INITIAL CURRENT REDUCTION OF SYNCHRONOUS MOTORS WITH SALIENT POLES BY STATIC CONVERTERS USAGE

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The paper analyses the possibility of reducing the initial current of synchronous motor used for powering an excavator in an open coal-pit. The main generator group, which consists of three DC generators S = 1250 kW, reaches the torque moment through synchronous motor with salient poles usage, S_r = 1250 kW. The motor is accelerated as asynchronous squirrel cage motor, drawing attention to the machine acceleration period till the moment it enters synchronism. During this period, lasting up to 15 seconds, it is necessary to connect the rotor winding through a resistor, to start the acceleration as asynchronous motor and pull the machine into synchronism. After that, a synchronous motor powers the DC generators and operates as a synchronous compensator. The excitation circuits of electromotor were originally powered by the DC generators. Now, these systems are replaced by more efficient thyristor static converters. In this way, the excavator efficiency is increased, a faster response of excitation circuit is obtained and initial currents of synchronous motor are significantly reduced.

Keywords: *DC generators, initial current, synchronous motor, thyristor rectifier*

Smanjenje struje pokretanja sinhronih motora s istaknutnim polovima pomoću statičkih pretvarača

U članku je analizirana mogućnost smanjenja struje pokretanja sinhronih motora za potrebe pogona bagera za otvoreni kop ugljena. Glavna generatorska skupina koja se sastoji od tri generatora istosmjerne struje S = 1250 kW dobiva okretni moment pomoću sinkronog motora sa istaknutim polovima S_r = 1250 kW. Motor se zaliJeće kao asinkroni kavezni motor što usmjerava pozornost na period zaleta stroja do ulaska u sinkronizam. Tijekom tog perioda, koji traje do 15 sekundi, neophodno je namot rotora spojiti preko otpornika, pokrenuti zalet kao asinkroni motor i uvesti stroj u sinkronizam. Nakon toga sinkroni motor pokreće generatore istosmjerne struje i radi kao sinkroni kompenzator. Uzbudni krugovi elektromotora prvotno su bili napajani iz generatora istosmjerne struje pogonjenih asinkronim motorom. Sada su ti sustavi zamjenjeni učinkovitijim tiristorskim statičkim pretvaračima. Na ovaj je način povećan stupanj korisnog djelovanja bagera, dobiven je brži odziv uzbudnog kruga i značajno su smanjene struje pokretanja sinkronog motora.

Ključne riječi: *generatori istosmjerne struje, sinkroni motor, struja pokretanja, tiristorski ispravljač*

1 Introduction

ES-6/45 dragline excavators, which are primarily used for the excavation in the open trench of a coal mine, operate on different surfaces during coal mining works. These machines are highly productive, operating 24 hours a day with the average life span of 40 years and have the lowest cost of material removal per unit. For the powering of the main generator group, which consists of three DC generators with total capacity S_r = 1250 kW, synchronous motors with salient poles, rated power S = 630 kV·A, are applied. The observed synchronous motor has special construction / performance because it accelerates as an asynchronous squirrel cage motor. Special attention should be paid to the acceleration period of the machine till it is pulled into synchronism, which takes up to 15 seconds. In this period, it is necessary to connect the rotor winding through the resistor, start the acceleration as asynchronous motor and pull the machine into synchronism. After that, a synchronous motor powers the DC generators and works as a synchronous compensator. Taking into consideration the excavators' manufacturing date, technical solutions used at that time and their long life span, some original technical solutions have become outdated in the meantime, so it is necessary to replace them with new, more efficient solutions. The original powering by Ward Leonard group, with two DC generators powered by asynchronous motors was replaced by thyristor static converters. In this way, excavator efficiency has been increased, faster response of the excitation circuit has been obtained and initial currents of synchronous motor have been significantly reduced.

When selecting static devices for DC powering and synchronous motor drivers, it is necessary to take into consideration the specifics of the motor drive. Synchronous motor is started 3 times in 24 hours. Attention should be paid to its electrical characteristics and working conditions. The paper presents an approach to the selection of an appropriate DC supply of such specific high-power electric motors and their impact on reducing the initial current of synchronous motor on the ES-6/45 excavator.

For both DC machines excitation circuits and synchronous motor power supply, rotational systems of Ward Leonard group, with two generators connected to the asynchronous motor shaft, were originally used. Ward-Leonard groups are nowadays mostly replaced by static excitation systems. The main generator group is powered by synchronous motor of 630 kV·A, the mechanical characteristic of which does not depend on the load.

A synchronous motor with salient poles can be described by the following equations [1]:

The apparent power is presented by formula:

$$|\underline{S}| = \sqrt{P^2 + Q^2} \,. \tag{1}$$

Active power is described as:

$$P = \frac{3 \cdot U \cdot E}{X_d} \cdot \sin\delta + \frac{3 \cdot U^2 \cdot \sin 2\delta}{2} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d} \right). \tag{2}$$

Reactive power is expressed as:

$$Q = \frac{-3 \cdot U \cdot E}{X_d} \cdot \cos\delta + 3 \cdot U^2 \cdot \left(\frac{\sin^2\delta}{X_q} + \frac{\cos^2\delta}{X_d} \right). \qquad (3)$$

And moment is presented by:

$$M = \frac{3 \cdot U \cdot E}{\omega \cdot X_d} \cdot \sin\delta + \frac{3 \cdot U^2 \cdot \sin 2\delta}{2 \cdot \omega} \cdot \left(\frac{1}{X_q} - \frac{1}{X_d} \right). \qquad (4)$$

Fig. 1 shows three different moments: synchronous M_s, reluctance M_r and total moment M.
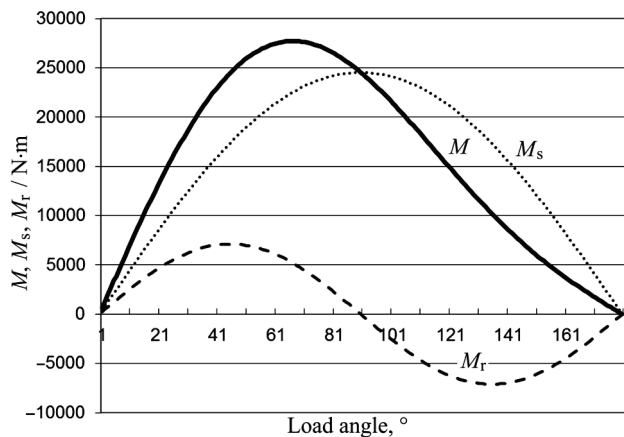

Figure 1 The mechanical characteristic of synchronous motor with salient poles

Since the machine has specific construction (it consists of two machines located in one), we should stress the importance of how it is started. In the initial stage the synchronous motor actually works as asynchronous, and that period is limited to 10 seconds. During the motor starting period three DC generators are started, too.

Although DC generators are unloaded, ample masses of the rotor are significant and represent the real load which influences the initial current and moment. All electrical devices are powered by high voltage cables, which are exposed to external influences and which are moved together with electrical equipment.

DC motors which drive the working mechanisms of excavators have the constant power supply independent of the load, which enables the excavator to freely perform its function in different operation modes. Drive mechanisms in the excavator operational cycle work at different speed and often with different direction of rotation which varies widely. This system has special construction because one generator supplies two DC motors that drive one working mechanism. Therefore, all electric motors require quality DC power supply for excitation windings and a sufficiently quick response [2].

Synchronous motor drives three DC generators whereby lifting and digging generators have the installed power capacity of 500 kW and the rotating generator power capacity of 250 kW, shown in Fig. 2. Lifting and digging generators supply electricity to DC motors with the installed power capacity of 2 × 190 kW while the rotating generator supplies electricity to motors with the installed power capacity of 2 × 100 kW. The synchronous motor with a relatively high installed power capacity of 630 kV·A [3] has been designed for DC generators drive. For the power supply of excitation circuits of the motor and generator, it is necessary to ensure quality DC power supply.

The static excitation systems of synchronous machines consist of the following parts:

- excitation transformer
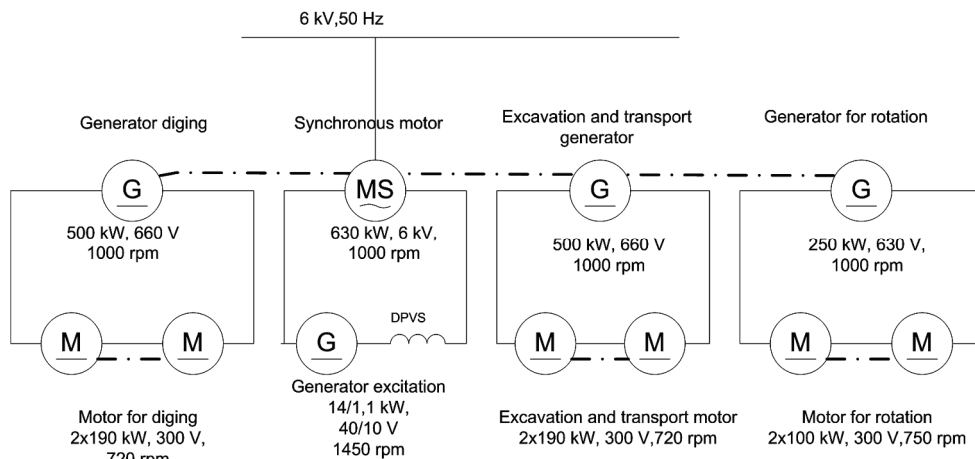- thyristor rectifier
- digital regulator.

Figure 2 Ward Leonard group on the ES-6/45 excavator

Therefore, it is extremely important to dimension the cables properly, that is, not to over-dimension them for easier manipulation, or, more precisely, to reduce mechanical damage of electric cables.

In this way, all three DC generators rotate at a constant speed regardless of the load of the motors. In the case of torque variation, DC generators would not be able

to produce the necessary energy for DC motors at higher loads.

- de-excitation circuit
- overvoltage protection.

Excitation power is obtained through the excitation transformer and thyristor rectifier, connected to the

synchronous motors connection. In comparison with other types of excitation systems, static excitations have the following advantages:

- there are no rotating parts
- greater reliability
- high efficiency
- faster regulation response speed
- low maintenance costs
- dimensions independence from machine speed and power capacity
- nonexistence of rotating masses
- higher regulation speed
- increased availability.

By installation of microprocessor control units, the device acquires the following advantages:

- great operational speed
- greater reliability and accuracy
- better communication and automatization
- simpler testing and monitoring
- simpler maintenance
- accurate repeatability and stability of the preset values.

When selecting the excitation system, attention should be paid to the compatibility of the device with motor operating conditions. In this case, the excitation system with thyristors in anti-parallel circuit was used, while control and management system is performed by a microprocessor.
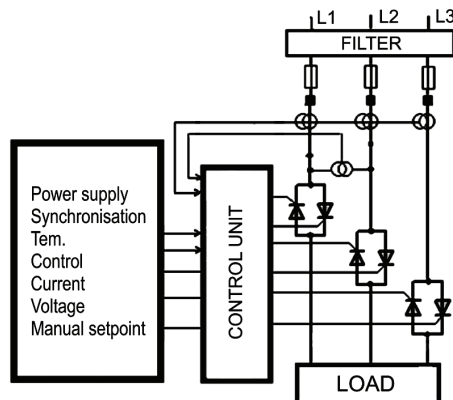

Figure 3 Excitation system scheme

2.1 Ward Leonard system

Ward Leonard system has been implemented since 1891 and the same system can be found in many power systems today. The system consists of a drive motor, which is usually asynchronous, and two DC generators. On the ES-6/45 excavator the induction motor runs two DC generators on its axis, as is shown in Fig. 4.
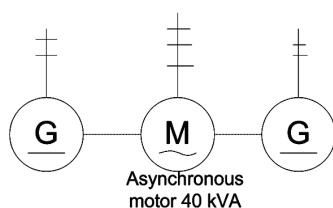

Figure 4 Ward Leonard group

2 The role of LeBlanc's absorber in synchronous motor operation

Synchronous motors with salient poles are not able to get started themselves. One way of starting them is the usage of LeBlanc's absorber when the machine starts as asynchronous motor. To avoid electric shock, the stator is connected to a lower voltage ranging between $0,25U_r$ and $0,3U_r$. The rotor begins to rotate, where the LeBlanc's absorber is in fact the rotor in a short circuit. When the rotor speed almost reaches synchronous speed of rotation, the rotor excitation is carried out to attach it to the stator rotation flux and to pull it into synchronism. Finally, the voltage is raised to the nominal value and the rotor begins to rotate at synchronous speed.

During the synchronous speed of rotation in LeBlanc's winding the voltage is not induced. Out of the synchronous speed, a squirrel cage acts like a winding in an asynchronous motor (like it is a squirrel cage asynchronous motor) while at synchronous speed squirrel cage acts like it does not exist. If the rotation speed is lower than synchronous speed, the absorber acts as a rotor of asynchronous motor and seeks to increase the speed of the rotor. At each speed state, the absorber seeks to reduce the oscillation amplitude and bring the rotor back into synchronism.

The absorber dumps all magnetic excitation forces and fluxes which are rotating with it at synchronous speed. Magnetic excitation force and stator flux are the result of a series of harmonic components in which only one has a wavelength equal to the double pole step, whereas all others have 5, 7, 11 ... times lower speed. Only the basic wave rotates at synchronous speed with the rotor and LeBlanc's absorber. Therefore, only the basic wave of stator flux penetrates into the rotor through the absorber, while others rotate at a lower speed, in the opposite direction. The higher order components of the basic flux rotate at speeds that are lower than synchronous speed. At the same time, they intersect absorber conductors inducing electric forces and currents in them. The magnetic effect action of these currents leads to the annulment and minimizing of higher harmonics. After the higher order fluxes suppression, the electromotive force in the stator is cleared of higher harmonic components.

2.1 The Görges phenomenon

During the starting phase of the synchronous motor the excitation coil is short-circuited, therefore participating in creating the momentum that at certain speeds of rotation of the induction motor operates in the opposite direction of the asynchronous moment. The electromotive force in excitation winding of frequency $f_2 = s \cdot f_1$ is induced by the rotating magnetic field of the stator winding. As a result of the electromotive force in the excitation winding, electric current of the corresponding frequency flows through the circuit creating a pulsating magnetomotive force F_{mu}. The magnetomotive force F_{mu} can be broken down into direct F_{mud} and inverse F_{mui} components. The direct component moves in the same direction as the rotating stator's magnetic field while the inverse component of the

magnetomotive force moves in the opposite direction. In relation to the stator's rotating magnetic field, the direct component of the magnetomotive force of excitation coil F_{mud} is rotating at the speed $n_{ud} = n + (n_s - n) = n_s$ (rpm), while the inverse component of the magnetomotive force of the excitation coil F_{mui} has the following speed: $n_{ui} = n - (n_s - n) = 2 \cdot n - n_s$. The voltage of the stator winding of frequency defined by (5) is induced by the existing rotating magnetomotive force F_{mui}.

$$f_{ui} = \frac{p \cdot (2n - n_s)}{60} = \frac{[2n_s \cdot (1-s) - n_s]p}{60} = \frac{p \cdot n_s}{60} \cdot (1 - 2s). \quad (5)$$

The direct component of the magnetomotive force F_{mud} induces voltage in the stator winding with the frequency f_1. Due to the influence of the induced voltages in the stator, electric currents of the corresponding frequencies flow and together with the excitation coil's magnetomotive forces F_{mud} and F_{mui} generate additional stator moments. The resultant torque of the magnetomotive force F_{mud} and the magnetomotive force caused by the direct electric current of the stator of frequency f_1 is useful while starting the electric motor because it supports the asynchronous torque. On the other hand, the inverse component of the momentum generated between $n = 0$ and $0,5 \cdot n_s$, has the opposite direction in comparison with the asynchronous momentum. If angular velocity has values higher than $0,5 \cdot n_s$, the frequency of inverse component is zero, or, better to say, the inverse component disappears completely $f_{ui} = 0$, Eq. (5).
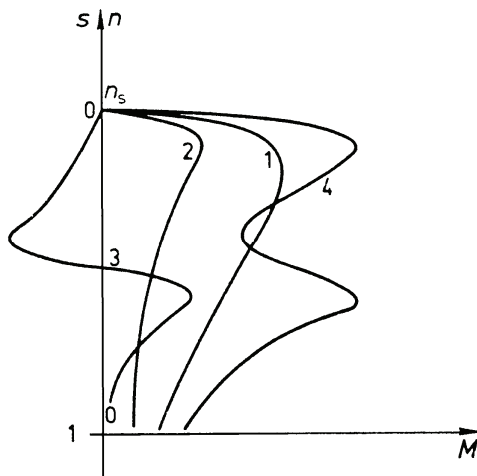

Figure 5 Moments during the induction motor starting:
1 - asynchronous torque; 2 - torque due to the direct component of the excitation coil; 3 - torque due to the inverse components of the excitation coil; 4 - total torque

When the rotor speed is lower than $0,5 \cdot n_s$ the inverse field rotates in the opposite direction of the asynchronous torque $-(2n - n_s) < 0$ of the stator field (it supports the asynchronous torque). But in the case when the rotor speed is higher than $0,5 \cdot n_s$, the inverse field rotates in the direction of the rotating stator field (it weakens the asynchronous torque). The total torque during the starting phase of the induction motor is the sum of all developed moments, so there is a possibility of the significant reduction of the total engine torque due to the inverse

components causing the discontinuation of the motor rotation or reaching a decreased speed (a half speed or even less). This phenomenon is called the Görges phenomenon and occurs when the load torque is significant to move by the induction motor, or when the excitation coil develops a large inverse torque [4]. To reduce the negative impact of the inverse torque of the excitation coil, a resistor with the resistance of approximately 10 times higher than the coil's resistance is inserted in the excitation coil circuit. This additional resistance reduces the operating point of the maximum torque value generated by the direct magnetomotive force F_{mud} or, in other words, the operating point moves to larger slip values. In the same way the moment curve sag, which is a result of the existing inverse component F_{mui}, is either damped or completely absorbed.

3 Initial currents of synchronous motor

Initially, the motors were started directly, i.e. the motor was connected directly to the power supply network. The initial currents of asynchronous motor are $5 \div 7$ times higher than the rated current, which has to be taken into consideration while designing the cables, and according to which the conductors' cross sections are dimensioned. The synchronous motor has the nominal power of $S = 630$ kV·A, and the nominal current of $I = 72$ A. At the moment of synchronous motor switching on to the power supply, the following values are measured:

$$P_m = 2098,15 \text{ kW}.$$

The reactive power is calculated:

$$Q_m = 3252,26 \text{ kvar}.$$

The total apparent power which the motor draws from the network is:

$$S_m = \sqrt{P_m^2 + Q_m^2}, \text{kV} \cdot \text{A}.$$

The total apparent power is:

$$S_P = \sqrt{2098,15^2 + 3252,26^2} = 3870,3 \text{ kV} \cdot \text{A}.$$

At that moment, the initial current of the synchronous motor is:

$$I_{P1} = \frac{S_p}{\sqrt{3} \cdot U_r} = \frac{3870,30}{1,732 \cdot 6} = 372,42 \text{ A}.$$

Now, we can determine the ratio of the starting and rated current as:

$$\frac{I_{P1}}{I_r} = \frac{372,42 \text{ A}}{63,5 \text{ A}} = 5,87.$$

When a synchronous motor is driven by the static thyristor excitation system with rectifiers, lower values of initial currents are obtained, as shown in Fig. 6. The synchronous motor drive has the LeBlanc's absorber installed on the rotor which enables it to accelerate as a squirrel cage asynchronous motor.

During the acceleration period such motors draw currents higher than the rated current and act as an inductance. During the motor starting period the current circuit of the rotor is bridged by resistor with resistance of $R = 10·R_r$. This is done to minimize the negative consequences of Görge's phenomenon [5] or movement of the moment created by the excitation winding. Otherwise, there would be a possibility of the motor not achieving synchronous speed. During the motor starting period, the value of the stator current was higher than the rated current and its greatest measured value was: $I_{p2} = 190{,}163$ A. The procedure of motor starting (acceleration) lasted altogether $t_1 = 12$ s, after which the resistor in the rotor circuit was disconnected and the rotor was further excited by the current of 191 A which kept it running for the following 131 seconds ($t_2 = 131$ s).
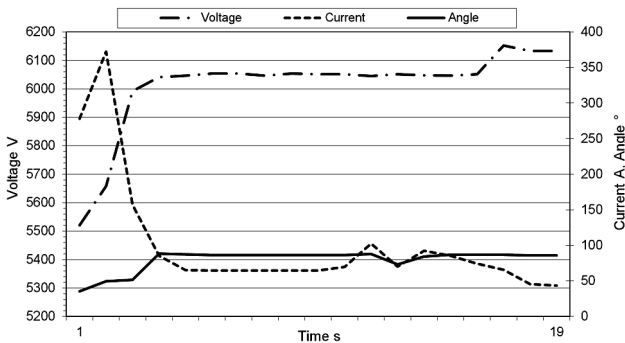

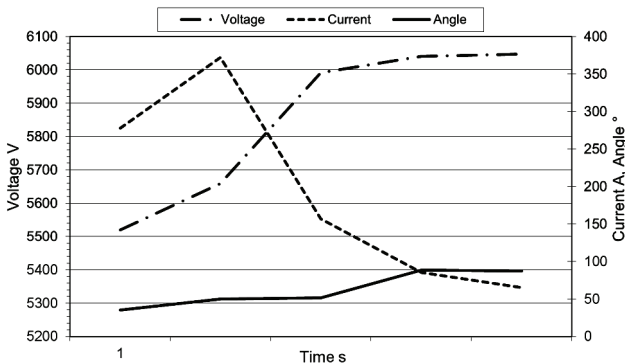**Figure 6** The power values of synchronous motor during the start-up

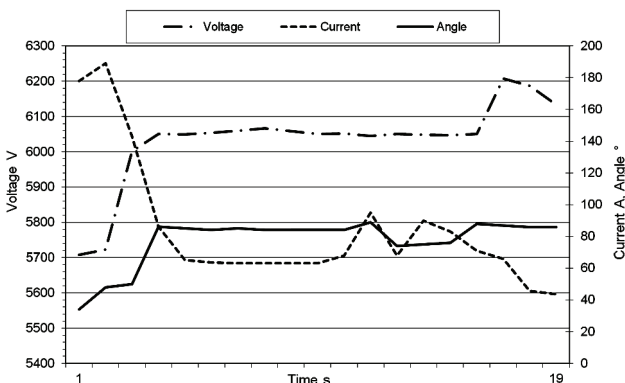**Figure 7** Initial current of synchronous motor during the first 5 seconds

Figure 8 The values of voltage, current and angle during the starting period of a synchronous motor with the static excitation system
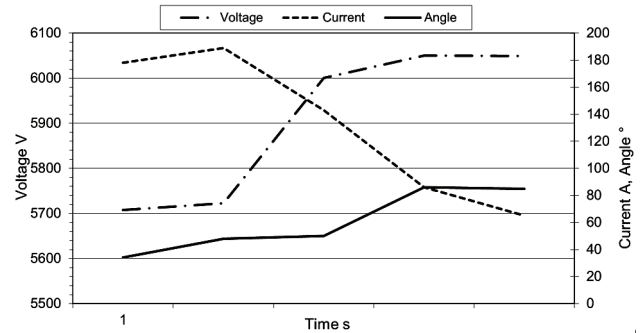

Figure 9 The values of voltage, current and angle during the starting period of a synchronous motor with the static excitation system during the first 5 seconds

After replacing Ward Leonard group with static thyristor rectifier and synchronous motor starter, the ratio of initial and nominal currents intensity at the start of the switching on was as follows:

$$\frac{I_{p1}}{I_{p2}} = \frac{372{,}42\,\text{A}}{190{,}163\,\text{A}} = 1{,}96.$$

So, the initial current is reduced by as much as 1,96 times. The excavator power supply is implemented by EpN78 3×35 mm² cable, in a variable length of 400 m (rolled on pulley). Based on the cable manufacturer's technical specifications the permissible nominal current for that cable is 170 A, while the same specifications state that the permissible value for the EpN78 3×25 mm² cable is 137 A. The transformer of 250 kV·A nominal power and 6/0,4 kV voltage ratio is located on the excavator as well, through which other devices are powered [6].

$$I = I_{SM} + I_{TR} = 72 + 24{,}05 = 96{,}05\,\text{A}.$$

Since all devices do not work at full load at the same time, the maximum current value is lower than 96,05 A [8]. So, based on this data, it is possible to replace the EpN78 3×35 mm² power cable with EpN78 3×25 mm² power cable and thus achieve a financial profit.

In addition, the EpN78 3×25 mm² cable with the total length of 400 m (on the pulley) weighs less than the EpN78 3×35 mm² cable [7]. It is 244 kg lighter and also 16 % cheaper. The cable is normally in usage from 8 to 10 years, depending on the damage or deterioration.

Mechanical and electrical consumable parts of rotating rectifiers require maintenance. Routine maintenance is carried out every year due to difficult working conditions, which cause a shorter working life span.

At maximum transformer load, the current would be:

$$I_{TR} = \frac{S}{\sqrt{3}U} = 24{,}05\,\text{A}.$$

Therefore, the total maximum load of excavator can be:

$$THDI = \sqrt{\sum_{n=2}^{\infty}\frac{I_n^2}{I_1^2}} \cdot 100\ \% . \tag{6}$$

Table 1 Constructional parameter features of power cables

Construction	Maximum electric resistance at 20 °C	Operating capacity	Operating inductivity	Allowed continuous current in air	Weight
Measurement unit	Ω/km	nF/km	mH/km	A	kg/km
3×25 mm²+3×10 mm²	0,795	0,34	0,348	137	3760
3×35 mm²+3×10 mm²	0,565	0,39	0,328	170	4370

Installation of stationary devices increases the reliability of excitation circuits power supply and reduces initial currents. The total value of current is reduced as well, which allows the power supply cables to be designed with smaller cross sections.

5 Harmonic distortion

The substitution of a rotary device for a static device has caused the changes in the harmonics of electrical networks. The most common causes of non-linear harmonics are consumers who generate non sinusoidal current's wave forms and inject them into the power system. Harmonics deviation can cause serious long term consequences [8] in the power networks. The most important consequences are:

- Increased heating of the transformers and the neutral conductors due to the current harmonics of higher frequency which is the multiplier of number 3.
- Impact on the capacitor (damage due to the increased voltage and current);
- Impact on the protective devices (incorrect response);
- Impact on the accuracy of measurement display device
- The neutral conductor is usually not overload protected, so an increased level of the 3rd harmonics can cause overheating.
- Power transformer heating is caused by higher harmonics and the consequence is the reduction of the rated power of power transformers.

Harmonics THDIP1 = 27,852 %, DC Generator

Figure 10 The values of harmonics for current I_{p1}

Harmonics THDIP2 =31,465 %, Static Excitation

Figure 11 The values of harmonics for current I_{p2}

The emergence of Harmonics in the power system causes interferences in the telecommunication lines.

Although power losses are reduced by static excitation device installation instead of the classic approach to excitation, the distortion of the current and voltage wave forms are significantly increased, (Fig. 11).

Table 2 Values of individual current harmonics

	I_{P1} / A	I_{P2} / A
Harmonics	DC Generator	Static Excitation
1	360	191
2	5	10
3	78	56
4	5	4
5	42	14
6	4	4
7	35	11
8	4	4
9	20	10
10	4	3
11	20	5
12	4	3
13	10	5
14	4	2
15	9	3
THDI / %	27,85	31,47

6 Conclusion

Devices that have a long working life span become outdated over time and it is necessary to improve some technical solutions, while keeping pace with new technological advances. Synchronous motors were originally DC powered from the rotation devices. Today, static devices serve that purpose, and one of the performances employs thyristor rectifiers. Static rectifiers, in comparison with rotation devices, are more efficient and therefore consume less power, which results in the usage of supplying power cables with smaller cross sections and reduces overall power consumption of the excavator. With the proper selection of static devices, it is possible to reduce electricity consumption significantly and, in addition, increase the reliability of the drive. The proper selection of devices requires a quality analysis of the electromotive drive and takes into account the specificities of driving device. The synchronous motor, which has LeBlanc's absorber installed in stator poles and by which it starts as an asynchronous motor, has been observed here. In this way, the initial currents are reduced and thus the load of high voltage electrical equipment. Also, overheating of power cables and electric motors is reduced. Since the initial currents are decreased by 1,9 times, during the modernization process it will be possible to design cables with smaller cross sections, which will inevitably lead to lower costs and less damage of power cables which are in constant motion.
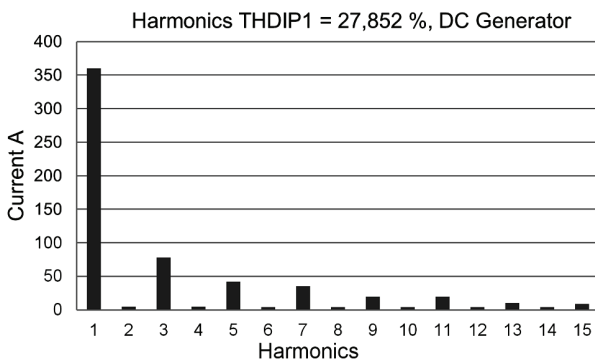
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