{a4} \sum_i s_{4i}$	(4)

Step 3. In accordance with the load cycle, the values of combustion engine power $N_{spj} = f\,(M_{spj}, \omega_{spj})$ are compared, with reference to the assumed area allowable j^{th} work point, to the power demand of $N_{oi}(M_{oi}, \omega_{oi})$ in t_i time.

As:

- the power of the primary source and load power are expressed by applicable values of their M_{spj} and M_{oi} effort variables and ω_{spj}, ω_{oi} flow variables;
- values of engine power N_{spj} and load N_{oi} are generally diverse, then the function of the hydrostatic power transfer unit is:
- accurate transformation of the forms of M_{sp} effort variable and ω_{sp} flow variable of the combustion engine to the form required by M_o effort variable and ω_o flow variable of the load;
- balancing the power supplied by the primary source of energy with the load power demand by means of taking the excess of the energy to the accumulator or supplementing its insufficiency with it.

The power of the primary source, in the form of the M_{sp} and ω_{sp} signals, is transmitted to the shaft of the positive-displacement pump of changeable efficiency. The initial values of M_p and ω_p are transformed for the given p pressure – by means of solving the equations which describe the real power characteristic features of the M_p and Q_p pump – into the deflection signals for the element which controls the efficiency ε_p.

While the momentary value of load power, in the form of M_o and ω_o signals, is transmitted to the shaft of the hydrostatic engine of changeable absorption capacity. The values of M_o and ω_o are transformed for the given p pressure by means of solving the equations which describe the real power characteristic features of M_s and Q_{sh} (hydrostatic unit) into the signals which control ε_{sh}. Power losses related to Q_p and Q_{sh} that flows in the hydraulic system referred to the summing junction, where p pressure is present, were projected in other diagrams. In the summing junction, by the given value of p pressure, power is balanced due to the flow continuity equation $Q_p + Q_{sh} + Q_a = 0$ being met. If the power from the primary source is in excess in relation to the load, the accumulator collects the fluid stream with the power of $p \cdot (Q_p - Q_{sh})$, while in the case of insufficiency, it gives back the power of $p \cdot (Q_{sh} - Q_p)$.

Pressure p in the summing junction is related to the accumulator power condition. It is not, however, a simple and unambiguous dependency in general. It depends on the type of accumulator applied and how it is controlled. In the system, a hydraulic accumulator was applied which was directly connected with the hydraulic system.

The kinetostatic method was specified as a consequence of own research. A modified algorithm of the step is presented in Fig. 5.

In **block A**, p pressure for the given (k-th) iteration in the summing junction is calculated. The pressure value depends on the accumulator load condition. For the given M_o values of load and M_{spj} combustion engine torque, the values of ε_p and ε_{sh} parameters for units control (**diagram B**) are calculated. The values in relation to their previous values in $t_i - \Delta t$ time have to meet the condition for the border clipping velocity.

In the event that the conditions are not observed (**diagram C**), it goes back to diagram A. If the maximum clipping velocities of the pump and hydrostatic engine are real, then we need to check whether the swash plate angle of the hydrostatic engine is greater than the self-locking range. If this condition is observed, we move to **diagram D**. The engine will be found within the specified zone, so in order to minimise the volumetric losses, we need to decrease the swash plate angle to zero and attempt to do this as quickly as possible. In **diagram D**, we calculate the power loss. To start, we determine the real pump capacity Q_p and engine absorption capacity Q_{sh}. We then determine the power loss within time $t_i - t_{i-1} = \Delta t$:

- in the positive-displacement pump $\Delta E_p(\omega_p, p_p, \Delta_p)$;
- in the hydrostatic engine $\Delta E_{sh}(\omega_{sh}, p_{sh}, \Delta_{sh})$;
- in the hydraulic unit $\Delta E_t(Q_{sh}, Q_p)$;
- in the energy accumulation unit $\Delta E_a(E_a, N_a)$ (with use of the *BWR* model).

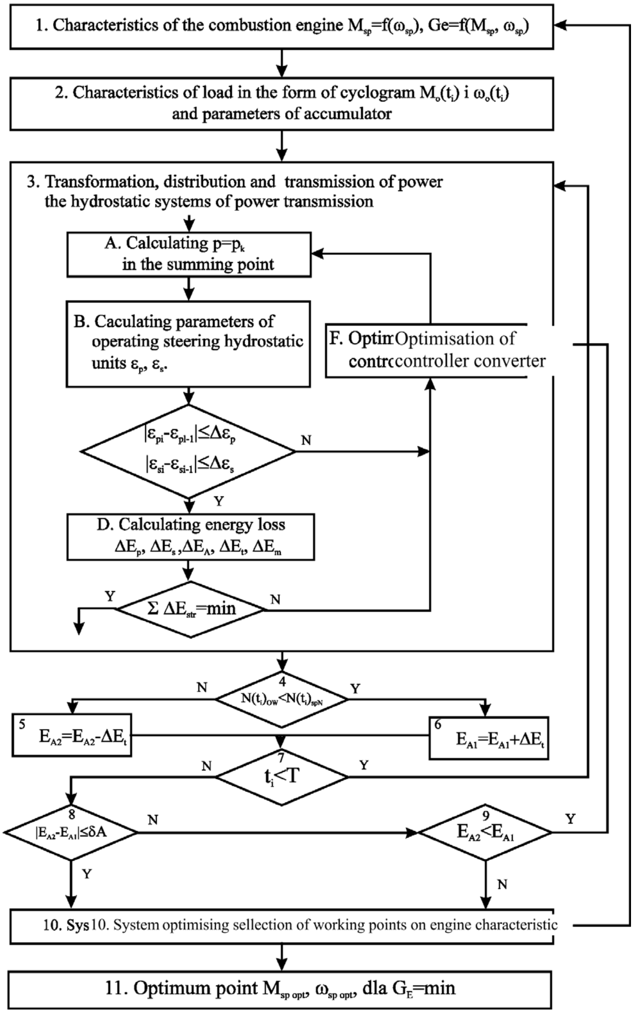

Fig. 4. The procedure of the method applied for the purposes of determining the control parameters for the set load of the hybrid system – kinetostatic method

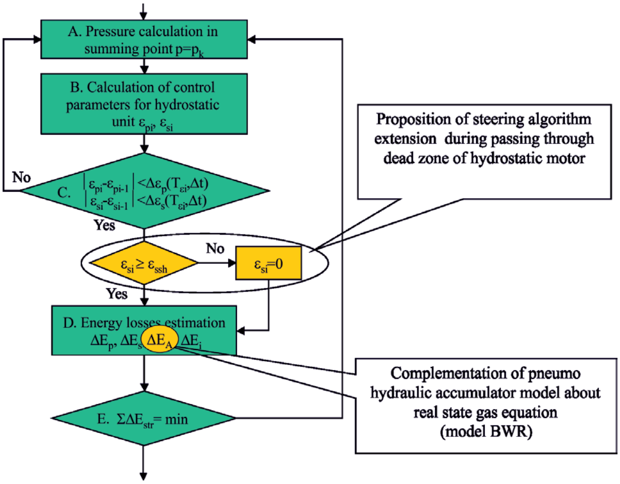

Fig. 5. Unit 3 of power transformation and transmission in the power transfer hydrostatic unit

Power losses in the accumulation unit depend on: the E_a accumulator charge condition; charging and discharging velocity $\frac{dE_a}{dt}$ (power that is supplied or taken back); power storage time in the accumulator; accumulator structural parameters (wall thickness, wall thermal conductivity co-efficient, ambient temperature, etc.)

In **diagram E**, the decision is made about moving on to subsequent 4 step of the algorithm or subsequent iteration $k + 1$ and moving on to searching for another possible transducer control. The general problem then involves the selection of the power transducer controlling signal E_a so that for:

- combustion engine work point M_{spj}, $\omega_{spj,}$
- the point from the load characteristics for the moment t_t, $M_o(t_i)$, $O_o(t_i)$,

the sum of power losses $\Sigma\Delta E_{str}$ is minimum.

Step 4. In the algorithm, the values of momentary power reduced to the summing junction are compared, in other words transformation and energy transfer losses are taken into account.

Step 5. In the block, the values of power taken from the accumulator E_{a2} are calculated.

Step 6. In the block, the energy supplied to the accumulator in time $\Delta t = t_i - t_{i-1}$, and reduced to the summing junction are calculated. The operation of diagram 5 or 6 depends on the inequality sign $N(ti)_{ow} < N(t_i)_{spw}$.

Step 7. This is where the calculations for the given moment of t_i cycle are completed. Providing that inequality $t_i < T$ is true, the algorithm loop for $t_i = t_i + \Delta t$ is repeated. After all the calculations in the working cycle are made (for $t_i = T$), we move to another diagram.

Step 8. This is where the condition $|E_{a2} - E_{a1}| < \sigma_a$ is examined. Depending on the result load obtained for the given cycle, the algorithm anticipates the following procedures:

- if the condition presented in **diagram 8** is observed, then the new work point of the combustion engine M_{spj}, w_{spj} is selected;

- if the condition is not observed, two possibilities should be considered – these are shown in Step 9.

Step 9.

1. When the power supplied to the accumulator is less for the given cycle than less than the collected one, it means a negative cycle power balance exists, while the insufficiency exceeds σ_a. This is an unacceptable option, therefore, it is necessary to move on to step 10 and select the new work point of the combustion engine M_{spj}, ω_{spj}.

2. When the power supplied to the accumulator is, for the given cycle, greater than the collected one and the excess exceeds σ_a, it is necessary to go back to diagram 3 (determination of the signal which controls the power transducer) and recalculate the load cycle under consideration for the given work point of the combustion engine M_{spj}, ω_{spj}.

Step 10. The power analysis presented in the algorithm is run by the optimisation unit (**diagram 10**) until quality criteria for the moment the characteristics of the engine point $M_{spop}t$, and ω_{spopt} for the given load cycle are accepted: G_c fuel consumption reaches the minimum value within the set area.

3. Summary

The presented kinetostatic method allows for the multisource drive system, determination of the control parameters for all components of the system, using any criterion of control e.g.: G_c – fuel consumption in the cycle, CO – carbon monoxide content in exhaust gases, NO_x – nitrogen oxides content in exhaust gases, as well as DYM – range of smokiness. It enables free choice of criteria, depending on the location of the machine, for example, on highways it can be controlled due to the minimum cost of fuel (min G_c). In mines and urban areas, the cost of fuel is a secondary consideration; ecology, and ensuring the health and safety of workers through minimising the emission of harmful substances becomes the most important criterion.

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