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Investigation and optimisation of the functioning parameters of the milking machine electronic unit, diagnosing the state of the udder quarters of cows for mastitis

© 2022. Peter A. Savinyh[1]✉, Aleksandr A. Rylov[1], Valeriy N. Shulatiev[1], Semjons A. Ivanovs[2]

[1]*Federal Agricultural Research Center of the North-East named N. V. Rudnitsky, Kirov, Russian Federation*
[2]*Latvia University of Life Sciences and Technologies, Riga, Latvia*

The article informs on the search of values of setting the parameters of electronic unit of the milking machine providing the current control of physiological state of udder quarters during milking. The milking machine is equipped with electrode sensor for quarterly control of the lactation intensity. A rotatable plan was used in the studies on a hexagon for two factors. The influence of delay duration of measuring and the duration of search for maximum on relative values of average y_{aver} and maximum y_{max} deviations from minimum voltage value at the lower voltage divider arm has been determined. The algorithm of the program for the functioning of the electronic unit provided for restrictions on the width $\Delta = 0.03$ s and height Un = 2.45 V of the lactation diagram. There were experimentally determined the values of the duration of the measurement delay 10 s and the duration of the search for the maximum 40 s, which ensure an adequate quarterly indication of mastitis during milking. The threshold for changing the colour of the LEDs of the electronic unit from green to red, signalling inflammation of the mammary gland in the quarters, is set to exceeding $y_{max} > 5$ %. Parallel samples of milk from the udder quarters for the kenotest confirmed the efficiency of application and expediency of the milking machine, performing the function of quarterly testing of the quarters for mastitis. Providing the option of quarterly control of udder quarters by milking machine does not need correction of the basic circuit of electronic unit and is achieved only by its programming considering physiological features of livestock kept. The results of investigations indicate that, on average, for healthy cows, the range of variation of the maximum relative voltage deviation on the lower divider of the electronic unit should not exceed 6...10 %.

Keywords: *voltage divider, mastitis, electrodes, electrical conductivity of milk, relative deviation*

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Исследование и оптимизация параметров функционирования электронного блока доильного аппарата, диагностирующего состояние четвертей вымени на мастит

© 2022. П. А. Савиных[1]✉, А. А. Рылов[1], В. Н. Шулятьев[1], С. А. Иванов[2]

[1]*ФГБНУ «Федеральный аграрный научный центр Северо-Востока имени Н. В. Рудницкого», г. Киров, Российская Федерация*
[2]*Латвийский университет естественных наук и технологий, г. Рига, Латвия*

Статья посвящена поиску величин настроек параметров электронного блока доильного аппарата, обеспечивающего текущий контроль во время доения над физиологическим состоянием четвертей вымени. Доильный аппарат оснащен электродным датчиком почетвертного контроля интенсивности молоковыведения. В исследованиях применен почти ротатабельный план на шестиугольнике для двух факторов. Определено влияние на относительные величины среднего $y_{ср}$ и максимального y_{max} отклонений от минимальной величины напряжений на нижнем плече делителя напряжения длительности задержки измерений и продолжительности поиска максимума. Алгоритм программы функционирования электронного блока предусматривал ограничения по ширине $\Delta = 0{,}03$ с и высоте $U_н = 2{,}45$ В диаграммы молоковыведения. Экспериментальным путем определены значения длительности задержки измерений 10 с и продолжительности поиска максимума 40 с, обеспечивающие во время доения адекватную почетвертную индикацию мастита. Порог изменения цвета светодиодов с зеленого на красный электронного блока, сигнализирующего о воспалении молочной железы в четвертях, настроен на превышение $y_{max} > 5$ %.

Параллельные пробы молока из четвертей вымени на кенотест подтвердили эффективность применения и целесообразность осуществления доильным аппаратом функции почетвертного тестирования четвертей на мастит. Обеспечение опции почетвертного контроля функционального состояния четвертей вымени доильным аппаратом не нуждается в доработке принципиальной схемы электронного блока, а достигается исключительно его программированием с учетом физиологических особенностей обслуживаемого поголовья коров. На наш взгляд, в среднем для здоровых коров диапазон варьирования предельного максимального относительного отклонения напряжения на нижнем делителе электронного блока не должен превышать 6…10 %.

Ключевые слова: *делитель напряжения, мастит, электроды, электрическая проводимость молока, относительное отклонение*

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Dairy farming is an important agricultural sector in the Baltic States, Northern and Central Europe, Russia and other countries and the dairy products are traditionally a popular food [1, 2]. There are ubiquitous various option for machine milking of cows allowing to carry out this process with high efficiency [3, 4, 5]. However, machine milking also has negative aspects, associated with the impact of the machine elements upon the animal health. For example, as a result of general use of machine milking in the industrially developed countries, the lactating cows have widespread mastitis [6].

Diseases of the mammary gland reduce the milk yield by 10...40 %, worsen the sanitary and technological quality of milk and, especially with the highly productive cows, lead to a decrease in the reproductive function [7, 8].

There are many scientific works devoted to the problem of reducing the mastitis morbidity, there are significant achievements in this direction [9, 10, 11]. Yet, unfortunately, the situation in practice remains tense as before, there is no final victory over this disease, and, moreover, mastitis is becoming the main reason for the short period of productive use of the high-yielding cows in the large modern automated dairy complexes. Such a situation forces the milk producers to exercise constant control [12, 13] over the functional condition of the mammary gland.

However, a veterinary control of this condition has a number of problems, and it is associated with high labour costs. There is no unequivocal solution to this issue by using automation tools yet. The search for efficient solutions of continuous control of the condition of the mammary gland is still an urgent scientific task [14, 15].

The purpose of the work is to study and optimise the parameters of the electronic unit of the milking machine, which diagnoses the functional state of the mammary gland directly during the milking of the cows.

Materials and Methods. An experimental milking machine was used for the investigations, equipped with a device for quarter-by-quarter control of the lactation intensity (Fig. 1).

Fig. 1. **General view of the milking machine, equipped with the device for the quarterly control of lactation intensity /**

Рис. 1. **Общий вид доильного аппарата, оснащенного устройством почетвертного контроля интенсивности молоковыведения**

The voltage on the lower arm of the divider of the electronic unit of the milking machine, equipped with a device for the quarter-by-quarter intensity control of the of milk output, adequately reflects the trend of changes in the intensity of the milk output from each quarter of the udder, i.e. the voltage is proportional to the intensity of lactation and electrical conductivity of milk. An objective difficulty in experimental determination of the functional condition of the mammary gland in cows directly during milking with a milking machine is created, firstly, by the presence of a biological object (cow), and, secondly, by the technical complexity of making a full-fledged and strictly organised measuring cell in the collector of the milking machine [7]. It is known [16] that, with the increase in the immersion depth of the electrodes of the lactation intensity sensor into the solution, the dependence of voltage on the lower arm of the divider upon its immersion decreases. Therefore, to reduce the degree of influence of the depth of immersion, it is necessary to measure the electrical conductivity in each quarter of the mammary gland during the onset of the maximum intensity of lactation in it.

The lactation intensity in each quarter is determined by the physiological and technological parameters of the biological and technical links that ensure the evacuation of milk from the nipple of the cow's udder. It should be noted that, when using the modern milking machines, the values of the technological and physiological parameters practically do not change during the attendance of each animal. For some time they may be approximately equal in the quarters as a result of active milk excretion, depending on the accuracy of the preparatory operations performed by the milker, on the functional state, and anatomical and morphological indicators of each cow. Consequently, for the ascending branch of the milk excretion, there is a necessary period of time, even if of a relatively short duration, and not necessarily simultaneous in all the quarters, during which there takes place practically the same intensity of lactation. During this period of time in healthy cows the spread of estimates of the current electrical conductivity by the quarters of the udder, proportional to the intensity of lactation, determined by the intensity of the milk excretion, will be minimal.

Figure 2 presents a diagram of voltage pulsations on the lower arm of the electronic unit divider during the milking of a cow by a milking machine, equipped with a device for the quarter-by-quarter control of the lactation intensity, and operating on a two-stroke cycle. The trend of the voltage pulsations on the lower arm of the divider is proportional by its scale to the intensity of the milk flow from a quarter of the udder to the electrodes of the sensor of the milking machine.

A start for the search program of the maximum intensity value (maximum voltage U_{max}, Fig. 2) should occur at point 1, located slightly above the voltage, equivalent to the minimum allowed lactation intensity, for example, 50 ml/min. The search for the maximum U_{max} should end at point 2, corresponding to a slightly lower voltage $U_к$, than voltage $U_н$ at point 1. The duration of the search for the maximum value U_{max} is regulated by the searching time $t_п$. The start of the search program should be performed when the width of the lactation diagram Δ (the time of intensive continuous outflow of milk) is reached after the measurement delay time $t_з$, has elapsed, required for a start of a stationary process of milk extraction

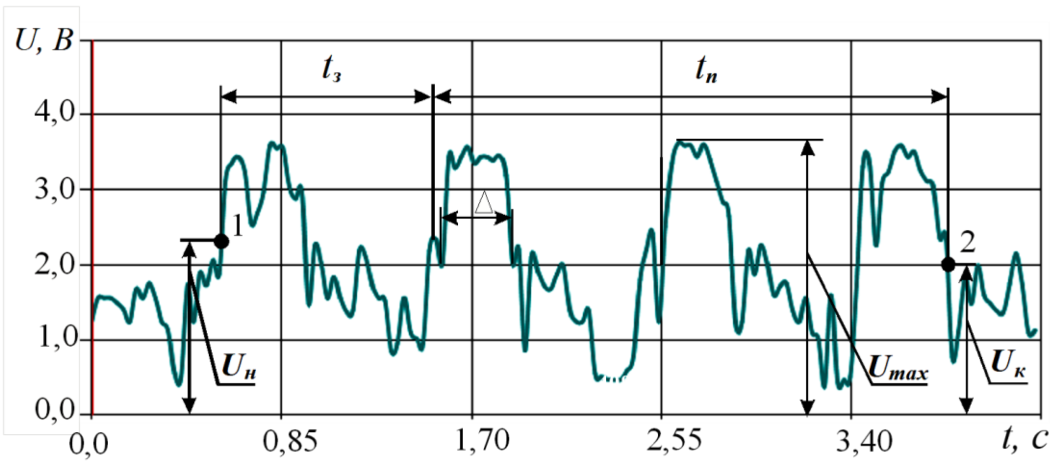

Fig. 2. **Diagram of the voltage pulsations on the lower divider arm of the electronic unit during milking of the udder quarter /**

Рис. 2. **Диаграмма пульсаций напряжения на нижнем плече делителя электронного блока во время доения четверти вымени**

The performed investigations [17] showed that, to achieve reliable and stable operation of the device for a quarter-by-quarter control of the lactation intensity, it is necessary that the width of the diagram Δ should be an order of magnitude less than the duration of the sucking cycle; since at setting Δ of one order of magnitude in duration with the sucking cycle, there is no light signaling about the appearance of milk from a quarter with an intensity of more than 50 ml min^{-1}. The flow of milk into the collector from the quarters of the udder is visually recorded, and the LEDs for the lactation intensity do not turn off. In addition, when milking cows, using a small volume milk and teat tanks, with a low intensity of the milk flow from the alveoli, no maximum value of tension is determined in the quarters of the udder for the entire period of milking. With the duration of the setting parameter Δ = 0.25 s, one order of the magnitude by the duration with the sucking cycle, the algorithm of the electronic unit program is unable to collect the amount of the necessary data during milking and, accordingly, process them. The search for the settings of the electronic unit that provide an objective assessment of the functional state of the udder quarters directly during milking was performed in a livestock complex with already healthy lactating cows. An almost rotatable design was implemented in the research for two factors from seven tests, providing for the variation of one factor at five levels, and the other factor at three levels [18]. To reduce the impact of uncontrolled factors upon the absolute values of the electrical conductivity of milk and to improve the diagnosing accuracy of mastitis, there were chosen in the studies as the target functions: the relative values of the average y_{aver} and the maximum y_{max} deviations from the minimum voltage value on the lower arm of the voltage divider. To test the mathematical models, experiments at the zero point of the plan were performed in triplicate and accordingly processed statistically [19, 20].

After the values of settings and the corresponding programming of the electronic unit were determined, the data, obtained when testing the cows in various functional states of the udder quarters by means of the milking machine, the results of the milk samples were compared in parallel for the kenotest.

Results ad Discussion. Finding the duration of the search of time t_n which guarantees an objective determination of the maximum lactation intensity in each quarter was experimentally performed on a dairy farm. To achieve in the experiments reliable fixation of the beginning of milking and its end, there were significantly lower requirement in the settings of the operation algorithm of the electronic unit for the width (Δ = 0.03 s) and the height ($U_н$ = 2.45 V) of the lactation intensity diagram. The search for the maximum voltage was carried out by varying the duration of the measurement delay time $t_з$ (x_2) and the duration of the search for the maximum t_n (x_1). Finding the maximum voltage took place by varying two factors (the periods of time $t_з$ and t_n), so that the search time in each channel (quarters) included a time interval of 50 s after the connection of the corresponding teat cup. This range contains, on average, an interval, sufficient to achieve the maximum lactation intensity for all the quarters of the lactating cows. The plan of experiments and the results of the studying the impact of factors upon the value of the relative average voltage deviation y_{cp} are presented in Table 1.

After mathematical processing of the results of the experimental data in Table 1, the following second-order equation was obtained (the factors are normalised):

$$y_{aver} = 3{,}38 - 1{,}22x_1 + 0{,}62x_2 - 6{,}93x_1x_2 + 8{,}33x_1^2 - 0{,}81x_2^2. \quad (1)$$

Statistical analysis shows that equation (1) with a significance level $q = 0.05$ at freedom numbers $f_1 = 1$ and $f_2 = 14$ adequately describes the results of the experiments since the calculated value of the Fisher criterion is less than the corresponding tabular value: $F_{cal} = 14.56 < F_{tab} = 18.51$.

The duration of the search for the maximum (x_1) and the measurement delay (x_2) time, starting from which the maximum voltage is found, in the preset interval of factor variation do not statistically significantly affect the value of the objective function y_{aver}, since the corresponding calculated values of the t-criteria are less than the tabular value with the level of significance q = 0.05: t_{cal} =1.58; 0.80 < t_{tab} =2.15. The coefficient at the first factor is negative, so it has an inverse effect on the value of the objective function. The coefficient at factor x_2 has a positive sign, which indicates its direct influence upon the objective function y_{aver}: the greater the delay time, the higher the average relative voltage deviation. The coefficient at the combined impact of the search duration x_1 and the delay time x_2 has a negative sign, and it statistically significantly affects the average value of the relative voltage deviation y_{aver} with a 5 % significance level since $t_{cal} = 4.48 > t_{tab} = 2{,}15$.

Table 1 – **The plan, levels of the factor variation, the measurement results and calculations of the average relative deviation /**
Таблица 1 – **План, уровни варьирования факторов, результаты измерений и расчетов среднего относительного отклонения**

No. / №	*The search duration t_n (x_1) of maximum voltage U_{max} / Продолжительность t_n (x_1) поиска максимума напряжения U_{max}*		*Duration of the search delay $t_з$ (x_2) for the maximum U_{max} / Продолжительность задержки $t_з$ (x_2) поиска максимума U_{max}*		*Average relative voltage deviation y_{aver}, % / Среднее относительное отклонение напряжения y_{aver}, %*
	level / уровень	*value, s / значение, с*	*level / уровень*	*value, s / значение, с*	
1	-1	10	0	10	15.85
2	1	50	0	10	7.58
3	0.5	40	0.866	15	2.84
4	0.5	40	-0.866	5	4.18
5	-0.5	20	0.866	15	10.09
6	-0.5	20	-0.866	5	2.37
7	0	30	0	10	3.38
8	0	30	0	10	3.95
9	0	30	0	10	1.85

Y_{aver}						
F_{cal}	14,56 (f_1 = 1; f_2 = 14)					
F_{tab}	18.51 (q = 0.05 provided / при f_1 = 1; f_2 =14)					
b_i	b_0	b_1	b_2	b_{12}	b_{11}	b_{22}
$t_{i\ cal}$	2.53	1.58	0.80	4.48	5.08	0.53
t_{tab}	2.15 (q = 0.05 provided / при f = 14)					

The coefficient at the quadratic term x_2 of the first factor exerts a statistically significant effect the objective function y_{aver} with a 5 % significance level since the calculated value of the t-criterion is considerably higher than the tabular value: t_{cal} = 5.08 (0.53) > t_{tab} = 2.15. The sign at the coefficient is positive; therefore, at the boundaries of the variation interval, the factor increases the value of the average relative voltage deviation. The sign at the coefficient is negative, therefore, at the boundary of the interval of variation of factor x_2, the value of the average relative voltage deviation decreases. Graphical interpretation of equation (1) is presented in Figure 3. The surface of the response function y_{aver} has a saddle shape with a minimax, equal to y_{aver} = 3.38 % at the center of the experiment. Fig.3 shows that the value of the average relative voltage deviation in the studied range of the factor variation varies in a wide range from 2.0 % to 8.0 %. The minimum values of the average relative voltage deviation are located in the first and third quadrants.

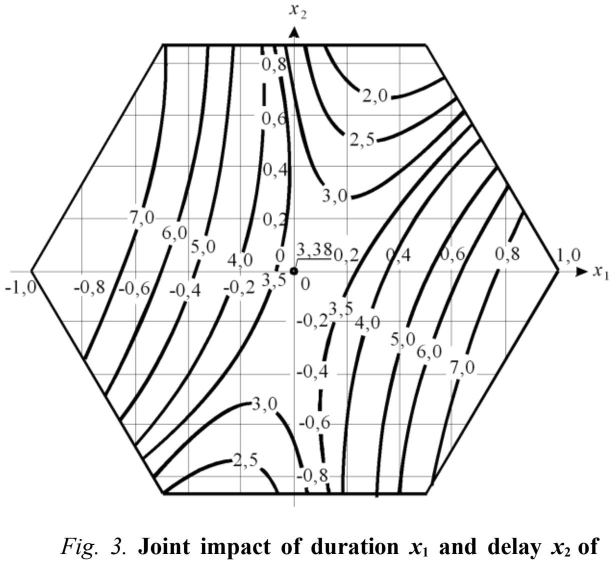

Fig. 3. **Joint impact of duration x_1 and delay x_2 of the search on the value of the average relative voltage deviation y_{aver} /**
Рис. 3. **Совместное влияние продолжительности x_1 и задержки x_2 поиска на величину среднего относительного отклонения напряжения y_{aver}**

In our opinion, an algorithm for the determination of mastitis by the electronic unit should contain intervals of variation as the delay duration intervals $t_з$ = 12.5...15.0 s; and search t_n = 34.0...38.0 s since with these adjustable parameters the value of the average relative voltage deviation y_{aver} will vary within a range: y_{aver} = 2.0...2.5 %. The range of variation of the average relative voltage deviation at the lower divider of the electronic unit should not exceed 3.0 %, which, in our opinion, should be considered the maximum allowable norm for healthy cows. The plan of experiments and the results of the research of the impact of factors x_1 and x_2 upon the value of the relative maximum voltage deviation y_{max} are presented in Table 2. As a result of mathematical processing of the experimental data, given in Table 2, a second-order equation was obtained (the factors are normalised):

$$y_{max} = 5{,}95 - 11{,}43x_1 + 1{,}17x_2 - 8{,}57x_1x_2 + 8{,}83x_1^2 - 0{,}71x_2^2 \quad (2)$$

The statistical analysis indicates that equation (2) with a significance level q = 0.05 at freedom numbers f_1= 1 and f_2= 14 adequately describes the experimental data since the calculated value of the Fisher criterion is less than the corresponding tabular value F_{cal} = 8.83 < F_{tab} = 18.51.

Table 2 – **The plan, levels of the factor variation, the results of measurements and calculations of the voltage maximum relative deviation /**
Таблица 2 – **План, уровни варьирования факторов, результаты измерений и расчетов максимального относительного отклонения напряжения**

No. / №	*The search duration t_n (x_1) of maximum voltage U_{max} / Продолжительность t_n (x_1) поиска максимума напряжения U_{max}*		*Duration of the search delay $t_з$ (x_2) for the maximum U_{max} / Продолжительность задержки $t_з$ (x_2) поиска максимума U_{max}*		*Maximum relative voltage deviation y_{max}, % / Максимальное относительное отклонение напряжения y_{max}, %*
	level / уровень	*value, s / значение, с*	*level / уровень*	*value, s / значение, с*	
1	-1	10	0	10	19.94
2	1	50	0	10	9.67
3	0.5	40	0.866	15	6.61
4	0.5	40	-0.866	5	6.11
5	-0.5	20	0.866	15	14.78
6	-0.5	20	-0.866	5	3.16
7	0	30	0	10	7.99
8	0	30	0	10	3.40
9	0	30	0	10	6.58

	Y_{max}					
F_{cal}	8.83 (f_1 = 1; f_2 = 14)					
F_{tab}	18.51 (q = 0.05 provided / при f_1 = 1; f_2 =14)					
$t_{i\ cal}$	*b_0*	*$t_{i\ cal}$*	*b_0*	*$t_{i\ cal}$*	*b_0*	*$t_{i\ cal}$*
t_{tab}	2.55	1.06	0.86	3.17	3.08	0.26
t_{tab}	2.15 (q = 0.05 provided / при f= 14)					

The duration of the search for the maximum x_1 in a preset interval of the factor variation does not statistically significantly affect the value of the objective function y_{max}, since the corresponding calculated value of the t-criterion is less than the tabular value with a significance level q = 0.05: t_{cal} = 1.06 < t_{tab} = 2.15. The coefficient at the first factor is negative, so it exerts an inverse effect upon the value of the objective function. The duration of the search delay x_2, after which the search for the maximum voltage begins in the particular interval, does not statistically significantly affect the value of the objective function y_{max} either since the corresponding calculated value of the t-criterion is less than the tabular value with a significance level q = 0.05 (t_{cal}= 0.86 < t_{tab} = 2.15). The sign of the coefficient is positive; therefore, the factor has a direct impact upon the objective function. The coefficient at a joint impact of factors x_1 and x_2 in equation (2) has a statistically significant effect upon the magnitude of the maximum relative voltage deviation with a 5% significance level since t_{cal} = 3.17 > t_{tab} = 2.15, the at the coefficient at a joint impact of factors is negative. The coefficient at the quadratic term of factor x_1 exerts a statistically significant effect upon the objective function y_{max} with a 5 % significance level since the calculated value of the *t*-criterion is much higher than the tabular value, since t_{cal} = 3.08 > t_{tab} = 2.15. The sign at the coefficient is positive, therefore at the boundaries of the variation intervals the factor increases the value of the maximum relative voltage deviation. The coefficient at the second quadratic term does not statistically significantly affect the objective function y_{max} with a 5 % significance level since the calculated value of the *t*-criterion is significantly less than the tabular value, since t_{cal} = 0.26 < t_{tab} = 2.15. The sign at the coefficient is negative, therefore at the boundaries of the variation intervals the factor somewhat reduces the value of the maximum relative voltage deviation y_{max}.

Graphical interpretation of equation (2) is shown in Figure 4.

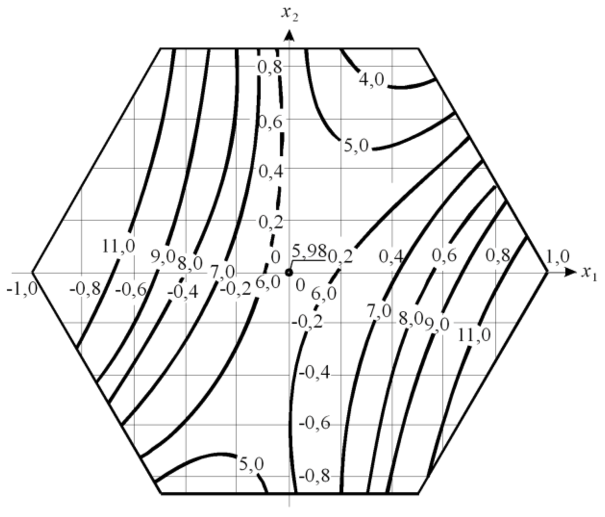

Fig. 4. **Impact of duration x_1 and delay x_2 of the search on the value of the maximum relative voltage deviation y_{max} /**
Рис. 4. **Влияние продолжительности x_1 и задержки x_2 поиска на величину максимального относительного отклонения напряжения y_{max}**

The response surface y_{max} has a saddle shape with higher objective function values and a minimax of 5.98 % at the center of the study. It follows from Figure 4 that the value of the maximum relative voltage deviation y_{max} in the studied range of the factor variation varies within a wide range from 4.0 % to 11.0 %. The minimum values of the maximum relative voltage deviation are located in the first and third quadrants. The first quadrant should be considered more preferable since a larger range of the factor variation corresponds to the minimum of the objective function: y_{max} ≤ 5 %. It should be noted that the desired interval of variation of the objective function y_{max} ≤ 5% coincides with the optimum range of variation of factors for the objective function y_{aver}: $t_з$ =12.5..15 s; t_n = 34…38 s. At the final stage, based on the generalisation of the research results, and also taking into account the presence in the herd of cows of the first year of lactation (first-calf heifers), which, as a rule, quickly shed milk, the following settings being established for the algorithm of the functioning of the electronic unit of the milking machine: t_n = 40 s; $t_з$ = 10 s; Δ. = 0.03 s; $U_н$ = 2.45 V. The threshold of changing the color of the LEDs from green to red is set at the maximum relative voltage deviation y_{max} > 5%. The results of testing the cows with various functional states of the udder quarters during milking, after programming the electronic unit of the milking machine, are compared with the diagnoses of the veterinary service of the farm, made by parallel testing of the milk samples of the diagnosed cows, supplied by parallel testing of the milk samples of the diagnosed cows from the udder quarters for kenotest.

For the first-calf heifer No.1, during milking by a milking machine, equipped with a quarter-by-quarter control of the lactation intensity, with the above settings, the LEDs did not change the green light after the end of milking. The relative maximum voltage deviation was y_{max} = 3.76 %. Similar indicators were obtained when milking the first heifer No.2: y_{aver} = 2.80 and y_{max} = 3.94 %. For the first-calf heifer No.3, the veterinarian diagnoses a suspicious inflammatory process in the posterior right quarter, based on a milk sample for kenotest, which practically coincides with the results of digital control by an electronic unit of the maximum relative voltage deviation in this quarter: y_{max} = 5.1 %, slightly more than 5 %. For the first-calf heifer No.4, the milk sample for kenotest indicates an inflammatory process in the front left and rear right quarters, which coincides with the results of testing with a milking machine: there was a change of the green color of the LEDs to red; the maximum relative voltage deviations in quarters were, respectively, y_{max} = 13.6 % and y_{max} = 11.3 %. For the first-calf heifer No.5, the veterinary service diagnoses an inflammatory process in the anterior left and posterior left quarters, which coincides with the results of testing the mammary gland quarters with a milking machine during milking: the LEDs changed to red, the maximum relative voltage deviations in these quarters reached the values y_{max} = 12.8 and 9.7 %. The conclusion of the veterinary service about mastitis in the anterior left quarter of the first heifer No.6 coincides with the readings of the electronic unit: the red color of the corresponding LED and the digital estimates of the electronic unit of the maximum relative voltage in the divider since y_{max} = 6.7 % exceeds 5.0 %. Mastitis in the anterior left quarter of the first heifer No.7 is diagnosed by the red glow of the LEDs and the digital assessment of the maximum relative voltage deviation in it since y_{max}= 8.9 % > y_{max} = 5.0 %.

Consequently, the results of testing the cows with different functional states of the udder quarters during milking, after programming the electronic unit of the milking machine and comparing them with the diagnoses by the veterinary service, show the efficiency of the proposed solution.

Conclusions. The investigations have confirmed the technical viability, technological feasibility and operational efficiency of the implementation of milking machines, equipped with a device for quarterly control of the lactation intensity, checking the functional state of the quarters of the udder of cows for mastitis immediately during milking. The additional option of quarterly indication of mastitis in the quarters of the udder does not require technical intervention in the elemental and structural base of the electronic unit but it is carried out exclusively by its programming and settings, taking into account the zootechnical, morphological and physiological characteristics of the lactating herd.

In our opinion, the permitted range of values of the maximum relative voltage deviation on the lower divider of the electronic unit should not exceed 6.0...10 %, which should be considered the maximum allowable norm for healthy cows. For such parameters it is necessary to program an electronic unit that provides color information about the functional state (mastitis) of the lobes of the mammary gland immediately during milking.

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Information about the authors

✉ **Peter A. Savinyh,** DSc in Engineering, professor, Head of the Laboratory, Federal Agricultural Research Center of the North-East named N. V. Rudnitsky, 166a, Lenin str., Kirov, Russian Federation, 610007, e-mail: priemnaya@fanc-sv.ru, **ORCID: http://orcid.org/0000-0002-5668-8479**, e-mail: peter.savinyh@mail.ru

Aleksandr A. Rylov, DSc in Engineering, associate professor, Federal Agricultural Research Center of the North-East named N. V. Rudnitsky, 166a, Lenin str., Kirov, Russian Federation, 610007, e-mail: priemnaya@fanc-sv.ru, **ORCID: http://orcid.org/0000-0002-8431-1521**

Valery N. Shulatiev, DSc in Engineering, professor, Federal Agricultural Research Center of the North-East named N. V. Rudnitsky, 166a, Lenin str., Kirov, Russian Federation, 610007, e-mail: priemnaya@fanc-sv.ru, **ORCID: http://orcid.org/0000-0002-5686-863X**

Semjons A. Ivanovs, DSc in Engineering, Director of Ulbroka research center of Latvia University of Life Sciences and Technologies, Instituta str., 1, Ulbroka, LV-2130, Riga, Latvia, **ORCID: https://orcid.org/0000-0002-9072-1340**

Сведения об авторах

✉ **Савиных Петр Алексеевич**, доктор техн. наук, профессор, зав. лабораторией, ФГБНУ «Федеральный аграрный научный центр Северо-Востока имени Н. В. Рудницкого», д. 166а, ул. Ленина, г. Киров, Российская Федерация, 610007, e-mail: priemnaya@fanc-sv.ru, **ORCID: http://orcid.org/0000-0002-5668-8479**, e-mail: peter.savinyh@mail.ru

Рылов Александр Аркадьевич, кандидат техн. наук, доцент, ФГБНУ «Федеральный аграрный научный центр Северо-Востока имени Н. В. Рудницкого», д. 166а, ул. Ленина, г. Киров, Российская Федерация, 610007, e-mail: priemnaya@fanc-sv.ru, **ORCID: http://orcid.org/0000-0002-8431-1521**

Шулятьев Валерий Николаевич, доктор техн. наук, профессор, ФГБНУ «Федеральный аграрный научный центр Северо-Востока имени Н. В. Рудницкого», д. 166а, ул. Ленина, г. Киров, Российская Федерация, 610007, e-mail: priemnaya@fanc-sv.ru, **ORCID: http://orcid.org/0000-0002-5686-863X**

Иванов Семен Агафонович, доктор инженерных наук, директор Улброкского научного центра Латвийского СХУ, ул. Института, 1, Улброка, г. Рига, Латвия, LV-2130, **ORCID: https://orcid.org/0000-0002-9072-1340**

✉ – Для контактов / Corresponding author