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Sensorless control of the high-speed switched reluctance generator of the micro power plant *

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Бездатчиковое управление высокооборотным вентильно-индукторным генератором микроэнергетической установки***

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Introduction. In the distributed and autonomous generation systems using renewable energy sources, low-power generating units (not more than 100-200 kW) based on microturbines function. Microturbines operate most efficiently at high rotational speeds. In this regard, the generator running with a microturbine must also be a high-speed one. A generator is a switched reluctance electric machine (EM) that needs information on the rotor position. It is difficult to use a position sensor in such mechanisms at high speeds. This paper discusses the issues of sensorless control of a high-speed switched reluctance electric generator in conjunction with a steam microturbine.
Materials and Methods. So, it is required to evaluate the proof-of-principle developed to control a high-speed switched reluctance EM. For this purpose, a mathematical model has been created including models of the investigated EM, an electric power converter, and a control system. For the EM under consideration, the active resistance is determined, as well as the dependence of the phase flux linkage on the current flowing through it and the position of the moving element. The method used involves probing the idle phase of an electric machine with short voltage pulses of equal duration, and measuring the current in this phase. If the voltage pulse length is much shorter than the phase time constant, then the current pulse amplitude is inversely proportional to the inductance. Thus, registering the maximum current pulse amplitude, it is possible to determine the rotor passage through an uncoordinated position for the probed phase. This information is used to form control actions by other phases. Moreover, the length

Введение. В распределенных и автономных системах генерации, использующих возобновляемые источники энергии, действуют генерирующие установки малой мощности (не более 100–200 кВт) на базе микротурбин. Наиболее эффективно микротурбины функционируют на высоких частотах вращения. В связи с этим генератор, работающий с микротурбиной, тоже должен быть высокооборотным. Генератор — это вентильно-индукторная электрическая машина (ЭМ), которой необходима информация о положении ротора. В таких механизмах при высоких оборотах затруднительно применение датчика положения. В данной статье рассматриваются вопросы бездатчикового управления высокооборотным вентильно-индукторным электрогенератором совместно с паровой микротурбиной.
Материалы и методы. Итак, необходимо оценить правильность разработанного принципа управления высокооборотной вентильно-индукторной ЭМ. С этой целью создана математическая модель, включающая модели исследуемой ЭМ, преобразователя электроэнергии и системы управления. Для рассматриваемой ЭМ определены активное сопротивление, а также зависимости потокосцепления фазы от протекающего через нее тока и положения подвижного элемента. Используемый метод предполагает зондирование неработающей фазы электрической машины короткими импульсами напряжения равной длительности и измерение тока в этой фазе. Если длительность импульса напряжения намного меньше постоянной времени фазы, то амплитуда импульса тока обратно пропорциональна индуктивности. Таким образом, регистрируя максимум амплитуды токового импульса, можно определить прохождение ротором несогласованного положения для зондируемой фазы. Эта информация используется для формирования управляющих воздействий другими фазами. При этом длительность тестовых импульсов

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of the test voltage pulses, required to obtain current pulses sufficient for measuring the value, is of significance versus the duration of the pulsing time. Hence, with an increase in the rotational speed, the number of test pulses is insufficient for measuring the position with the accuracy required for the control goals. This reduces drastically the precision of determining the rotor position; therefore, at high speeds, the application of this method is limited without further refinement of the rotor position. In this case, to increase the precision of measurements, it is necessary to evaluate the rate of current rise when applying the basic voltage pulse or the voltage pulse rate forming the phase current before switching to a single-pulse control mode.
Research Results. Two conclusions important for correcting the estimation of the rotor position in a single-pulse operation mode of a reluctance EM are proved. The first conclusion is on the efficiency of the proposed technique of filtering phase current measurement data, the second one concerns the applicability of the identified information criteria. The analysis results of the processes in the switched reluctance EM using sensorless control that implements the described principles for determining the rotor position are presented.
Discussion and Conclusions. To correct the estimation of the rotor position, the following information criteria can be used: the presence of a pause between the excitation pulse and the start of the generation process; the decrease in current by the time the generation begins. To refine the estimate, the following fact can be used: on the generation interval, the current curve knee corresponding to the maximum phase inductance is observed at the same rotor position.

напряжения, необходимая для получения импульсов тока достаточной для измерений величины, является значительной по сравнению с длительностью времени подачи этих импульсов. Поэтому с ростом частоты вращения за интервал измерений подается количество тестовых импульсов, недостаточное для измерения положения с необходимой для целей управления точностью. Это существенно снижает точность определения положения ротора, поэтому на высоких скоростях вращения ограничено применение такого метода без дополнительного уточнения положения ротора. Для повышения точности измерений в этом случае следует оценить скорость нарастания тока при подаче основного импульса напряжения или частоту следования импульсов напряжения, формирующих ток фазы до перехода в одноимпульсный режим управления.
Результаты исследования. Доказаны два вывода, важные для коррекции оценки положения ротора в одноимпульсном режиме работы реактивно-индукторной ЭМ. Первый — об эффективности предложенного метода фильтрации результатов измерения токов фаз, второй — о возможности использования выявленных информационных признаков. Приведены результаты анализа процессов в вентильно-индукторной ЭМ при использовании бездатчикового управления, реализующего описанные принципы определения положения ротора.
Обсуждение и заключение. Для коррекции оценки положения ротора могут быть использованы следующие информационные признаки: наличие паузы между импульсом возбуждения и началом процесса генерации; снижение тока к моменту начала генерации. Для уточнения оценки может использоваться следующий факт: на интервале генерации перегиб кривой тока, соответствующий максимуму индуктивности фазы, наблюдается при одном и том же положении ротора.

Keywords: microturbine, electric generator, switched-reluctance machine, sensorless control.

Ключевые слова: микротурбина, электрогенератор, вентильно-индукторная машина, бездатчиковое управление.

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Introduction. One of the directions of energy development is associated with the use of distributed and autonomous generation systems using renewable energy sources. In such systems, low-power generating units operate (not more than 100-200 kW). Their characteristic property is the combined use of various types of energy: solar radiation, wind, geothermal sources, waste disposal, etc. The most difficult from the point of view of using distributed or autonomous generation systems is thermal energy since it needs to be transformed into electric energy. In the energy systems under consideration, it is reasonable to use steam microturbines for this purpose. They operate on wet or superheated steam which the generator converts into electric energy. To solve the problem of compactness and efficiency of the turbine, it is required to provide its high rotation frequency. Accordingly, the generator should also be designed for high speed operation.

The application of a high-speed turbine imposes restrictions on the design of the conjugated generator. Due to the high rotation speed, it is good to perform it on a common shaft with a steam turbine, since the presence of couplings for interfacing the turbine and the generator complicates significantly the design and subsequent maintenance. In the autonomous and distributed energy systems, synchronous electric machines (EM) with permanent magnets on the rotor are widely used as electric generators at powers up to 200 kW. They have the best specific characteristics. However, given high rotational velocities, the design of such electrical machines is complicated by the problems of mounting permanent magnets and balancing the rotor. In addition, if the generator is operating in the immediate vicinity of the turbine, it will be in the zone of high temperatures that are not acceptable for permanent magnets. Therefore, as an electric generator designed to work in conjunction with a steam microturbine, it is reasonable to use a switched reluctance EM which has no winding and permanent magnets on the rotor.

To control the switched reluctance EM, information on the rotor position is needed. In most cases, a rotor position sensor is used for this. When operating at high velocities, it is undesirable to locate the generator in the immediate vicinity of the steam turbine, since this greatly complicates the design. There are various methods for determining the position of the switched reluctance EM rotor without a position sensor [1–4]. However, their use for a high-speed generator requires considering a number of features. The presented paper is devoted to the issues of using sensorless control of a high-speed switched reluctance generator designed to operate together with a steam microturbine.

Materials and Methods

Overview of existing solutions and problem statement. As a rule, in the switched reluctance EM, discrete-type rotor position sensors are used. Such a solution increases the dimensions of the electric machine and complicates the assembly and tuning technology.

Currently, principles of sensorless control are developed for rotating switched reluctance EM. They differ in the use of various information signs for determining the rotor position [2–4]. In most cases, such solutions cannot be applied directly for high-speed generators.

Almost all techniques of determining the position of the switched reluctance EM rotor without using physical sensors are based on a one-to-one dependence of the phase inductance on the position of the rotor (Fig. 1).

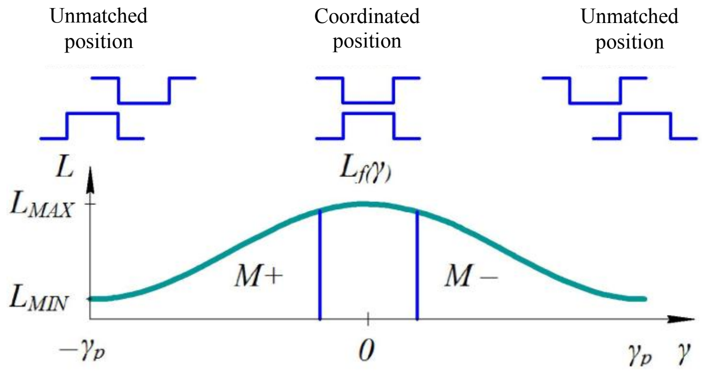

Fig. 1. Dependence of phase inductance of the switched reluctance machine on the rotor position

In the coordinated position (the rotor tooth is under the stator tooth), inductance is maximum, in the unmatched position (the rotor tooth is between the stator teeth), it is minimal. Saturation of the magnetic system affects the difference between the maximum and minimum values of inductance, but does not change the nature of the dependence. Therefore, the position of the movable element can be determined using an indirect measurement of the phase inductance of the switched reluctance EM. Options for implementing this technique differ in the method for assessing the inductance of one or several phases during the operation of a switched reluctance EM [3, 4]. The technique used involves probing an idle phase of an electric machine with short voltage pulses of equal length and measuring current in this phase. If the voltage pulse length is much less than the phase time constant, then the amplitude of the current pulse is inversely proportional to the inductance. Thus, the passage of the rotor through the unmatched position for the probed phase can be determined by recording the maximum amplitude of the current pulse. This information is used to form control actions by other phases. Test pulses are applied in series during the time corresponding to the passage of the rotor through an unmatched position. Accuracy of determining the rotor position depends on the frequency of the test pulses.

A variation of the technique for determining the position of the switched reluctance EM rotor by changing the phase inductance is to use voltage as the main test pulse (see Fig. 1). The implementation of this method is possible in both motor and generator mode. Notice the limited use of the method based on probing the idle phase by test pulses for a high-speed switched reluctance EM. The length of the test voltage pulses required to obtain current pulses sufficient for measuring the value is significant compared to their pulsing time duration. Therefore, with an increase in the rotation frequency, the number of test pulses insufficient for measuring the position with the accuracy needed for control purposes is taken as a measurement interval. This reduces significantly the accuracy of determining the rotor position; therefore, at high speeds, the application of this method is limited without further clarification of the rotor position. In this case, to increase the accuracy of measurements, it is necessary to evaluate the current rate of rise when the main voltage pulse is fed, or the repetition rate of voltage pulses that form the phase current before switching to single-pulse control mode.

Formulation of the problem of sensorless control of a high-speed switched reluctance electric generator. A design feature of the switched reluctance EM is a unique dependence of the phase inductance on the rotor position relative to the stator. This effect can be used to indirectly determine the position of the rotor. As noted above, this technique of determining the rotor position is the most common. It should be considered that the saturation of the magnetic system significantly affects the inductance. The tendency to reducing the size of the rotor to decrease the moment of inertia and improve strength indicators has led to the fact that the generator in question is a highly saturated electric machine. At the maximum stator current, the inductance in the coordinated position is reduced by more than three times compared to the inductance in the unsaturated state. Fig. 2 shows dependences of the phase inductance on the angle of rotation of the rotor at different currents.

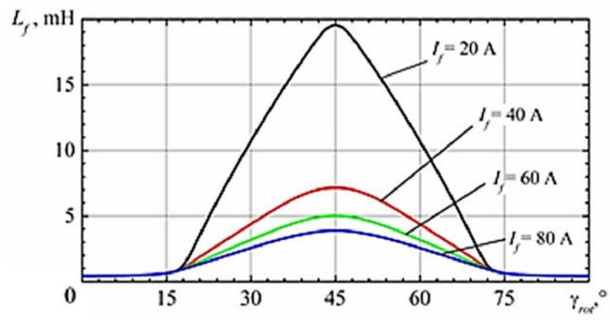

Fig. 2. Dependences of stator phase inductance on rotor rotation at different currents

The repetition rate of the test pulses used to evaluate the phase inductance is determined by the type of analogue-to-digital (A-to-D) converter applied. When using the built-in converters of microprocessor control devices, the conversion time is about 2-3 msec. If we use the same ratio of stator and rotor teeth at a rotor speed of 12,000 rpm (200 Hz), then the frequency of the pulses of the phase current should be four times greater — 800 Hz. As indicated above, test pulses are fed in the absence of current in the phase if the inductance changes from the position of the rotor. This interval in the generation mode corresponds to an increase in inductance and amounts to about one quarter of the current pulse repetition period [3]. From the dependences shown in Fig. 2, it can be seen that the change in inductance required for measurements occurs at a rotor angle of rotation in the range from 20° to 45°.

For the case under consideration, the time interval for feeding test pulses is about 300 μs. During this time, the A-to-D converter can perform 100-120 counts. The fill factor of the test pulses cannot exceed 0.5 because otherwise, after removing the voltage, the current will not have time to go down to zero. In practice, the fill factor of the test pulses does not exceed 0.25–0.3. So, to prevent current from too fast increase at the minimal phase inductance and to reduce the impact of electromotive force (EMF) arising in the phase under the rotor spinning on the measurement process.

It is required to consider the conversion errors and the need for reliable fixation of the maximum amplitude of the current pulse. In this regard, the minimum number of measurements per test voltage pulse is 10–15. Then, in the interval of test pulses, their number will not exceed 6–8, which gives a resolution of determining the rotor position at the level of 4–6°. This accuracy of the rotor position determination is insufficient for control purposes.

The phase inductance of the EM under consideration at the beginning of the measurement interval is about 5 mH in the unsaturated state (at a current of up to 20 A, see Fig. 2). At a voltage of 600 V in the DC link, the intensity of the current rise will be 120,000 A/s. It is advisable to evaluate the rotor position at a current of 5-10 A until saturation is obtained, since in this case, the dependence of the inductance on the rotor position is linear. Then, at the nominal rotation speed, about 20–30 counts will be carried out, which gives a resolution of 0.5–1°. Thus, the use of the main current pulse at high rotation speeds provides by an order of magnitude higher accuracy in estimating the rotor position (in comparison to the use of test pulses).

In the process of start-up and acceleration of the generator, the application of test pulses fed to the inoperative phase gives a more accurate estimate of the rotor position, therefore, a joint use of both methods is required in the control system.

Mathematical model of a switched reluctance electric machine. To evaluate the correctness of the developed control principle of a high-speed switched reluctance EM, a mathematical model (MM) was developed including models of the investigated EM, electric power converter, and control system. When compiling the model, assumptions were made that consider features of the problem being solved [5–8]. The basic ones are as follows: phases of the EM in point have magnetic circuits that are not magnetically interconnected, therefore, the processes in them are considered independently.

Under the assumptions made, the electromagnetic processes in the phase of this EM are described by the equation [1–4]:

$$\frac{d\Psi_{f1,2,3}}{dt} = U_{f1,2,3} - I_{f1,2,3}\left(\Psi_{f1,2,3}, \gamma_{rot}\right) R_{f1,2,3}, \tag{1}$$

where $\Psi_{f1,2,3}$, $U_{f1,2,3}$ и $R_{f1,2,3}$ are flux linkage, voltage and phase resistance; $I_{f\ 1,2,3}\left(\Psi_{f\ 1,2,3}, \gamma_{rot}\right)$ is the phase current determined depending on the magnitude of the phase flux linkage and rotor position.

For the EM under consideration, the real resistance and the dependence of the phase flux linkage on the current flowing through it and the position of the movable element were determined.

The processes in the DC link under the made assumptions are described by the following equations:

$$\begin{aligned} \frac{dI_0}{dt} &= \frac{1}{L_0}\left(E_0 - R_0 I_0 - U_c\right); \\ \frac{dU_c}{dt} &= \frac{1}{C}\left(I_0 - \left(I_{d1} + I_{d2}\right)\right), \end{aligned} \tag{2}$$

where E_0, L_0, R_0 are EMF, inductance and real resistance of a direct current link; C, U_C are capacitance in the DC link at the input of the converter and the voltage on it.

The voltage at the phases is formed in such a way as to provide the creation of a current pulse of a given magnitude and length. According to the made assumptions, the magnitude of the voltage applied to the phase is determined under the following conditions:

$$U_f = \begin{cases} U_c, \text{ если } I_f \in \left[0, I_m - \frac{\Delta I}{2}\right[\vee I_{f3} \in \left[I_m - \frac{\Delta I}{2}, I_m + \frac{\Delta I}{2}\right] \wedge \frac{dI_f}{dt} > 0; \\ 0, \text{ если } I_f \in \left[I_m - \frac{\Delta I}{2}, I_m + \frac{\Delta I}{2}\right] \wedge \frac{dI_f}{dt} < 0; \\ -U_c, \text{ если } I_f = 0 \wedge I_f > 0. \end{cases} \tag{3}$$

Here, I_m is the amplitude of the generated phase current pulse; ΔI is the width of the current corridor.

The length and phase of the current pulse of a rectangular shape with a given amplitude is determined by the initial and final angles $\alpha 0$ and $\alpha 1$ counted from the coordinated position of the phase.

The currents consumed by the phases from the DC link, when using the principle of switching power semiconductor devices, are determined by the expression:

$$I_{d1,2,3} = \text{sign}(U_{f1,2,3}) I_{f1,2,3}, \tag{4}$$

where $\text{sign}(U_{f1,2,3})$ — is the phase voltage sign selection function

The equations (1) and (2) considering the expressions (3) and (4), are MM describing the processes in the switched reluctance EM under consideration. It was applied to simulate processes in EM using a sensorless control algorithm. In the calculations, in addition to the indicated parameters and characteristics of the EM, the following values were used: the real resistance and inductance in the DC link are taken equal to R_0 = 0.1 Ohm; L_0 = 0.001 H; DC link condenser capacitance C = 5000 μF; EMF of the DC link E_0 = 595 V.

Research Results. To study the considered options for sensorless determination of the position of a high-speed switched reluctance generator rotor, the mode of operation with a nominal speed is of main interest. In this mode, the EM is controlled under the single-pulse mode. The moments of turning on and off the power keys are determined depending on the position of the rotor. The condition for the most efficient energy transfer by the working phase is the current of a given magnitude in the phase by the time the rotor is in the position corresponding to the start of the generation interval of this phase (see Fig. 1). For this, a positive voltage pulse is applied to the phase with a certain lead: both power switches are closed (for example, for phases *A*, *S*1 and *S*2). After the rotor takes the position corresponding to the generation process onset, the power switches are turned off, and the generation process starts. To limit the uncontrolled increase in current when it reaches the set value, one of the switches opens, and a phase short circuit is formed through a closed power switch and a diode.

Fig. 3 presents the results of simulating the electromagnetic processes in the switched reluctance generator at a nominal speed.

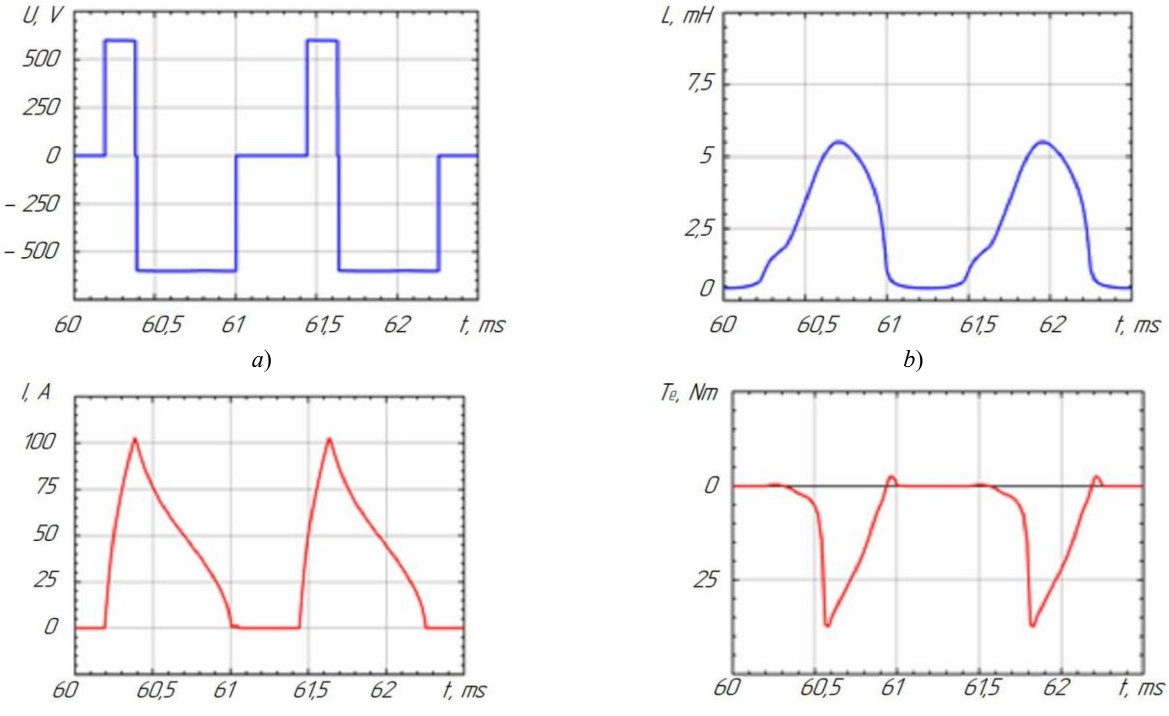

Fig. 3. Results of mathematical simulation of processes in switched reluctance generator at nominal speed:
a) voltage; *b*) inductance; *c*) current; *d*) electromagnetic torque

The excitation pulse parameters are calculated so that by the generation process onset, the phase current reaches a predetermined value of 100 A. In this case, there is no pause between the excitation pulse and the start of generation, during which the phase is under the short-circuit condition. Fig. 3 shows the dependences of the voltage, current, and inductance of the phase, as well as the electromagnetic moment it develops.

As follows from the above description of the control principle, in a single-pulse mode, the generation process is uncontrollable, and the EM is regulated by the excitation pulse parameter variation. The moments of its start-up and end depend on the position of the rotor. Therefore, the accuracy of determining the position is important for the efficient operation of EM [9, 10]. If the excitation pulse is fed ahead of time, it shifts towards a decrease in the phase inductance, its current rises with a higher intensity, and the phase switches to the short circuit mode. The pause between the end of the excitation pulse and the generation process onset depends on the discrepancy between the calculated and actual position of the rotor and can be used to correct the estimate of the rotor position.

If the excitation pulse is delayed relative to the calculated moment of time, it is shifted toward a higher inductance, and its length is not enough to increase the current to a predetermined value. Therefore, a decrease in the current magnitude at the end of the excitation pulse is a sign that the rotor position is implemented to be behind the actual value. Fig. 4 shows the dependences of the phase current for cases of coincidence, lead, and lag of the estimate of the rotor position from its actual value.

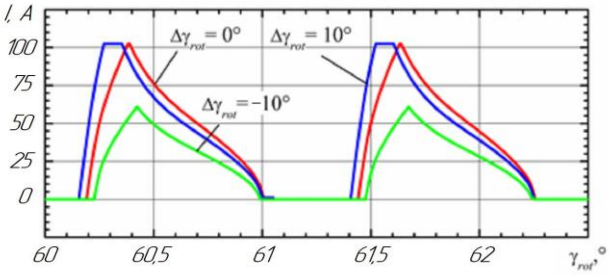

Fig. 4. Dependences of the current phase of switched reluctance EM for cases of coincidence, lead and lag estimates of rotor position

Comparison of the curves obtained specifies the following feature. The phase current curve under the generation mode has a knee point corresponding to the maximum phase inductance. In the case of a constant phase current (see Fig. 2), it corresponds to the coordinated position of the stator and rotor teeth. With a decrease in current during the rotor movement, the saturation of the magnetic system decreases, and the position of the maximum inductance of the phase shifts toward wide angles. This effect has a peculiarity: the position of the knee point of the current curve does not depend on the time of the excitation pulse feed, and will be determined only by the value of the current at the generation process onset. This feature can also be used to refine the position of the switched reluctance EM rotor when operating under the single-pulse mode.

The application of the described information features requires control of the current, its first and second derivatives. When using common types of the A-to-D converters (ADC), the measurement error will reach 5–10%. Therefore, to filter the current signal in the control system of a high-speed switched reluctance generator, a third-order Kalman filter is proposed, using a phase current model based on the equation:

$$\frac{dI_f}{dt} = \frac{1}{L_f\left(\gamma_{rot}, I_f\right)}\left(U_f - R_f I_f - I_f \omega_{rot} \left.\frac{\partial L_f\left(\gamma_{rot}, I_f\right)}{\partial \gamma_{rot}}\right|_{I_f=\text{const}}\right). \tag{5}$$

Fig. 5 shows the analysis results of processes in a switched reluctance EM using a sensorless control that implements the principles for determining the rotor position described above.

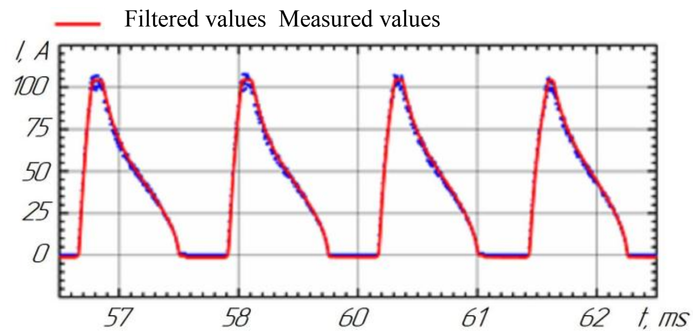

Fig. 5. Correction of rotor position estimation under single-pulse mode of switched reluctance EM operation

The calculations were carried out under the following conditions. The EM rotates at nominal speed. The excitation pulse has the same parameters as for the case considered earlier. The stator phase currents are measured by the ADC with a conversion time of 5 μs and have an error of 10% normally distributed. At the initial moment, the estimation of the rotor position differs from the real one by 10 degrees. The correction of rotor position estimation is presented. The end-point analysis showed the efficiency of the proposed technique for filtering the phase current measurement results and the applicability of the identified information signs to correct the of the rotor position estimate under a single-pulse operation mode of the switched reluctance EM.

Discussion and Conclusions. The end-point analysis affords to draw a number of conclusions. A switched reluctance generator designed to operate in conjunction with a steam microturbine is controlled without a rotor position sensor using the appropriate algorithm. There is an unambiguous relationship between the rotor position and the stator phase inductance, therefore all methods of sensorless determination of the rotor position are based on an indirect measurement of the phase inductance. At high speeds without a rotor position sensor, it is irrational to apply approaches based on feeding a series of test pulses to the idle phase, since the resolution of this method is insufficient for effective control of the generator. In this case, it is rational to control the parameters of the main current pulse.

Under the generation mode, the switched reluctance EM is controlled through the feed time variation and the length of the voltage pulse (excitation pulse), which generates current in the EM phase at the generation process onset. The instant of feed and the length of the excitation pulse are determined by the position of the rotor; therefore, an effective control of the generation process is possible only with an accurate estimation of the rotor position. To correct the rotor position estimate, the following information signs can be applied:

— the presence of a pause between the excitation pulse and the generation process onset (the estimate is ahead of the actual rotor position);

— the decrease in current by the time the generation starts (the estimate lags behind the actual rotor position).

To refine the estimate, the following fact can be used: on the generation interval, the current curve knee corresponding to the maximum phase inductance is observed at the same rotor position.

Application of these information signs provides creation of an effective algorithm for determining the rotor position in a high-speed switched reluctance generator without a physical sensor.

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