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## RESEARCH OF TRANSIENT PERFORMANCE IN ELECTRIC SYSTEMS OF MINE PLASMAS EQUIPMENT

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## ДОСЛІДЖЕННЯ ПЕРЕХІДНИХ ХАРАКТЕРИСТИК ПЛАЗМОВОГО ОБЛАДНАННЯ У ШАХТНИХ ЕЛЕКТРИЧНИХ СИСТЕМАХ

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## ИССЛЕДОВАНИЕ ПЕРЕХОДНЫХ ХАРАКТЕРИСТИК ПЛАЗМЕННОГО ОБОРУДОВАНИЯ В ШАХТНЫХ ЭЛЕКТРИЧЕСКИХ СИСТЕМАХ

**Abstract.** For the combined networks of options of plasma expansion of mining holes appeared impossible to apply the devices of protective disconnection, before developed for the cable networks of alternating current and contact networks of direct current, because first from them were under influence of working alternating current of the combined network. Presented are the results of research of a plasma devices electrical network modes under the rising of single pole leakages to the earth in the supply line of a plasmatron. A non-linear model of a semiconductor converter taking into account currents of back bias diodes of this converter is used. Experimental data received with a pilot plasmatron in the conditions of the Krivoy Rog iron-ore mines have been analysed, and it has been found that a relatively high specific resistance of ferruginous quartzites helps to formate emergency operations in combined supply lines of plasmatrons, which have essential differences in comparison with conventional ones. That is why for electric safety of plasmatrons for iron ore mines it is necessary to apply a high sensitivity directed current protection, which control, to raise selectivity, stable and transitional values of leakage currents. An estimation of the current value in single pole leakage when the current takes place under normal plasmatron operations and under the absence of isolation failure in the plasmatron supply line leading to lowering of the resistance of this isolation to the relation to the earth has been made.

**Keywords:** transition procession, current of escape, diode, resistor and rectifier.

### PREFACE

Preparation of charge cavities for placing of explosives in a iron-ore array is an important technological link at explosive works. In the strong magnetite quartzites of mines Kryvbassa creation of caldron cavities is presently possible only by a technical plasma method with the use of electro-arc plasmatrons (EAP) in quality the executive

working branch of rock machine – setting of plasma expansion of mining holes (SPEMH).

Application SPEMH of large power 150-200 kvt [1] in mining industry requires the safe EAP external environments. The results of experimental researches during work of the EAP mine showed that at the casual touch to some from 3th phases which a current flows on, branches fyder submachine gun is the magnetic allowing is setting, mine network 0,66 Kv exists shock hazard transitional processes arising up in the chain of loss under act of pulsating electrical arc [2,3].

It should be noted, that development and test of different modifications of the SPEMH options and working off the technological processes of destruction of strong ores in the Kryvbass mines passed ahead development of facilities of defense from the ground leakage, and the questions of safety decided on motion of the SPEMH test and introduction of technologies of ore-breaking of strong ores on a chamber, driving of the horizontal and vertical working of a different setting.

## 1. INTRODUCTION

Electric power of up-to-date mine plasma device is supplied from step-down transformer through semi-conductor (siliceous) rectifier. All these elements are electrically connected with each other and create combined electric system with three-phase alternating voltage with isolated neutral wire before rectifier and with direct voltage and insolated poles after it [1].

It is difficult to provide electro safety of personnel and control of insulation state of electric circuits in such systems due to difficulties in the detection of low-value current of single pole escape on the background of high-value current of plasmatron and comparable currents of technological escape from the case of plasmatron. Cabling between elements of mine plasma devices with the length of several tens of meters gives considerable electrical capacitance (of  $10^{-1}$   $\mu$ F order) of phases and poles of plants relative to the earth. All above factors in combination with high value resistance, of  $10^{-5}$  Ohm order, of escape current contours to the earth lead to formation of very durable transient processes with single phase and single pole ground connection and disconnection.

## 2. METHODS

High-value resistance of escape current contours that are caused by high-level specific resistance of solid rocks like ferriferous quartzites with high effectiveness of usage of plasma plants and frequent usage of idling modes of rectifier of plant in auxiliary operations when the arc in plasmatron doesn't burn, are the cause of strong influence on values and character of changes in time of escape current to earth of forward and reverse diode resistances of semiconductor rectifier. Thus, the simplest model of semiconductor diode in the form of unistor [3], when resistance of diode is not taken into consideration at direct bias of its **p-n** junction and is assumed equal to infinity of its resistance at reverse bias of its **p-n** junction, does not suit for creation of mathematical model of electric system of mine plasma devices. Consideration of semiconductor gates is more adequate when used for analysing semiconductor con-

verters [4] for which idling modes are more typical. However, in mine plasma devices the range of changes of forward current of diodes is significantly wider if compare with instrument transducers due to operational modes of plasmatron when forward currents of diodes are close to their nominal currents. Besides, consideration of cubic resistance of diode base is needed with high level of injection [3]. Significant reverse voltage (hundreds of volts) on power rectifier diodes of mine plasma plant leads to occurring of generation current  $I_g$  in reverse-biased **p-n** junction, which can be considered as proportional to the value of voltage on **p-n** junction due to Early effect [2, 3].

### 3. RESULTS

Taking into consideration all above-mentioned non-linear model of diode of semiconductor rectifier was used in this work. This model takes into account peculiarities of the volt-ampere characteristic of siliceous power diodes used in above-mentioned plants; and such peculiarities are essential for established and transitional processes. Current of diode at forward bias of **p-n**-junction defined by ratio [2, 3]:

$$i = I_0 \left( e^{\lambda u_{dc}} - 1 \right), \quad (1)$$

$$I_0 = S \cdot q \cdot \left( \frac{p_n D_p}{L_p} + \frac{n_p D_n}{L_n} \right), \quad (2)$$

$$\lambda = \frac{q}{kT} \quad (3)$$

where  $q$  – is a value of electron charge;  $k$  – is Boltzmann's constant;  $T$  – is absolute temperature of **p-n** junction;  $S$  – is a square of **p-n** junction;  $p_n$  – is concentration of holes in semiconductor of n-type;  $n_p$  – is concentration of electrons in semiconductor of n-type;  $D_n$ ,  $D_p$  – are coefficients of diffusion of electrons and holes, respectively;  $L_p$  – average length of diffusion of holes in n-area;  $L_n$  – average length of diffusion of electrons in p-area;  $u_{dc}$  - voltage on **p-n** junction.

Voltage on **p-n** junction is defined by the voltage on diode  $u_D$ , which takes into account voltage drop on cubic resistance of base  $R_B$  with evident ratio

$$u_{dc} = u_D - i \cdot R_B \quad (4)$$

Value of resistance of base  $R_B$  is considered as a constant, independently on the level of injection of neon carriers in base-area. Resistance of diode with straight bias of **p-n** junction is

$$R_{fB} = \frac{u_D}{i} = \frac{u_D}{I_0} \cdot \frac{1}{e^{\lambda(u_D - iR_B)} - 1} \quad (5)$$

With reducing of the value of straight current through diode  $i$ , values of  $U_D$  and  $R_{fB}$  increases, respectively. If  $i = 0$  in (5) and (1) we can get:

$$R_{fB0} = \lim_{i \rightarrow 0} R_{fB} = \lim_{i \rightarrow 0} \left[ \frac{1}{\lambda(i + I_0)} + R_B \right] = \frac{1}{\lambda I_0} + R_B \quad (6)$$

As in reverse current of siliceous diode the component  $I_g$  is predominated and because it is caused by generation of pair “electron-hole” in volume of **p-n** junction, we will consider reverse resistance of such diode as a constant in the whole range of tolerated reverse voltages of the diode

$$R_{BB} = \frac{u_{D0}}{i_{BB}}, \quad (7)$$

where  $u_{D0}$  – is absolute value of reverse current of diode;  $i_{BB}$  – is a value of reverse current through diode at voltage  $u_{D0}$ .

Comparing (6) with (7) and taking into account that  $I_g/I_0 \approx 10^3$  as well as  $1/\lambda = 0.025$  V at  $T = 300$  K it can be seen that  $R_{fB} \approx R_{BB}$ , i.e. resistance **p-n** junction at starting space of volt-ampere characteristic will be of the same order with resistance of reverse-biased **p-n** junction of this diode with straight current passing through this diode.

Influence of capacitance between anode and cathode of diode can be disregarded when frequency of supply voltage is close to 50 Hz; in this case its equivalent circuit can have a form presented in the Fig. 1. On this figure VD1, VD2 are ideal diodes-unistors,  $R_{fB0}$  is a nonlinear resistor, resistance of which is changed according to ratio of (5),  $R_{BB}$  is a linear resistor, resistance of which is defined by equation (7).

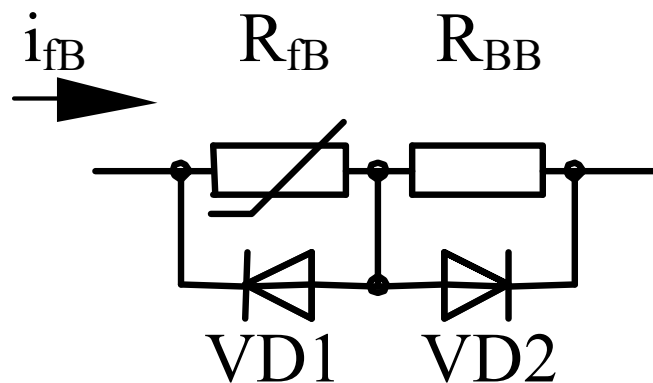


Figure 1 – Equivalent circuit of siliceous power diode

Total resistance of the circuit (Fig. 1) is defined by singular function in the form of

$$R_D = R_{fB} \frac{\operatorname{sgn} u_D + 1}{2} + R_{BB} \frac{|\operatorname{sgn} u_D - 1|}{2}, \quad (8)$$

where

$$\operatorname{sgn} u_D = \begin{cases} 1 & \text{if } u_D > 0 \\ -1 & \text{if } u_D < 0 \end{cases} \text{ - is Kroneker's symbol}$$

$u_D > 0$  corresponds to forward bias of **p-n** junction of diode.

For calculation of established and transitional processes let's represent electric system of mine plasma plant as an equivalent circuit with concentrated parameters, shown on the Fig. 2

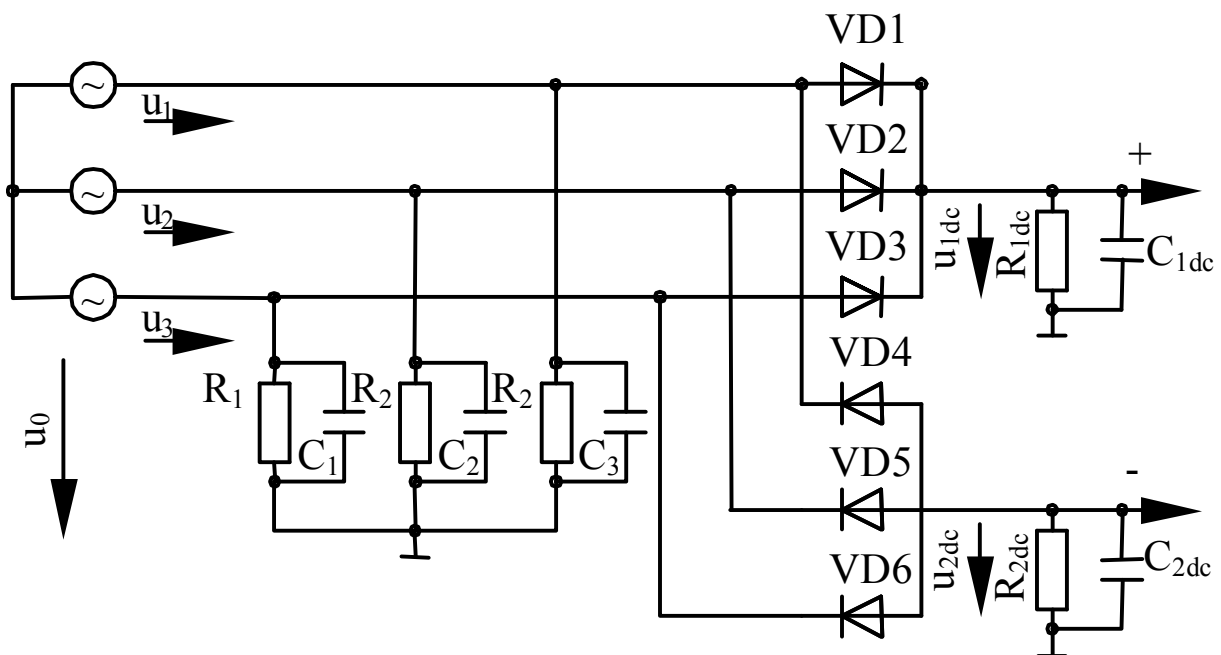


Figure 2 – Equivalent circuit of mine plasma devices

Transformer substation feeding the plant creates three-phase system of voltages  $u_1, u_2, u_3$ . Output winding of transformer is switched on according to the circuit with insulated neutral wire together with cable connecting transformer substation with plasma plant, it has active resistance of earthing insulation  $R_1, R_2, R_3$  and capacitance  $C_1, C_2, C_3$  relative to the earth. On output of converter the wires and cables connecting converter with plasmatron have active resistance of earthing insulation  $R_1, R_{2dc}$  and capacitance  $C_{1dc}, C_{2dc}$  relative to the earth. Converter is based on three-phase bridge circuit with power siliceous gates VD1-VD6.

Due to essential non-linearity of diodes VD1-VD6 we analyze established and transitional processes with instant values of current and voltage in the circuit (Fig. 2). Parameters of diodes in (5) and (6) are defined through voltages on these diodes and voltage of contact with poles and phases of electric system are input values for de-

vices of personnel security from electric injuries. And, at last, system (Fig. 2) contains a great number of independent contours and relatively not great number of nodes. So it is reasonable to fulfill analysis with the help of method of node voltage.

Figure 2 demonstrates node voltage, which allows defining the mode of system operation and parameters of its non-linear elements. According to the second Kirchhoff's law, voltages on diodes VD1-VD3 can be defined by equations:

$$\left. \begin{aligned} u_{D1} &= u_1 - u_{1dc} + u_0 \\ u_{D2} &= u_2 - u_{1dc} + u_0 \\ u_{D3} &= u_3 - u_{1dc} + u_0 \end{aligned} \right\} \quad (9)$$

and similarly for diodes VD4-VD6:

$$\left. \begin{aligned} -u_{D4} &= u_1 - u_{2dc} + u_0 \\ -u_{D5} &= u_2 - u_{2dc} + u_0 \\ -u_{D6} &= u_3 - u_{2dc} + u_0 \end{aligned} \right\} \quad (10)$$

Minus sign in the left parts of equations (10) takes into account opposite polarity of switching-on of diodes VD4-VD6 relative to VD1-VD3.

Full volume of currents of escape through insulation (taking into account their capacitance components) are defined by node voltage in equations recorded on the basis of the first Kirchhoff's law:

$$i_{1dc} = C_{1dc} \frac{du_{1dc}}{dt} + \frac{u_{1dc}}{R_{1dc}} \quad (11)$$

for current of escape from positive pole and

$$i_{2dc} = C_{2dc} \frac{du_{2dc}}{dt} + \frac{u_{2dc}}{R_{2dc}} \quad (12)$$

for current of escape from negative pole.

For circuit on the figure 2 current of one-pole escapes  $i_{1dc}$ ,  $i_{2dc}$  is earthed through resistance and capacitance of phases of cable feeding converter, so values of this current must take into account parameters of  $R_1$ ,  $R_2$ ,  $R_3$ ,  $C_1$ ,  $C_2$ ,  $C_3$ .

#### 4. CONCLUSION

Experimental-industrial operation of mine plasma devices at Krivorozhsky iron-ore basin demonstrate that it is necessary to differ two modes of one-pole escapes to the earth due to great specific resistance of ferriferous quartzites, which were used for plant's operation: escape through earthing and rocks, where the plant was installed, and escapes to the case of the plant, which was metallicly connected with earthing

contour of working place of enterprise. The second type of escapes is more dangerous for personnel.

Defining of current of one-pole escapes outside the plat's case, i.e. escapes from connecting cables and from case of plasmatron, is more important for personnel security. So apparatus of protection from one-pole escapes must be of directional effect and this will allow adjusting the operational current of plasmatron and technological escapes from its case.

Significant specific resistance of rocks where the plant operates, and comparatively small space of contact between case of plasmatron and rocks limit the values of technological current of one-pole escapes on the level of several milliampere with operational voltage of DC up to 800-900V.

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**Анотація.** Для комбінованих мереж установок плазмового розширення свердловин виявилось неможливим застосувати пристрою захисного відключення, раніше розроблені для кабельних мереж змінного струму й контактних мереж постійного струму, тому що перші з них підпадали під вплив робочого змінного струму комбінованої мережі. Викладені результати дослідження режимів електричної системи рудничної плазмової установки при виникненні однополюсних витоків на землю в ланцюзі живлення плазмотрона. При аналізі використання нелінійна модель силового напівпровідникового перетворювача установки, що враховує струми генерації зворотнозмінних діодів цього перетворювача. Така модель дозволяє визначити струми однополюсного витоку напруги дотику в електричних системах із кремнієвими вентилями, для яких величина струму генерації на три порядки перевищує зворотний струм неосновних носіїв заряду. Показано, що опор ізоляції і ємності фаз стосовно землі ланцюгів живлення силового напівпровідникового перетворювача суттєво впливають на процеси, що протікають в електричній системі установки при однополюсних замиканнях на землю і витоків на землю в ланцюзі живлення плазмотрона. Проаналізовані результати експе-

риментальних досліджень, виконаних на досвідчене-промислової плазмовій установці в умовах залізорудних шахт Криворізького басейну. Виявлене, що відносно високий питомий опір залозистих кварцитів, що добуваються в цьому басейні, сприяє формуванню аварійних режимів у комбінованих мережах живлення плазмотронів, що суттєво відрізняються від тих, що мають місце в загальнопромислових плазмових установках. Тому для забезпечення електробезпечності експлуатації рудничних плазмових установок в умовах залізорудних підприємств необхідне використання високочутливих спрямованих струмових захистів.

**Ключеві слова:** перехідні процеси, струм витоку, діод, резистор і випрямляч.

**Аннотация.** Для комбинированных сетей установок плазменного расширения скважин оказалось невозможным применить устройства защитного отключения, ранее разработанные для кабельных сетей переменного тока и контактных сетей постоянного тока, так как первые из них подвергались влиянию рабочего переменного тока комбинированной сети. Изложены результаты исследования режимов электрической системы рудничной плазменной установки при возникновении однополюсных утечек на землю в цепи питания плазмотрона. При анализе использована нелинейная модель силового полупроводникового преобразователя установки, учитывающая токи генерации обратносменных диодов этого преобразователя. Такая модель позволяет определить токи однополюсной утечки напряжения прикосновения в электрических системах с кремниевыми вентилями, для которых величина тока генерации на три порядка превышает обратный ток неосновных носителей заряда. Показано, что сопротивление изоляции и емкости фаз по отношению к земле цепей питания силового полупроводникового преобразователя существенно влияют на процессы, протекающие в электрической системе установки при однополюсных замыканиях на землю и утечках на землю в цепи питания плазмотрона. Проанализированы результаты экспериментальных исследований, выполненных на опытнопромышленной плазменной установке в условиях железорудных шахт Криворожского бассейна. Выявлено, что относительно высокое удельное сопротивление железистых кварцитов, добываемых в этом бассейне, способствует формированию аварийных режимов в комбинированных сетях питания плазмотронов, существенно отличающихся от тех, что имеют место в общепромышленных плазменных установках. Поэтому для обеспечения электробезопасности эксплуатации рудничных плазменных установок в условиях железорудных предприятий необходимо использование высокочувствительных направленных токовых защит.

**Ключевые слова:** переходные процессы, ток утечки, диод, резистор и выпрямитель.

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### **КОНТРОЛЬ ГЕРМЕТИЧНОСТИ ШАХТНЫХ ТРУБОПРОВОДОВ СЖАТОГО ВОЗДУХА ПО МЕТОДУ ФИКСИРОВАННЫХ ОБЪЕМОВ**

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### **КОНТРОЛЬ ГЕРМЕТИЧНОСТІ ШАХТНИХ ТРУБОПРОВОДІВ СТИСНЕНОГО ПОВІТРЯ ПО МЕТОДУ ФІКСОВАНИХ ОБ'ЄМІВ**

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### **LEAKAGE MONITORING OF COMPRESSED AIR MINE PIPE-LINES ACCORDING TO THE FIXED VOLUMES METHOD**

**Аннотация.** В статье предложен новый метод определения степени негерметичности шахтных трубопроводов сжатого воздуха с целью повышения энергосбережения при производстве, транспортировании и потреблении сжатого воздуха шахтным пневматическим оборудованием. Предлагаемая методология фиксированных объемов предусматривает использование двух эталонных емкостей, в одной из которых фиксируются начальные параметры измерений, а в другой – текущие. На основании феноменологического подхода к описанию исследуемых физических процессов построена математическая модель определения степени негерметичности с использованием данного метода. В математической модели использованы основные закономерности молекулярно-кинетической теории газов с учетом взаимосвязи давления, температуры, объема и вида используемого газа. Выполнено математическое описание процессов, происходящих при определении утечки из замкнутого объема с использованием разработанного метода. Показано, что эффективность нового метода обусловлена применением в расчетном алгоритме закона сохранения массы при поэтапном рассмотрении процессов утечки и теплообмена. Применение предложенного метода фиксированных объемов позволит повысить требования по контролю герметичности пневматического оборудования и систем воздухоподачи во время проведения ремонтных и регламентных работ.

**Ключевые слова:** сжатый воздух, шахтные трубопроводы, степень негерметичности, метод фиксированных объемов, замкнутый объем, избыточное давление.