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REDUCTION OF ELECTRIC LOCOMOTIVE'S ENERGY CONSUMPTION BY SCALABLE TRACTIVE POWER CONTROL

Summary. At the beginning of the paper, the analysis of energy efficiency indicators for freight electric locomotive with asynchronous traction drive feeding from AC network under various operating conditions including when working with trains of various masses is made. The movement on different railway sections is considered. The graphs of locomotive’s speed, traction force, consumed power, and power for the traction obtained by on-board recorder are shown.

In addition, the dependence of the locomotive's energy efficiency from the degree of using of its available traction capacity has been experimentally obtained, the greater is the using of the locomotive’s capacity, the greater will be its efficiency. On the basis of the performed analysis of energy efficiency indicators for various operating conditions, the proposals for their improvement are formulated. The algorithm ensuring the stabilization of the instantaneous value of efficiency at partial load to its nominal level at full load is presented. This algorithm is the implementation of Scalable Power Control Technology with respect to the problem of reducing electricity consumption for electric locomotive traction. The direct the experimental confirmation of energy consumption reduction for freight electric locomotive due to the application of our proposals (under the same operating conditions of the locomotive) is obtained.

1. INTRODUCTION

Rail transportation is currently one of the most energy efficient (per passenger-km, or ton-km) and environmentally compatible transportation mode. Nevertheless, the energy consumption is a major part of rail operation costs and for this reason, it is at the focus of rail systems technology development initiatives. The majority of energy consumed by passenger and freight rail systems is used to move the trains. In recent years, energy saving technologies for rail vehicle power systems have been implemented on many rail systems worldwide [1].

Improving the railway energy efficiency results in not only the reduction in energy consumption and cost, but also the reduction in pollution due to power generation. In an effort to promote environmental quality and energy efficiency, energy usage in rail systems is analyzed to identify new technologies, developments, and procedures for increased efficiency.

Nowadays, the electric locomotives are equipped with regenerative braking system (with the return of electric energy to the contact network). The share of the stock equipped with regenerative brakes may vary considerably between European countries, but is generally high. In the new stock, regenerative braking is the standard technology [2].

Energy storage devices are used, both trackside and on-board. The mechanical energy storage device is a flywheel [3]. Electrochemical energy-storage devices are traction batteries and ultracapacitors, the development of which led to the emergence of a hybrid traction drive – see for example [4].

To reduce the resistance to movement, new roller bearings and lubricants are used. The high-speed trains head cars have an aerodynamic form of the aircraft-shaped body, also for reducing the air resistance.

Optimal train operating systems to ensure minimum energy consumption have been developed, which guarantees a minimal energy consumption during the movement of the train in this section for a given time [5].

However, there are still significant opportunities to reduce the electrical energy consumption when the locomotive is operating with an incomplete load. Really, the freight locomotives of JSC "Russian Railways" mainly work on "round-trip" lines. In the forward ("go") direction, the locomotive drives a heavy train weighing 6000 tons or more, and practically all of its power capacity is used; but in the reverse direction ("return"), the locomotive drives an empty train, which weighs 3 to 4 times less, and so the locomotive power is used only partially.

Modern freight electric locomotives have a multi-engine electric traction drive (4 - 6 - 8 - 12 - 16 traction motors) and are equipped with an individual control system (per axis) of the traction force.

Therefore, the approach of the Scalable Power Control Technology [6,7], namely by regulating the number of traction motors (TM) turning on simultaneously, seems quite reasonable.

According to [6], the load scalability is the ability for a distributed system to easily expand and contract its resources to adopter heavier or lighter loads. Alternatively, the ease with which system components can be added, or removed, to adopter-changing load.

In our case, if the full locomotive tractive power is not needed within a certain time interval, one or more TM are shut down automatically. On the contrary, if additional tractive power is required, one or more TM must automatically turned on.

In this paper, we propose the method to increase the energy efficiency: the purpose is to put the number of the simultaneously connected engines in correspondence with the instantaneous power necessary to drive the train. The direct consequence of this will be the reduction of electrical energy consumption.

2. INDICATORS OF ENERGY EFFICIENCY FOR ELECTRIC LOCOMOTIVE

The energy efficiency of an electric locomotive is characterized by its coefficient of performance (COP) and its capacity of utilization coefficient (CUC).

The COP of an electric locomotive η can be presented as:

$$\eta = \frac{P_{\mathrm{u}}}{P_{\mathrm{a}}} = \frac{P_{\mathrm{tr}}}{P_{\mathrm{tr}} + P_{\mathrm{p}} + P_{\mathrm{pb}}}, \tag{1}$$

where P_{u} – power output, kW; P_{a} – power consumption, kW; $P_{\mathrm{tr}} = P_{\mathrm{u}}$ – traction power (tangent power), kW; P_{p} – loss power, kW; P_{pb} – power of own needs (auxiliary loads), kW.

The traction power of an electric locomotive (its tangent power) P_{tr} is equal to:

$$P_{\mathrm{tr}} = F_{\mathrm{tr}} \cdot V, \tag{2}$$

where F_{tr} – locomotive tangential force of traction, kN; V – speed, m/s.

It is necessary to distinguish between the COP of a locomotive operating in stationary mode at its nominal power (precisely this value of the COP is indicated in the technical documentation), and the operational COP. The latter depends on the working time of the locomotive in its different modes while in movement and the energy consumption for maintaining the locomotive ready during the stops.

The CUC of an electric locomotive γ is the quotient of the traction power P_{tr} at a given instant by its available capacity P_{cap}:

$$\gamma = \frac{P_{\mathrm{tr}}}{P_{\mathrm{cap}}}. \tag{3}$$

Note that P_{cap} in (3) is equal to the number of working TM multiplied by the rated power of one TM: $P_{cap} = N_{TM} \times P_{TM}$, where P_{TM} is the rated power of one TM.

Note that the values of COP (1) and CUC (3) can be expressed in %%.

3. MAIN TECHNICAL CHARACTERISTICS OF 2ES5 ELECTRIC LOCOMOTIVE

The double-section 8-axle heavy freight locomotive 2ES5 «Scythian» is produced by CJSC TransMashHolding [8]. The locomotive is powered by AC 25 kV, 50 Hz network. The long-term capacity is $P_{cap} = 8 \times 1050 = 8400$ kW.

In each section, there are four independent power channels feeding the TM. The schematic diagram of the electrical circuit of one section is shown in Fig. 1 (T – traction transformer; U1-U4 – traction converters; 4qs – rectifier; C – power capacitor; Inv – autonomous voltage inverter; and M1-M4 – traction motors).

The traction converters are realized on IGBT-transistors, thus the torque on the shaft of each motor can be adjusted from 0 to 100%. A slip control system is used.

In the long-term mode, the value of locomotive's COP is equal to 86.25 %.

The electric locomotive is equipped with an on-board recorder, which is capable to write more than 1000 parameters.

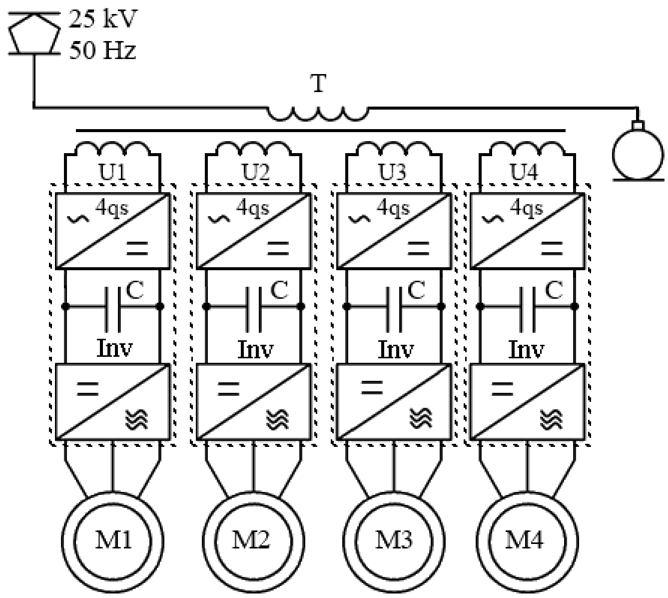

Fig. 1. Schematic diagram of the 2ES5 electric power circuit (for 1 section)

4. INDICATORS OF ENERGY EFFICIENCY FOR 2ES5 ELECTRIC LOCOMOTIVE

Let us pass now to the analysis of the records obtained during the operation of the 2ES5 electric locomotive with a heavy train, the total mass of which is 5770 tons (including 200 tons – the mass of the electric locomotive and 5570 tons – the mass of the train) on the line Timashevskaya – station 9th kilometer – the Wolf Gate pass – port of Novorossiysk of North-Caucasus railway (the branch of JSC Russian Railways).

From Timashevskaya to the station 9th km, the track profile is flat, then follows the rise up to the Wolf Gate pass and then the descent to the port of Novorossiysk station.

Flat profile track (Timashevskaya → station 9th km). Figure. 2 shows the charts of speed V (dotted line) and of traction force F_{tr} (solid line) as a function of the passed path for the flat profile track Timashevskaya – station 9th km.

It can be seen that the speed V reaches 75–80 km/h. The traction force F_{tr} is in the range of 200–300 kN, and only once reaches 300–400 kN. We also note that the electric locomotive passes a considerable part of the way in the run-out mode (the traction force is zero).

Figure. 3 shows the power consumed from the contact network P_a (dotted line) and the traction power P_{tr} (solid line). It is seen that the traction power P_{tr} is mainly in the range of 1500–4000 kW and only once reaches the value of 5500 kW, whereas the locomotive's long-term capacity is 8400 kW. Thus, the electric locomotive's CUC is 18 –48%, and for a short time, it reaches 66%.

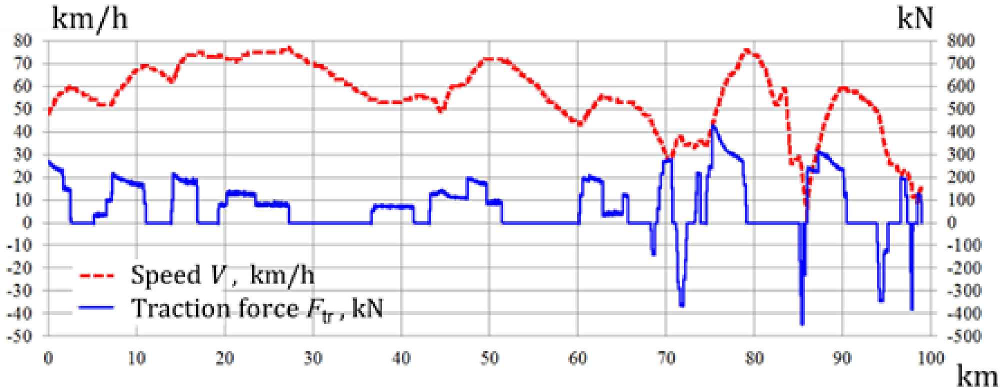

Fig. 2. Flat *profile track*: speed V (dotted line) and of traction force F_{tr} (solid line) as function of the passed path

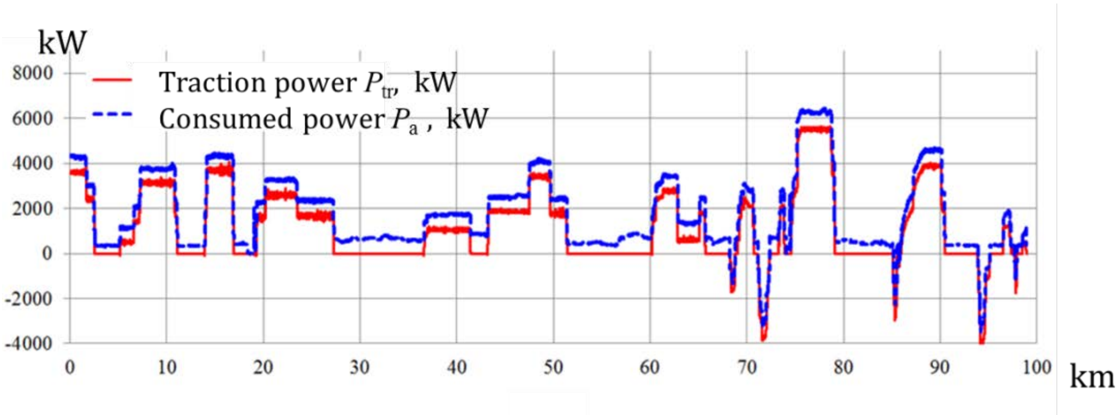

Fig. 3. *Flat profile track*: consumed power P_a (dotted line) and traction power P_{tr} (solid line) as function of the passed path

Mountain profile track (station 9th km –Wolf Gate pass – port of Novorossiysk). Figure. 4 shows the charts of speed V (dotted line) and of traction force F_{tr} (solid line) as a function of the passed path. From the 40th to the 70th km, the train rises to the Wolf Gate pass and then descends from it, and the electric locomotive enters the electric braking mode with energy recovery (the traction force has negative values that is the braking force).

When rising up to the pass, the speed is in the range of 50–60 km/h, whereas the traction force reaches 600 kN.

Figure. 5 shows the power consumed from the contact network P_a (dotted line) and the traction power P_{tr} (solid line). It can be seen that, in the traction mode, the power consumed from the contact network P_a is more than the traction power P_{tr}. When descending from the pass, when electric braking with recuperation is applied, the power returned to the contact network is less (in modulus) than the mechanical power of the braking force in the wheel–rail contact.

When rising up to the pass, the traction power exceeds 8000 kW and the electric locomotive's CUC approaches 100%.

From the analysis made above, it can be deduced that the traction power is used more fully during the acceleration phase and during uphill driving in mountainous areas. To maintain the speed on the flat areas, the traction power is used only partially.

The specificity of a freight locomotive is that the weight of the loaded train is 3 –4 times higher than its unloaded weight.

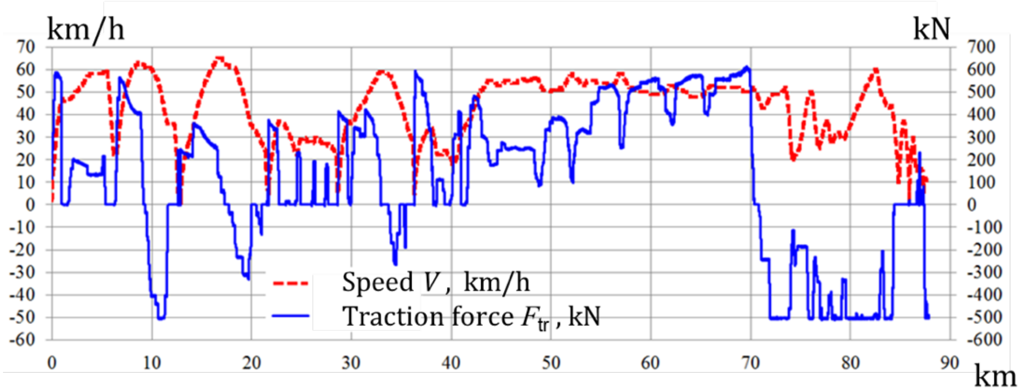

Fig. 4. *Mountain profile track*: speed *V* (dotted line) and of traction force F_{tr} (solid line) as function of the passed path

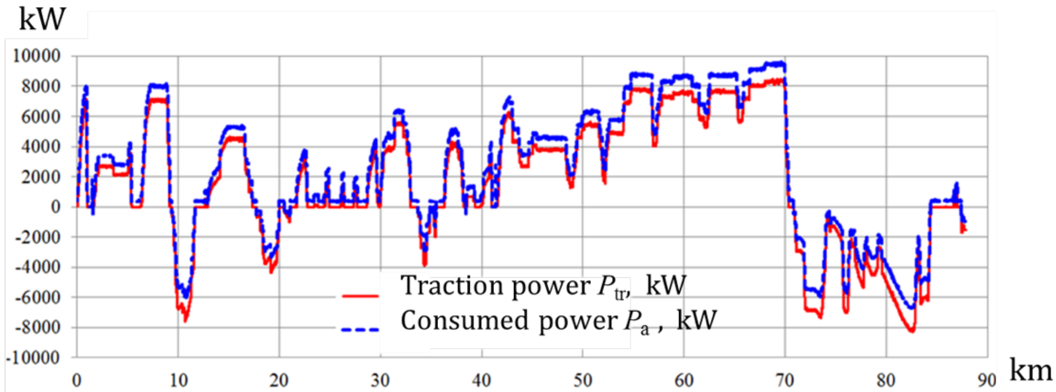

Fig. 5. *Mountain profile track*: consumed power P_a (dotted line) and traction power P_{tr} (solid line) as function of the passed path

The results, similar to those presented in Figs. 2 to 5 for the train with the mass of 5770 tons, were also received for heavy trains with a mass of 5226 tons and empty trains with a mass of 2214 and 2192 tons. The heavy trains moved in the forward ("go") direction (Timashevskaya → Novorossiysk) and the empty trains moved in the reverse ("return") direction (Novorossiysk → Timashevskaya).

5. DEPENDENCE OF LOCOMOTIVE'S ENERGY EFFICIENCY FROM THE DEGREE OF USING ITS TRACTION CAPACITY

As the electric locomotive operates in variable modes, let us represent its COP η in function of its instantaneous traction power P_{tr}.

Figure. 6 shows the experimental data obtained from the on-board recorder when electric locomotive operates with loaded and empty trains, both in the forward and reverse directions. The horizontal axis represents the electric locomotive's traction power P_{tr}, and the vertical axis – its COP when operating in the traction mode.

By processing the experimental data, the dependence of the COP on the traction power of the form $\eta = \eta\,(P_{tr})$ was found (shown by the red line in Fig. 6):

$$\eta = \eta(P_{tr}) = \frac{P_{tr}}{aP_{tr} + b}, \tag{4}$$

where the coefficients *a*, *b* are equal (with 95% confidence interval):

a = 1,055 (1,054, 1,056);
b = 564,2 (563,1, 565,3).

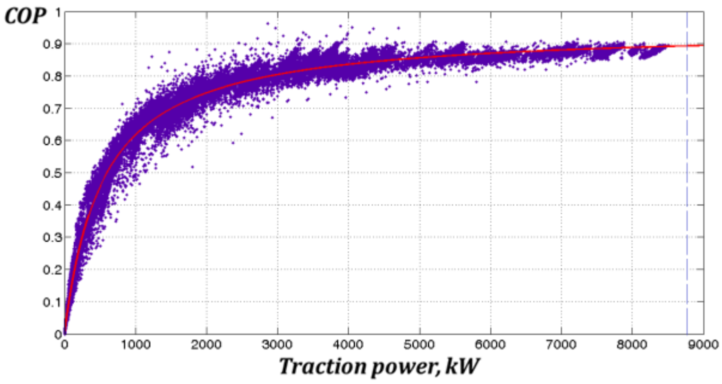

Fig. 6. Dependence of the COP on the traction power

We emphasize once more that formula (4), which expresses the dependence of the COP η with respect to the traction power P_{tr}, is obtained by processing the motion parameters stored in the on-board recorder. The functioning of the whole-energy conversion system is taken into consideration here, taking into account the main transformer, converters and traction motors, the friction, thermal and electromagnetic losses, and the power necessary for the own needs. It may be said that this is the result of experiments repeated many times, the conditions of which are determined by the modes of operation.

If we divide the expression (4) by P_{cap}, we obtain the dependence of the COP η on the CUC γ in the following form:

$$\eta = \eta(\gamma) = \frac{\gamma}{a\gamma + c} \quad , \tag{5}$$

where $c = b \,/\, P_{cap}$ = 564,2 / 8400 = 0,0672.

Note that the general form of the dependences (4) - (5) for the freight electric locomotive 2ES5 was similar to the formulas obtained in [9,10] for the passenger electric locomotive EP20. The difference lies in the values of the coefficients a, b, and c.

These experimental results show that the character of dependence $\eta = \eta(\gamma)$ is following with the growth of the CUC and there is a non-linear increase in the COP. In other words, when functioning, the more complete the use of capacity, the higher will be the locomotive's efficiency, and vice versa.

As noted in paragraph 4, when driving the train with the mass of 5770 t on a flat-profiled track, the locomotive tractive power P_{tr} is mainly in the range of 1500– 4000 kW, that is, the locomotive operates at partial load. In this situation, if all the eight TMs are operating simultaneously, then at the tractive power P_{tr} = 1500 –4000 kW, the electric locomotive efficiency according to (4) will be 0.7–0.83 (the nominal efficiency is 86,25%).

With empty trains weighing about 2000 tons on a flat-profiled track, the efficiency of the electric locomotive becomes even lower.

The quality law, expressed quantitatively by the formulas (4) and (5), allows, for locomotives equipped with a multi-engine traction drive, to suggest the way [9,10] ensuring the stabilization of the instantaneous value of efficiency at partial load to its nominal level at full load.

The traction drive of the locomotive is multi-motor and it is possible to control the individual power of each engine until it is turned off. Therefore, in order to improve the energy efficiency of the locomotive at partial load, it seems appropriate to develop an adaptive algorithm determining automatically the number of traction motors running simultaneously. The algorithm must be designed in such a way that the traction motors remaining in work provide the largest possible COP [9]. At present, for the new electric locomotive, a control system is being developed that implements the proposed algorithm. To debug the control system at the stage of design work, it is advisable to apply the computer simulation methods.

It should be noted that, when locomotive operate at partial load, the proposed algorithm gives the best effect if instantaneous traction power P_{tr} is less than 50–60% of the nominal locomotive capacity P_{cap}. Otherwise, the COP increase does not exceed 2–3%.

Therefore, the most appropriate use of the algorithm is mainly for heavy-duty freight locomotives because the weight of the empty train is several times less than its loaded weight.

6. DIRECT CONFIRMATION OF ELECTRICITY CONSUMPTION REDUCTION FOR FREIGHT ELECTRIC LOCOMOTIVE

The energy consumption results given below were obtained in May 2016, during two trips with the electric locomotive 2ES5 towing empty freight trains. The mass of the train, in both cases, was about 2200 tons (including the locomotive). The railway section "station 9th km – Timashevskaya" has a flat-track profile and its length is about 108 km.

The two trips were made with the same time schedule.

During the 1st trip, all the eight motors were constantly in traction (N_{TM} = 8), in this case the available traction capacity of the locomotive is equal to $P_{cap(8)} = 8 \times 1050 = 8400$ kW.

During the 2nd trip, half of the motors were disconnected (only four motors were constantly in traction, N_{TM} = 4). Consequently, the available traction capacity of the electric locomotive became equal to $P_{cap(4)} = 4 \times 1050 = 4200$ kW.

During both trips, the values of speed, traction force, traction power, and power consumption were recorded, and the diagrams similar to those shown in Fig. 2 and Fig 3 were obtained.

With all eight motors constantly in traction ($P_{cap(8)}$ = 8400 kW), according to the recorder's data, the value of CUC was within 35..–40%, and short-term value reaching 62%.

With only four motors in traction ($P_{cap(4)}$ = 4200 kW), the value of the CUC was 65.–.70%, short-term value reaching 98%, that is, the available power was used much more fully.

As a result, we get an increase in efficiency and a reduction in energy consumption when only four motors are running: the energy consumption for both trips measured by the counter is presented in the table below:

Table 1

Increase in efficiency and a reduction in energy consumption

	8 motors in traction	4 motors in traction
Work performed by the locomotive in traction mode, kWh	2174	2117
Electrical energy consumed by the locomotive in traction mode, kWh	3222	2682
COP in traction mode	67,5%	78,9%

As a result, the energy consumption for traction measured by the counter was reduced by more than 16% by cutting the number of working traction motors from eight to four.

We emphasize that the application of the algorithm in its entirety (with adaptive disconnection / connection of traction motors, depending on the instantaneous power required for traction) will give an even more significant reduction in energy consumption.

7. CONCLUSION

The proposals for energy consumption reduction for freight electric locomotive operating with partial load based on the scalable power control technology are formulated.

1. The graphs of locomotive's speed, traction force, consumed power, and power for the traction under various operating conditions including when working with trains of various masses, and obtained by on-board recorder are presented. The analysis of energy efficiency indicators for freight electric locomotive is made.
2. The dependence of the locomotive's COP on its traction power P_{tr} has been experimentally obtained; greater is the use of locomotive's traction capacity, the greater will be its efficiency. The analytical dependence of the COP on the traction power of the form $\eta = \eta\ (P_{tr})$ was build.
3. The algorithm, realizing the scalable-power control technology and providing the stabilization of the instantaneous value of the COP at partial load to its nominal level at full load, is proposed. This is ensured by the fact that the number of operating traction engines is promptly brought into line with the traction power that is needed at this instance to conduct the train.
4. The direct experimental confirmation of electricity consumption reduction by 16% is obtained (mass of the train about 2200 tons, flat-track profile, and length of 108 km).
5. For the new electric locomotive, a control system is being developed that implements the proposed algorithm.

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