



## The model of wireless charging infrastructure for electric transport of open-pit mining enterprises

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### Abstract

The prospects for implementing battery-powered dump trucks at open-pit mining enterprises are considered. Main attention is on the problem of charging infrastructure for adopting the unmanned production concept. The suggestion is to use wireless charging stations to join charging with particular technological operations, thereby reducing battery capacity and increasing the utilization rate of electric vehicles. To determine effective charging infrastructure solutions, it is necessary to evaluate the interaction between the dump truck and charging stations. The research aims to develop a model reflecting the power flows between the charging infrastructure and the dump truck battery while an operational process is being executed. The model takes into account the work cycle parameters, dump truck parameters with powertrain options providing energy recovery at braking, and charging infrastructure parameters in three options: one stationary charging station located outside the operating routes designed for the simultaneous charging of several dump trucks (option A); stationary charging stations for one dump truck located at loading points (option B); and a dynamic charging station that charges in motion (option C). The method for determining the power of a single wireless charging station is proposed, along with a related method for determining battery capacity. When establishing capacity, the parameters of the charge-discharge cycle and the charging current ratio are considered. The described model is implemented in MATLAB Simulink using *m*-files for processing satellite data of route parameters from geographic information systems, as well as elements of the Stateflow and Simscape Electrical libraries. The capabilities of the model were demonstrated on the example of the Lebedinsky GOK, with the BelAZ-7558E selected as a battery-powered dump truck. In the example considered, the total capacity of the wireless charging infrastructure for options A, B, and C was 10.6; 6.3, and 13.5 MW, with option B providing the highest value of the battery average state of charge of 0.65 p.u., with the lowest specific power demand per dump truck of 2.4 MW·h. The simulation results allow us to determine various operating factors of the system, evaluate the power compliance of system elements, compare wireless charging infrastructure options, and make informed design decisions.

### Keywords

dump truck; battery-powered electric vehicles; wireless charging station; charging infrastructure; work cycle; power flow; computer model

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## Introduction

The widespread adoption of digital technologies in production machines and mechanisms is a basic prerequisite for designing unmanned production. This process is also typical for mining [1]. For example, unmanned down-the-hole drills, scrapers, mining trucks, and charging vehicles have been developed for underground metal mine [2]. For open-pit mining enterprises, intelligent systems for



unmanned shovels [3, 4], dump trucks [5-7], and dispatching in shovel-truck systems with unmanned transport [8, 9] are being actively developed.

It is worth noting the growing role of electric transport in this process. Battery-powered electric vehicles have been thoroughly developed as objects of automation [10, 11]. The use of electric motors and batteries enables a higher level of energy efficiency of the vehicle itself [12]. Their integration with the power supply optimizes the overall energy consumption at the enterprise level [13]. Active developments are ongoing for battery-powered electric vehicles for open-pit mining [14, 15], for instance, such battery-powered dump trucks as eDumper [16], BYD V60 [17, 18], BelAZ-7558E [19], as well as battery-powered and autonomous Volvo HX series [20].

The article discusses battery-powered dump trucks. For open-pit mining enterprises, extensive areas and complex relief are typical. Due to heavy loads, the dump truck must have a large battery reserve on board or recharge the battery during the operational process. The technologies currently used for charging batteries require a wired connection to the power supply [21] or removal of a discharged battery and replacement with a charged one at a special battery swapping station [22, 23]. Both technologies require human participation, which contradicts the unmanned production concept. This contradiction can be overcome by developing additional automation tools. For an unmanned wired connection, an automated system can be considered, which includes a specialized vision system for parking and robotic connectors [24]. For battery swapping stations, robotic systems that operate on similar principles as [25] can be considered. Currently, there are no ready-made solutions for such automation systems designed for powerful, large-sized electric vehicles operating in dusty and vibration-intensive conditions, and the need for their development is an additional obstacle to implementing unmanned electric transport.

An alternative solution to the problem of charging battery-powered dump trucks within the unmanned production concept could be the wireless charging systems [26, 27]. Their additional advantage is the ability to join battery charging with particular technological operations, which increases the utilization rate of electric vehicles and allows using batteries with a lower capacity. However, wireless charging technology is currently in the early stage of commercial application, with various circuit designs being developed for charging station infrastructure, and no general guidance for selecting a specific design solution that takes into account a wide range of technical and economic factors. Any open-pit mining project requires significant investment and energy costs. In this regard, making design decisions is associated with high risks and requires a comprehensive analysis of possible options for wireless charging infrastructure.

Examples of adopting this technology for systems with relatively high power relate to the freight and passenger transportation field. Like urban electric transport, the open-pit mining operational process has a cyclical nature. Existing methods cannot be directly applied to the problem under consideration but can serve as a basis. Requirements for batteries and charging infrastructure capacity can be established analogously with [28, 29], which are concerned with electric buses, while considering differences in their operating conditions. It should be taken into account that the type and capacity of the battery used are significantly influenced not only by the operating conditions, but also by the selected charging scenario. To determine effective charging infrastructure solutions for various charging scenarios, it is necessary to conduct a thorough assessment of the interaction between the dump truck and charging stations and develop a model reflecting the power flows between the charging infrastructure and the dump truck battery while an operational process is being executed. The development of such a model is the objective of this research.

## Methods

*General approaches to the model.* The structure of the developed model is shown in Fig.1. The initial data used are the work cycle parameters and the dump truck parameters, which determine the power consumption of the battery.

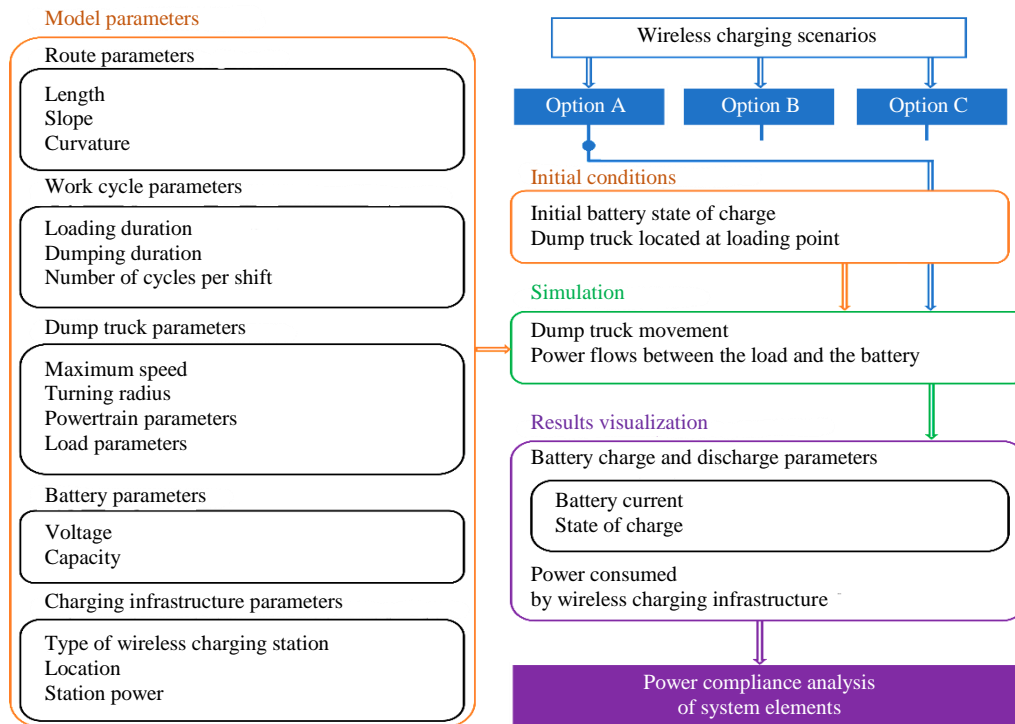


Fig. 1. The model structure

The work cycle is considered in a simplified form, omitting the quality of face preparation and the shovel efficiency, which excludes from consideration the downtime at the face while waiting for loading. The basic technological operations are loading and dumping with durations  $T_l$  and  $T_d$ , as well as the trip on the route. The duration of trip on the route depends on the route length  $L$  and the route profile, including its slope  $\alpha$  and curvature  $\kappa$ . The dump truck trip on straight sections of the route is assumed to be at a constant speed, and a slowdown occurs on sections with a curvature comparable to the turning radius of the dump truck  $R_t$ . Slowdowns due to traffic congestion or road surface deterioration are not taken into account.

The dump truck parameters for the model are divided into two groups: those describing the powertrain and those determining the load on the motor-wheels. The first group includes the gearbox gear ratio  $i$ , the radius of the dump truck wheels  $R_w$ , the efficiency of the gearbox  $\eta_g$ , and the motor-wheel  $\eta_m$ . The second group includes the dump truck empty weight  $M_d$  and its payload  $M_p$ , the coefficient of rolling friction  $f$  for the tire type used, the frontal area of the dump truck  $A$ , and the coefficient of frontal resistance  $C$  to air with density  $\rho$ . The simulation assumes that the dump truck trip to the unloading point is uphill (the average value of  $\alpha$  is positive), the transported rock mass is constant and equal to the payload  $M_p$ , and the trip to the loading point is downhill with the empty dump truck. The coefficient  $f$  is assumed to be constant, regardless of seasons and possible precipitation.

During the simulation process, the shaft power consumed by the motor-wheel is determined, having the battery as the source. The power consumed by any other electrical receivers connected to the battery is negligible. The motor-wheel transients are not considered. The power electrical converters that control the motor-wheels and battery charging are assumed to be ideal. The powertrain is considered in two options: one that provides energy recovery to the battery at braking, and one that does not. The initial battery parameters for this model are the nominal voltage  $U$  and the capacity  $AH$ .

Battery is recharged using wireless charging stations, with the following options being considered: A. One stationary charging station located outside the operating routes and designed for the simultaneous charging of several dump trucks. B. Stationary charging stations for one dump truck located at loading points. C. A dynamic charging station that charges in motion. The input parameters of the wireless



charging infrastructure are the station power  $P_e$ , the efficiency  $\eta$ , and the location. In option A, it is assumed that the wireless charging station is located at a distance  $L_c$  from the unloading point, and the dump truck is sent there after a specified number  $N$  of loading and unloading cycles. In option B, the route section equipped with the proper infrastructure has a length of  $L_d$  and begins at a distance of  $L_s$  from the loading point. The battery charge duration for option A is limited by the specified time  $T_c$ , for option B by the duration  $T_l$ , and for option C by the duration of the dump truck trip on the equipped route section.

The battery charging occurs when the dump truck is at the location where the wireless charging infrastructure is located, provided that the current state of charge  $SOC$  has reached the lower threshold. The charging current value is determined by the battery type and is specified by the ratio  $K_c$  to the battery capacity in ampere-hours. If  $SOC$  reaches the upper threshold during charging, wireless power transfer ceases. While the battery is charging, the wireless charging station consumes power from the power supply. The idle power consumption of the station is set at 1 % of  $P_e$ .

*Determining the battery load.* Accurate assessment of energy consumption is crucial for electric vehicles due to the limited battery capacity. Various approaches to addressing this problem are outlined in [30-32]. This research primarily focuses on the route parameters that are associated with acceleration-deceleration patterns.

The power consumption from the battery is determined by the power consumed by the in-wheel motors:

$$P_m = M_m \omega_m \frac{1}{\eta_m}, \quad (1)$$

where  $\omega_m$  is the motor angular speed;  $M_m$  is the torque on the motor shaft,

$$M_m = M_w \frac{1}{i \eta_g};$$

$M_w$  is the torque on the wheel, calculated according to [33] from the ratio

$$\frac{M_w}{R_w} = mg \sin \alpha + \rho CA \frac{v^2}{2} + mgf \cos \alpha + v \frac{dv}{dt};$$

$m$  is the dump truck weight,  $m = M_d + M_p$  for the trip from the loading point to the unloading point,  $m = M_d$  for the trip in any other direction;  $v$  is the dump truck velocity.

The angular speed is calculated according to equation

$$\omega_m = v \frac{i}{R_w}, \quad (2)$$

where the velocity  $v$  is changed to ensure a safe velocity of motion on the curved section. According to [34], this dependence is complex. In this research, assuming that the tire grip on the road is constant, it is approximated by an exponential function depending on the route curvature  $\kappa$ :

$$v = v_{\max} \left( 1 - e^{-\frac{\kappa}{2\kappa R_t}} \right), \quad (3)$$

where  $v_{\max}$  is maximum velocity of the dump truck.

Parameters  $\alpha$  and  $\kappa$  vary along the route length. Considering newly established open-pit mining enterprises, their design values should be used. For active enterprises, using geodetic information [35] is the best solution. If instrumental measurements are not possible, the satellite data from geographic information systems is used. It is proposed to use Google Maps API to obtain the latitude  $\phi$  and



longitude  $\lambda$  coordinates of route points, and Elevation API to determine their above sea level height  $h$ . In this case, the slope in degrees is determined as

$$\alpha = \arctan\left(\frac{\Delta h}{\Delta d}\right), \quad (4)$$

where  $\Delta h$  is the difference in the two above sea level heights ( $h_2 - h_1$ ) of two adjacent route points with latitude and longitude coordinates  $\phi_1, \lambda_1$ , and  $\phi_2, \lambda_2$ ;  $\Delta d$  is the distance between these points, calculated using the haversine formula

$$\Delta d = 2r \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right),$$

$r$  is the radius of the Earth. The distance travelled by the dump truck along the route between these points will be equal to

$$\Delta l = \frac{\Delta d}{\cos \alpha}. \quad (5)$$

To determine  $\kappa$ , coordinates given by latitude and longitude are transformed into a Cartesian coordinate system with the  $x$ -axis pointing east and the  $y$ -axis pointing north:

$$\begin{aligned} x &= (r + h) \cos \phi \cos \lambda; \\ y &= (r + h) \cos \phi \sin \lambda, \end{aligned} \quad (6)$$

in which

$$\kappa = \frac{\left| \frac{\partial x}{\partial l} \frac{\partial^2 y}{\partial l^2} - \frac{\partial y}{\partial l} \frac{\partial^2 x}{\partial l^2} \right|}{\left( \left( \frac{\partial x}{\partial l} \right)^2 + \left( \frac{\partial y}{\partial l} \right)^2 \right)^{3/2}}. \quad (7)$$

Since all parameters in equations (1)-(7), which describe both the powertrain and the load on the motor-wheels, are known with some error, when determining the power of the wireless charging stations and the battery capacity, the corresponding reserve factors should be set.

*Determination of stations' power.* The power of the single wireless charging station, as well as the entire infrastructure, is determined using the energy balance method similar to [36]. The basis is the power required to fully charge one dump truck after a single cycle. Depending on the scenario chosen, the maximum number of dump trucks  $K$  simultaneously charging from the station, the total number of technological routes of the enterprise  $F$ , and the number of sections  $H$  equipped with dynamic charging infrastructure are taken into account.

Table 1 presents the general calculation procedure, where  $T_o$  is the trip time from the loading point to the unloading point;  $T_m$  is the trip time from the unloading point to the wireless charging station location;  $T_{cd}$  is the trip time along the route section equipped with the dynamic charging infrastructure;  $P_l$  is the average power consumed from the battery by one cycle;  $P_e$  is the installed power of the wireless charging station.

The trip time on different sections:

$$\begin{aligned} T_o &= \left\{ t \mid l(t) = \int v dt \rightarrow L^- \right\} - \left\{ t \mid l(t) \rightarrow 0^+ \right\}; \\ T_m &= \left\{ t \mid l(t) = \int v dt \rightarrow L + L_c^- \right\} - \left\{ t \mid l(t) \rightarrow L^+ \right\}; \\ T_{cd} &= \left\{ t \mid l(t) = \int v dt \rightarrow L_s + L_d^- \right\} - \left\{ t \mid l(t) \rightarrow L_s^+ \right\}. \end{aligned}$$



The average power is defined as

$$P_l = \frac{1}{T_{cd}} \int_0^{T_{cd}} P_m dt; \quad (8)$$

$$P_l = \frac{1}{T_{cd}} \int_0^{T_{cd}} \{P_m | P_m(t) > 0\} dt, \quad (9)$$

formula (8) is used for the option when energy recovery to the battery at braking is provided, and formula (9) is used when it is not.

The installed power is defined as

$$P_e = P_s \frac{k_p}{\eta},$$

where  $k_p$  is the reserve factor.

Table 1

Calculation formulas depending on the wireless charging scenario chosen

| Value  | Option A                            | Option B                    | Option C  |
|--|-------------------------------------|-----------------------------|---|
| Discharge duration per cycle $T_{cd}$                      | $2\left(T_o + \frac{T_m}{N}\right)$ | $2T_o$                      | $2T_o$  |
| Charge duration per cycle $T_{ch}$                         | $\frac{T_c}{N}$                     | $T_l$                       | $2T_{cd}$   |
| Wireless charging station output power $P_s$               | $P_l \frac{T_{cd}}{T_{ch}} K$       | $P_l \frac{T_{cd}}{T_{ch}}$ | $P_l \frac{T_{cd}}{T_{ch}} K; K = \left[ \frac{T_d}{L_d / \langle v \rangle} \right]$ |
| Total power of wireless charging infrastructure $P_\Sigma$ | $P_e$                               | $\sum_{i=1}^F P_{e_i}$      | $\sum_{i=1}^H P_{e_i}$  |

*Relationship between station power and battery capacity.* The battery capacity must be calculated based on the required run  $S$ , which depends on the wireless charging infrastructure option. For option A, the run  $S$  is determined as  $2(LN+L_c)k_a$ , and for options B and C is determined as  $2Lk_a$ , where  $k_a$  is the reserve factor. Under these conditions:

$$AH = \frac{P_l(T_{cd} + T_l + T_d)S}{3600UL}.$$

It should be noted that the battery charging current is limited. If the charging time is less than  $3600/K_c$ , the battery capacity must be increased proportionally. As the power of the wireless charging station is limited, the condition must be met

$$P_e \geq \frac{UAK_c}{\eta},$$

otherwise, the installed power of the wireless charging station must be increased proportionally.

The consumed current of the battery (assumed positive) or its current output is determined from the ratio

$$IU = \begin{cases} UAK_c - P_m & \text{while wireless charging;} \\ -P_m & \text{outside the charging station,} \end{cases}$$

besides, if the considered option is not providing energy recovery to the battery at braking, the value of  $P_m$  is only considered under the condition that  $P_m > 0$ .



The battery charge-discharge model can be implemented with different levels of detail [37-39]. In this research, the current state of charge of the battery is determined based on  $I$  using the coulometric method:

$$SOC = SOC_0 + \frac{1}{3600AH} \int Idt,$$

where  $SOC_0$  is the initial state of charge, and the current battery voltage depends on  $SOC$  as follows:

$$V = U \left( \frac{SOC}{1 - \beta(1 - SOC)} \right),$$

$\beta$  is the slope coefficient that is calculated so that the battery voltage is  $V_1$  when the given current capacity is  $AH_1$ .

It should be also taken into account that high  $K_c$ , ensuring rapid battery recharge, also contributes to accelerated fade. The main factors influencing battery fade are described in [40]. Based on them, rational parameters of the charge-discharge cycle should be formed (Fig.2).

The  $SOC_{on}$  and  $SOC_{off}$  values represent thresholds for activating and ceasing wireless power transfer when the dump truck is located at the wireless charging infrastructure location. When the dump truck is on the route,  $SOC$  may either increase above  $SOC_{off}$ , for example, due to energy recovery when downhill, or decrease below  $SOC_{on}$ . Reducing both  $\langle SOC \rangle$  and  $(SOC_{max} - SOC_{min})$  will help slow battery fade. Specific  $SOC_{on}$  and  $SOC_{off}$  values should be adjusted based on simulation results. However, to prevent battery overcharging,  $SOC_{off}$  should be set to less than one, proportionally increasing battery capacity.

### Results and discussion

*Computer model.* The described mathematical model is implemented using MATLAB Simulink. Processing of the route parameters is implemented as separate  $m$ -files, whose results are exported to 1-D Lookup Table. The computer model uses two of these elements: the first contains the dependence  $h(l)$ , and the second contains  $\kappa(l)$ .

Scenarios for the choice of trip direction along the route and activating-and-ceasing of wireless power transfer are implemented using Stateflow.Chart (Fig.3). The initial state is assumed to be that the dump truck has arrived at the loading point, that is, at  $t = 0$ , the value  $l = 0$ , and its battery is charged to  $SOC_0$ .

The computer model of the battery is implemented using the Simscape Electrical library (Fig.4), while the remaining model elements are based on standard Simulink library blocks. The Battery block of the Simscape Electrical library provides additional tools to enhance the battery

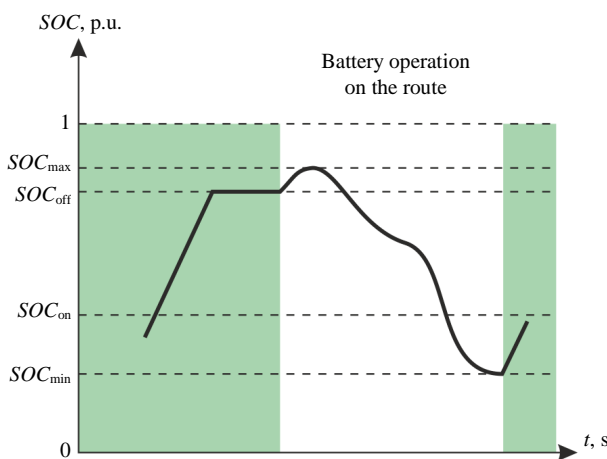


Fig.2. Charge-discharge cycle

model parameters. For example, the Thermal port setting allows, if necessary, to include in calculations the dependence of battery voltage and discharge curve parameters on battery temperature, while the Battery fade setting allows for battery fade. By default, the settings Thermal port and Battery fade are disabled.

*Simulation results.* The values of the computer model parameters are given in Table 2. The Lebedinsky GOK was taken as the model enterprise, for which the dump truck route location and the wireless charging infrastructure location were selected (Fig.5). The parameters of the wireless charging infrastructure were taken according to [36].

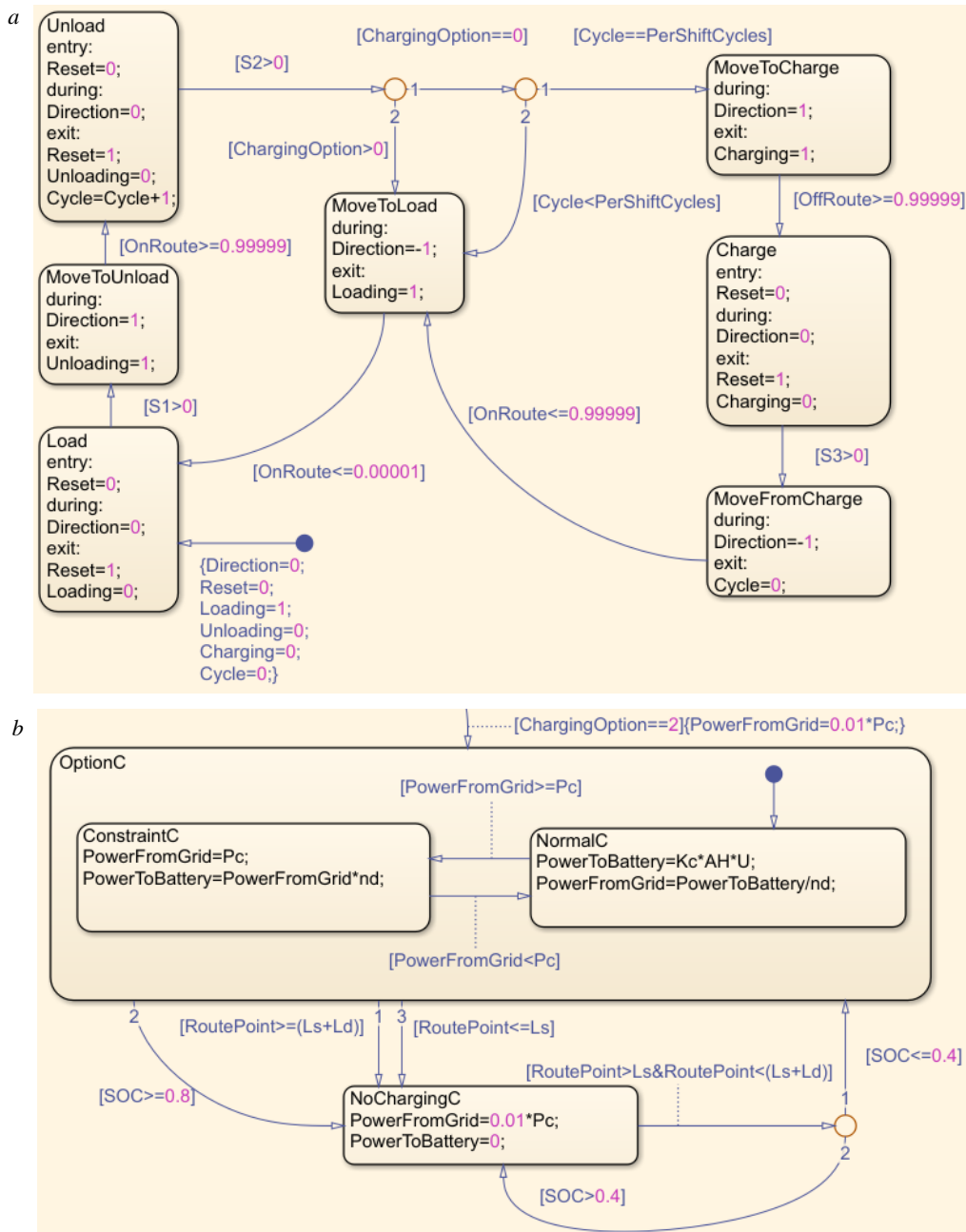


Fig.3. Fragments of the scenario interaction implementation:  
 a – choice of trip direction; b – wireless power transfer in option C

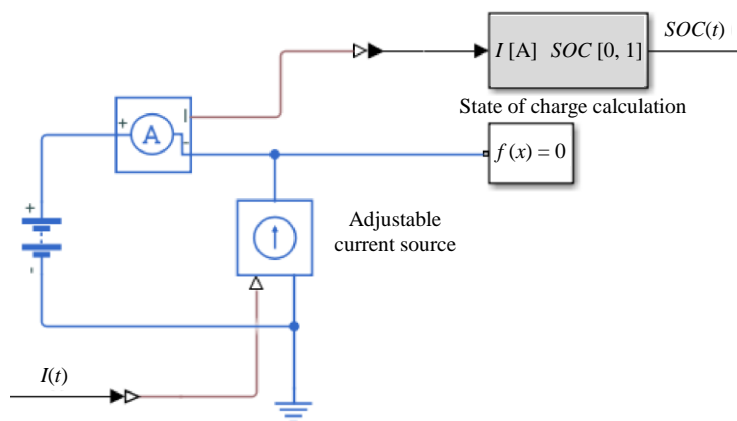


Fig.4. Implementation of the battery



Table 2

| Computer model parameters  |        |                    |          |          |          |
|----------------------------|--------|--------------------|----------|----------|----------|
| Parameter                  | Value  | Parameter          | Value    |          |          |
|                            |        |                    | Option A | Option B | Option C |
| $v_m$ , m/s                | 5.1667 | $P_e$ , MW         | 10.564   | 0.566    | 7.517    |
| $i$ , p.u.                 | 30.36  | $\eta$ , p.u.      | 0.95     | 0.95     | 0.4      |
| $R_w$ , m                  | 1.3395 | $AH$ , Ah          | 2472     | 412      | 412      |
| $R_t$ , m                  | 11     | $AH_1$ , Ah        | 1236     | 206      | 206      |
| $M_d$ , t                  | 74     | $SOC_{on}$ , p.u.  | 0.75     | 0.75     | 0.4      |
| $M_p$ , t                  | 90     | $U$ , V            | 712.8    |          |          |
| $\eta_g$ , p.u.            | 0.97   | $V_1$ , V          | 677.16   |          |          |
| $\eta_m$ , p.u.            | 0.98   | $SOC_0$ , p.u.     | 0.8      |          |          |
| $f$ , p.u.                 | 0.008  | $SOC_{off}$ , p.u. | 0.8      |          |          |
| $C$ , p.u.                 | 0.7    | $L$ , m            | 3860     |          |          |
| $A$ , m <sup>2</sup>       | 12.4   | $L_s$ , m          | 1620     |          |          |
| $\rho$ , kg/m <sup>3</sup> | 1.2255 | $L_d$ , m          | 1300     |          |          |
| $g$ , m/s <sup>2</sup>     | 9.8    | $L_c$ , m          | 4200     |          |          |
| $T_l$ , s                  | 460    | $N$                | 20       |          |          |
| $T_d$ , s                  | 100    | $T_c$ , s          | 1800     |          |          |

The BelAZ-7558E was selected as the model for the dump truck, and its powertrain and load parameters were used. The battery parameters differ from those of the BelAZ-7558E and were selected with the above-described approach. The specific battery type and its parameters were chosen from the options outlined in [41-43]. The best match to the calculated battery parameters was found to be for a lithium-iron-phosphate battery with a nominal capacity of 412 Ah. This battery was used for options B and C, and 6 units connected in parallel were used for option A.

The work cycle parameters should ideally be determined in conjunction with the optimization tools of the shovel-truck systems, as mentioned in [8, 44]. If such tools are not available, operational indicators are used. The values of average durations described in [45] were used as parameters of the model work cycle.

The simulation results allow us to determine various operating factors of the system and evaluate the power compliance of system elements. As an example, Fig.6 provides the transient curves of motor torque and angular speed of the truck motor-wheel for the trip along the route.

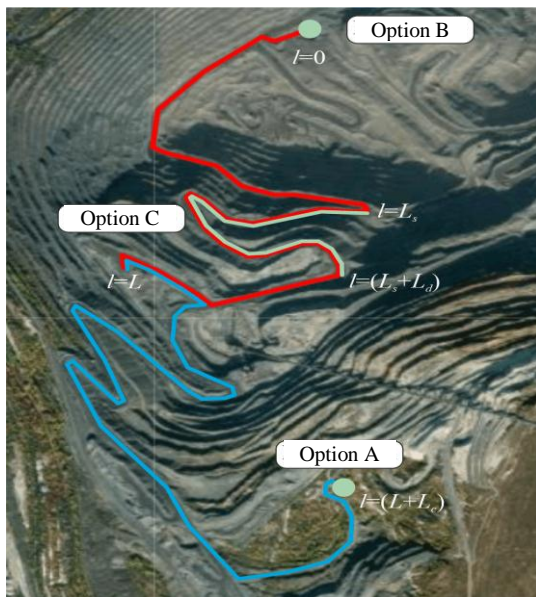


Fig.5. Location of the route and the wireless charging infrastructure

Analysis shows that the in-wheel motor spends most of the time of the dump truck trip in braking mode. If energy recovery to the battery at braking is not provided, then maintaining a rhythmic and continuous system operation is only possible by increasing the instantaneous power transferred to the battery from the wireless charging station. This increase can be achieved by increasing  $K_c$ .

As an illustration, Fig.7 shows transient curves of battery state of charge changes for different options of charging infrastructure. In the simulation, initially,  $K_c = 3$  was used to bring the battery charging time closer to the corresponding for the BelAZ-7558E. As can be seen in Fig.7, a, d, if energy recovery is provided, the battery is fully charged by one charge per cycle for both static (option B) and dynamic charging (option C).

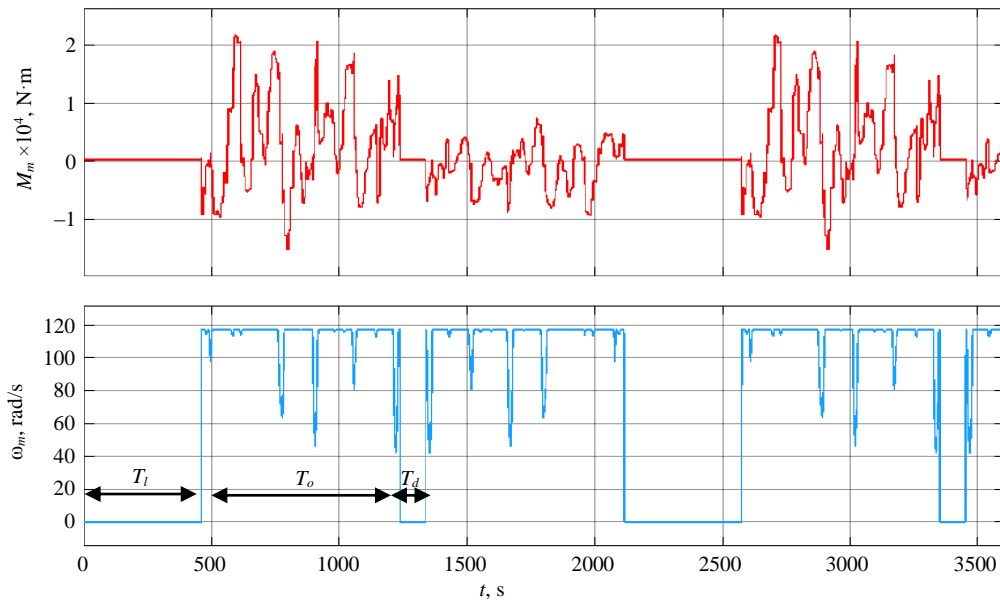


Fig.6. Transient curves of  $\omega_m(t)$  and  $M_m(t)$

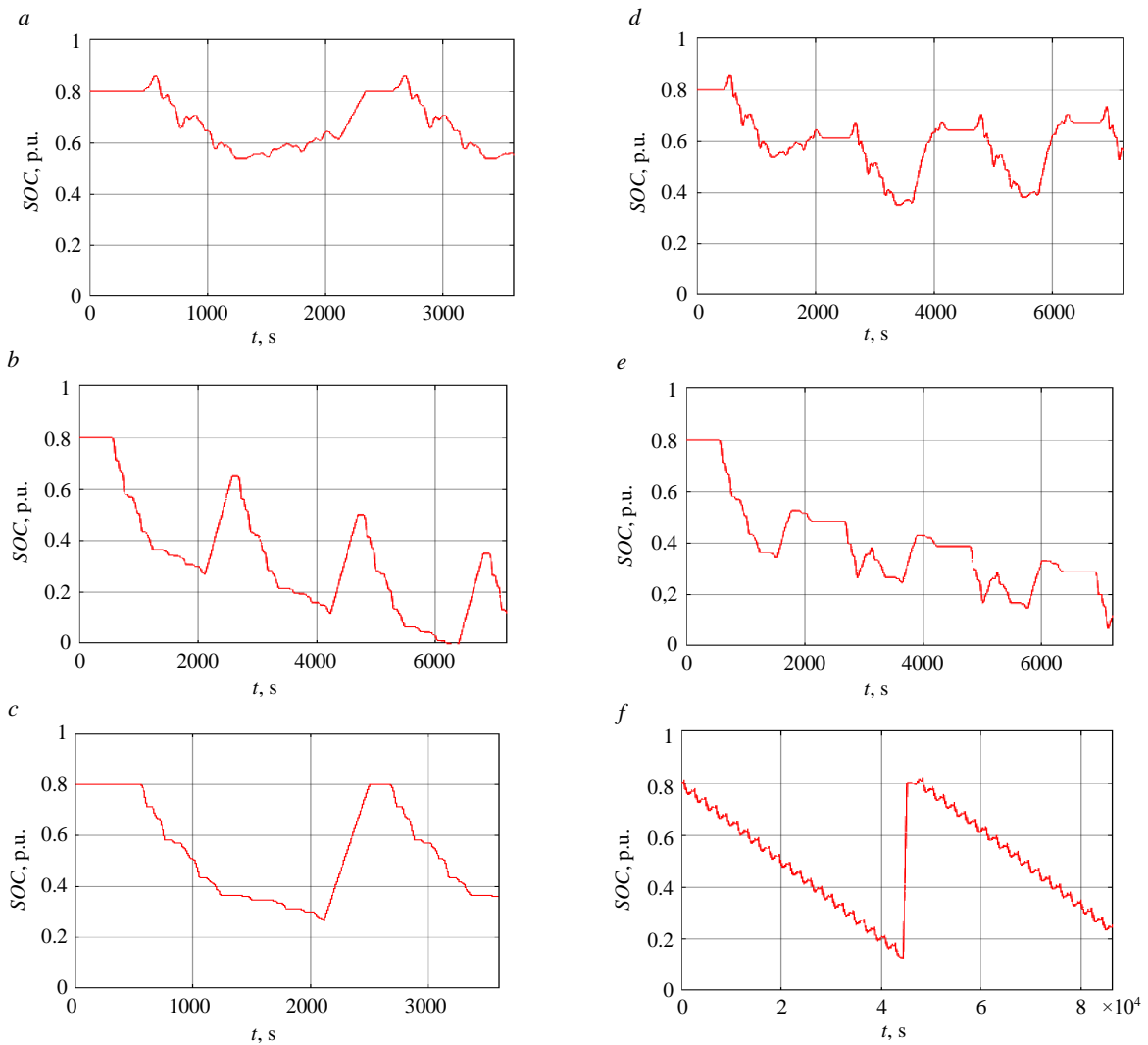


Fig.7. Transient curves of  $SOC(t)$ : *a* – option B, with energy recovery,  $K_c=3$ ; *b* – option B, no energy recovery,  $K_c=3$ ; *c* – option B, no energy recovery,  $K_c=5$ ; *d* – option C, with energy recovery,  $K_c=3$ ; *e* – option C, no energy recovery,  $K_c=3$ ; *f* – option A, with energy recovery,  $K_c=3$



If energy recovery at braking is not provided, for option B and option C, the battery is fully discharged within three cycles (Fig.7, *b*, *e*). However, increasing the charging current to  $K_c = 5$  maintains continuous operation of the dump truck (Fig.7, *c*).

In addition to operational continuity assessment, Fig.7 allows us to compare the rate of battery fade for different scenarios of interaction between the dump truck and the charging infrastructure. Figure 7, *c* demonstrates a higher difference ( $SOC_{max} - SOC_{min}$ ) at a higher charging current, which indicates, in comparison with Fig.7, *a*, a known shortage of the battery life for the options where energy recovery is not provided. Similarly, comparing Fig.7, *a* and *d*, it can be noted that with the same charging current and a similar difference ( $SOC_{max} - SOC_{min}$ ), the  $\langle SOC \rangle$  value for option B is lower. Therefore, with dynamic wireless charging, the battery life will be longer than with static wireless charging once per cycle.

A similar comparison with option A (Fig.7, *f*) is not possible due to the different battery capacities and charge-discharge cycle durations. It should be noted that with  $K_c = 3$  and one-charge operating range of more than 10 h, the  $\langle SOC \rangle$  value is approximately 0.38 with ( $SOC_{max} - SOC_{min}$ ) close to the 80-20 cycle recommended by battery manufacturers. This option is closest in battery parameters to the BelAZ-7558E, which operates with wired charging stations.

The comparison of power consumption by wireless charging infrastructure from the power supply is of interest. The results under consideration correspond to the single dump truck operation, while options A and B assume the possibility of simultaneous wireless charge for several vehicles. Thus, there is a good reason to consider the specific power consumption per dump truck and, taking into account the different charge-discharge cycle durations, to compare the daily power consumption  $W_e$ . If energy recovery at braking is provided and  $K_c = 3$ , the daily power consumption per dump truck for option A is 3.8 MW·h, for option B is 2.4 MW·h, and for option C is 7 MW·h. This is explained by the lower power of the wireless charging station for option B and a significantly higher efficiency for the stationary charging stations. As a result, although option A has a higher power of the charging station than option C, the power consumption for option A is lower. Moreover, options B and C have a higher specific utilization factor  $k_u$ .

A summary comparative analysis of the wireless charging infrastructure options when energy recovery at braking is provided, and  $K_c = 3$  is presented in Table 3. The following conclusions can be drawn. An average battery state of charge is close to 0.5 for all options, which indicates similarly efficient aging of the battery. However,  $AH$  for option A is significantly higher, indicating higher investment and operating costs for battery replacement, as the battery life is significantly shorter than that of a dump truck. In terms of installed power, which reflects investment costs, and energy consumption, which reflects operating costs, option B is the best, while option C is the worst. Based on the entire set of operational characteristics, option B is the best.

Table 3

Summarizing model parameters

| Parameter                    | Value    |          |          |
|------------------------------|----------|----------|----------|
|                              | Option A | Option B | Option C |
| $P_{\Sigma}$ , MW            | 10.6     | 6.3      | 13.5     |
| $P_e$ , MW                   | 10.6     | 0.6      | 7.5      |
| $W_e$ , MW·h                 | 3.8      | 2.4      | 7        |
| $k_u$ , p.u.                 | 0.04     | 0.16     | 0.19     |
| $AH$ , Ah                    | 2472     | 412      | 412      |
| $SOC_{min}$ , p.u.           | 0.12     | 0.54     | 0.32     |
| $SOC_{max}$ , p.u.           | 0.82     | 0.86     | 0.86     |
| $\langle SOC \rangle$ , p.u. | 0.44     | 0.65     | 0.52     |

## Conclusion

This paper proposes a mathematical model describing the interaction of the battery-powered dump truck with the wireless charging infrastructure under various charging scenarios. The model serves as a tool for comparing wireless charging infrastructure options and making design decisions. It describes the power flows between the charging infrastructure and the dump truck battery while an operational process is being executed. Under the assumptions of the constant duration of loading and dumping, the constant dump truck velocity on straight sections of the route, the constant coefficient of rolling friction, battery capacity and its discharge curve parameters, the



model allows us to calculate the parameters of the battery and wireless charging stations and to determine various operational characteristics of the system, in particular the power consumption of the charging stations.

The assumptions described restrict the application of the proposed mathematical model to the design stage. To improve its adequacy in actual practice, the model should be supplemented with components that more closely account for operational conditions, and the model parameters that affect energy consumption during route travel should be adjustable. For example, the coefficient of rolling friction  $f$  should be dynamic and dependent on the wear-out rate of the truck tire, temperature conditions, and precipitation. When determining the dump truck velocity  $v$  for the trip along the route, instead of the dependence on the curvature  $\kappa(l)$ , the dependence  $v(l)$  generated by statistical processing of operational dump truck tachograms should be used. This will consider the road surface conditions and the likelihood of congestion for the specific route and the specific dispatching system used. The transported material weight should be dynamically adjusted depending on the quality of the face preparation, which determines the particle size distribution of the transported material. These modifications are the subject of further research.

To implement the proposed mathematical model, the computer model in MATLAB Simulink was developed. This model was used to carry out the research for a specific dump truck operating on a given route in conjunction with one stationary charging station located outside the route, several stationary charging stations at the loading points, or the dynamic charging station that charges in motion. Dump truck powertrain options are considered providing energy recovery at braking and not. It is shown that the option without energy recovery is less efficient in energy performance and causes more accelerated battery aging. Among the charging infrastructure options, the charging stations at the loading points demonstrated the best performance. In the considered example, this charging infrastructure option consumes 37 % less electricity than the infrastructure with a stationary charging station located outside the route, and 66 % less than with the dynamic charging station that charges in motion, while providing  $\langle SOC \rangle$  higher by 48 and 25 %, respectively.

The research demonstrated that, given the parameters of the work cycle, the dump truck, and the route, it is possible to optimize the cooperative effort of electric vehicles at open-pit mining enterprises and the wireless charging infrastructure. The development of such optimization methods is the subject of further research. With the described model modification, periodic adjustments of the system power consumption parameters can be made while operating, taking into account the face advancing, the changes in condition of the operating routes, as well as seasonal changes, including temperature and precipitation. Based on these adjustments, regular adjustments to the optimization algorithms can be made.

The proposed model can also be used as a foundation for a more detailed analysis of the battery fade, evaluating the effects of temperature on it and identifying the technical and economic parameters of the system under consideration.

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