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Power-Supply Systems Reliability Control

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Abstract

System reliability control is proposed to maintain through the usage of the operating time between the system components' failure. Usually, trouble-free (reliability) is assessed considering component failures. Almost all the system probabilistic parameters were determined via the component failures. The system reliability control requires another approach to solve this kind of problem. The first thing is a rational system component selection, which is necessary to provide its reliable functioning in the process of exploitation, safe maintenance, cost-effective mounting and dismounting. Secondly, the components must meet technical and economic feasibility requirements. They cannot be used with high or low capacity. If the component capacity is overrated, you bear unjustified costs, i.e. you pay an increased price for the purchase of spare parts and new components if they are replaced. In case of the low capacity increasing loads on the system cause its component load increase, which leads to the breakdown. Prevention of the occurrence of failures in the system, will increase the system's trouble-free and, therefore, its reliability. Therefore, the system reliability can be controlled.

Keywords: system; electrical equipment; levels; probability; time between failure; reliability; maintenance; functioning; industrial enterprise.

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1. Introduction

As a result of numerous theoretical and operational studies, the electrical energy is proved to be the principle type of energy used by industrial enterprises. Technological machine electric power supply from power sources is carried out by using power supply systems. The power supply systems are multilevel. Eeach system level consists of a separate type of electrical equipment. Higher-level electrical equipment is designed to transfer more electricity than lower-level equipment. The basic estimation of the electrical equipment must be performed considering an acceptable reliability level, regardless of its level. In general, it is necessary to determine the maintenance and management personnel by power supply systems.

2. Theory of the issue

Evaluation of the reliability of the power supply system is proposed to be carried out in relation to the time between failures of electrical equipment. According to this time between failures, all other reliability parameters characterizing the trouble-free operation of the equipment are determined. The peculiarity here is that preventive maintenance periodicity periods are planned, and the failure elimination is not estimated. Let’s research the problem using the example of a power supply system for a separate industrial enterprise in order to understand it better. The power supply system is divided into levels. The levels` reliability is presented in the form of equivalent components. This allows equivalent components in relation to the accumulators of electrical power to be presented as a series. A random pulsed stream serves as a mathematical model of the equivalent component functioning.

3. Experiment process

When using the random pulsed stream, the system reliability is estimated by such parameters as the time between failures, the reliability probability, frequency of time of preventive repair. The reliability probability is the opposite to the preventive repair time probability. The time between failures in strict sequence follows the time of preventive repair. The frequency of their followings is the same. This is the link between the functioning and the planned equipment shutdown. That is why the mathematical apparatus in the form of a random pulsed stream was chosen for the estimation of the system reliability control.

4. Research methods

The assigned task is proposed to put through in a general way. The analyzed system is proposed to divide into levels. In our case we have six levels. If the system component trouble-free is assessed in time and new components are used if needed, i.e. the system reliability is controlled, then it becomes trouble-free. The first level executes the tasks assigned to the system. For the power supply system of industrial enterprises it usually consists of electric motors of driving devices. The last sixth level consists of a disconnector. The other system components are intermediate levels. The system division into levels is shorthand. The highest last system level can be not single. The number of similar levels in the system increases from the last to the first. If the upper levels are the component units, then the lower, especially the first ones, can be represented by any number. For industrial enterprises it depends both on the system structure and the technological process and their capacity.

The rational choice of the industrial enterprise system type selection relative to the level of reliability is applicable only if the break in their functioning results in the economic damage to the consumer and if this damage is caused by the enterprise quantitative and qualitative production limitation. When shutdowns in the operation of the system are dangerous to the human lives, to their health or are unacceptable at the state level, then the choice of the scheme variant by using the technical and economic analysis is unneeded taking into account the damage.

Reliability is characterized by a set of parameters. The key requirement is the probability of trouble-free operation of the system and its components. It is characterized by trouble-free operation, time between failures of the system for a certain time, year, day, etc. The required level of probability of trouble-free operation P, the reliability rate, is determined by the costs for the system redundancies [1-10], creating backup (additional) connections. The costs should be minimal.

$$P = \min(p_n K + Ce), \text{ provided } P(\tau) \leq P_{min,\ add}(\tau),$$

where $P_{min,\ add}(\tau)$ – the minimum permissible probability of trouble-free operation relative to the considered system level, its concrete component, the performer of the system functioning, etc.

The similar parameters and reliability of the system concrete level are not the same. Usually, as it is represented in [11-15], the smallest value of parameters characterizing the probability of trouble-free operation and time between failures meets the lower (first) level. The highest level of the system represents the biggest probability of trouble-free operation.

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Meanwhile, we will characterize the considered level, the separate component, the performer (accumulator), in addition to the probability of non-failure operation p, by such parameters as the density of probability of the time between failures $\alpha(\tau)$, time between failures $\overline{\tau}$, frequency of the planned shutdowns in the system functioning $\overline{\mu}$. In our case the opposite parameters of the trouble-free system performance are the planned events. These include: probability of the planned fault time $\overline{p}$, characterized by the time of component maintenance θ, and of course the law of distribution $\beta(\theta)$ values θ.

Components of the system levels with regard to reliability can be connected in series or in parallel, but cases that do not relate to either serial or parallel connections are possible. Consider in advance in general view the series connection in order to assess the structural interrelationship of the system components. Regardless of the component connection, the probability of their operation P_f is calculated by the multiplication of the probabilities of the times between failures and the component failure i.e. $P_f = \prod_{i=1}^{n} p$. The opposite event, the probability of planned fault time $\overline{P}_f = 1 - P_f$. In this case, from the position of reliability, it is implied that fault times for the concrete component units close each other. In fact, this is impossible for systems. It is impossible to transmit a signal (energy) to the performer (accumulator) with the planned fault time of a concrete element for the series connection. If it is true, then the probability for a series connection is equal to the sum of the planned fault times of the concrete components $\overline{P}_{sum}=\sum_{i=1}^{n}\overline{p}_i$. The probability of the trouble-free - $P_{sum}=1-\overline{P}_{sum}$. At the same time, with the increase in the number of components in the series connection and its tendency to infinity, the probability of the sum of the fault times will be bigger than one, and this is impossible. The number of components in a series connection of technical and even power supply systems is little, and their times between failures exceeds the planned fault times in hundreds or even thousands. Therefore, the second calculation approach is more rational to use for the analysis of system series connections. It allows to calculate the probability and frequency of planned fault time, which is relatively simpler than the first approach. The relative calculation error between the first and second approaches is $(P_f - P_{sum})100\%/P_f$. The lesser the number of components in the connection and the greater it is with respect to the time of planned fault times between failures, the lesser the error is. The absolute error for electric systems in this case is less than a thousandths of the probability of the time between failures of the considered connection level, and the relative error is even a thousand times lesser. Therefore, it is advisable to apply the second approach, using the frequency of the planned fault time of the connection equipment. This is more correct, as a simple one can be associated with servicing several units of elements. With this approach, the dependencies of the frequency and the probability of fault times representing the series connection of the system components is:

$$\overline{\mu}_{s,cons}=\sum_{i=1}^{n}\overline{\mu}_i; \qquad \overline{P}_{s,cons}=\sum_{i=1}^{n}\overline{p}_i \tag{1}$$

Here $\overline{\mu}_i$- frequency of fault times of i-component of the considered connection, and $\overline{p}_i$- probability of the planned fault times of i-component.

If the formulas (1) are used, the remaining average parameters for the series connection are

$$P_{s,cons}=1-\overline{P}_{s,cons}; \qquad \overline{\theta}_{s,cons}=\overline{P}_{s,cons}\left(\mu_{s,cons}\right)^{-1}; \qquad \overline{\tau}_{s,cons}=P_{s,cons}\left(\overline{\mu}_{s,cons}\right)^{-1} \tag{2}$$

If the densities of probability of the planned fault times of the i-component are known, then the density of probability of the connection fault times is:

$$_{s,cons}(\theta)=\frac{1}{\overline{\mu}_{s,cons}}\sum_{i=1}^{n}\overline{\mu}_i\beta_i(\theta) \tag{3}$$

More difficult thing is to determine the dependence of density of probability of the time between failures $\alpha_{s,cons}(\tau)$.

This is due to the fact that when the electrical equipment is connected in series, the failure time is overlapped in time. They cannot be lesser than the least of the time between failures of any unit of the equipment connection. However, these times are divided by the planned fault times into components during the system performance. For concrete connections of power supply systems of enterprises $\alpha_{s,cons}(\tau)$ is based on the experienced data. Dependence $\alpha_{s,cons}(\tau)$ is also determined theoretically, if the following approach is used. A random pause, the time of the planned repair, divides casually coincidental time between failures. This happens because different equipment will be characterized by unequal planned fault times. In the general case, the time between failures τ, of the concrete equipment type is divided into two parameters X and Y.

If we exclude from consideration the time of preventive maintenance, then the initial time between failures can be represented by a two-dimensional probability density

$$\Im(x,y)=\frac{1}{\overline{\tau}}\alpha(x+y), \tag{4}$$

with $\overline{\tau}$ - the considered time between failures, divided by the fault time caused by preventive repair (maintenance).

In general case the density of probability of random parameters X and Y is

$$\Im(x,y)=\frac{d^2}{dxdy}p(X\ge x, Y\ge y). \tag{5}$$

The components obtained by dividing the time between failures are equal in periodicity. This kind of event is characterized by the probability

$$p(x,y)=p\cdot p(X\ge x, Y\ge y), \tag{6}$$

In formula (6) $p=\overline{\mu}\overline{\tau}$. This lets to calculate the probability $p(x,y)$:

$$p(x,y)=\overline{\mu}(x,y)\overline{\tau}(x,y). \tag{7}$$

Equating the right sides of equations (6) and (7) we have

$$p(X\ge x, Y\ge y)=\frac{1}{p}\overline{\mu}(x+y)\overline{\tau}(x+y). \tag{8}$$

Transforming equation (8) and considering its parameters, we have

$$p(X\ge x, Y\ge y)=\frac{1}{\overline{\tau}}\int_{x+y}^{\infty}\tau-(x+y)]\alpha(\tau)d\tau. \tag{9}$$

The equation (4) solved considering (9) confirms, that the density of probability of the randomly divided time between failures into two components can be considered as two-dimensional. The resulting components are characterized by a one-dimensional density of probabilities. They are equal and can be calculated as the integral of the formula (4), i.e.

$$_1(x)=\int_0^\infty \Im(x,y)dx=\psi_2(x). \tag{10}$$

Solving (10) and considering the casual time δ we have $p(\delta)=\bar{\mu}(\delta)\bar{\tau}(\delta)$, and

$$\psi_1(x)=\psi_2(x)=\frac{1}{\tau}\int_x^\infty \alpha(\tau)d\tau \quad . \tag{11}$$

If the density of probabilities of times between failures of equipment is subject to exponential law $\alpha(\tau)=\frac{1}{\tau}e^{\frac{-\tau}{\tau}}$, then division of the time between failures into components will result in case when the density of probabilities of their times will also be subject to exponential distributions. In general case when the time between failures is divided into components

$$\alpha_n(\tau)=\frac{n}{\tau}e^{\frac{-n\tau}{\tau}}. \tag{12}$$

Figure n means the number of divisions of the time between failures is calculated via frequency of the planned preventive fault times of the equipment series connection: $n=\frac{\tau}{\tau+\theta}=\tau\bar{\mu}$. Considering the value of n figure (12) is calculated the following way

$$\alpha_{s,cons}(\tau)\quad \bar{\mu}_{s,cons}e^{-\bar{\mu}_{s,cons}}. \tag{13}$$

The processes performed by the system depend on the category of its components. In order to increase the reliability of the system, in addition to the basic components, the reserve (backup) systems and redundancy are also used. The systems are often formed from separate subsystems for these purposes, which like the main system are divided into levels. Parallel performance of the main and reserve components of the subsystems depends on the load and its functions. The probability that is to be determined is calculated by the sum of several incompatible events. In this case, each summand of the sum is an incompatible event probability multiplication. The number of factors in each summand of the sum is the same. It is equal to the number of events considered (units of components, including performing the same functions in parallel). The total group of the sum of incompatible events is one. Determine the probability of performance of at least one component in the following way

$$P_{n,1}(\tau)=1-\prod_{i=1}^{n}\bar{p}_i(\tau), \tag{14}$$

with $\prod_{i=1}^{n}\bar{p}_i(\tau)$- probability of simultaneous non-performance (planned fault time) of the system components; $\bar{p}_i(\tau)$-probability of the planned fault time of i-component from n, performing in parallel.

Formula (14) uses double index. The first number of the index "n" indicates the number of considered units of components, the second "1" - the number of performance of at least one component. In practice the systems usually use the reserve and basic components of the same type. The probabilities of such components` performance are equal to each other.

$$p(\tau_1)=p(\tau_2)=p(\tau_3)=\ldots p(\tau_n)=p.$$

Probabilities of the opposite events of the planned fault time are equal to each other:

$$\bar{p}(\tau_1)=\bar{p}(\tau_2)=\bar{p}(\tau_3)=\ldots\bar{p}(\tau_n)=1-p=q.$$

If the probability value q is put in the penultimate equation, we have

$$P_{n,1}(\tau)=1-q^n.$$

Thus, it is possible to determine the probability of any number of components working simultaneously. Usually systems of industrial enterprises have no more than two units of components performing. In our case the formula for determining the probability of simultaneous performance of at least two units of components is expressed in the formula

$$p_{n,2}(\tau)=1-\sum_1^n\prod_{i=1,j=1}^{n}\bar{p}_i(\tau)\bar{p}_j(\tau)-\prod_{i=1}^{n}\bar{p}_i(\tau). \tag{15}$$

This kind of dependence can be calculated for any number of components performing in parallel. This approach can be extended to opposite events, simultaneous non-performance, planned times between failures of the system components. It should be applied when there are fewer variants for calculating opposite than direct events. Determination of the remaining parameters characterizing the simultaneous performance of the components of the system, it is necessary to know their density of probability of the time between failures. In the general case it looks like that:

$$\alpha_{n,k}(\tau)=\frac{1}{p_{n,k}}\frac{d^2}{d\tau^2}p_{n,k}(\tau). \tag{16}$$

The average time between failures is calculated in the following way:

$$\bar{\tau}_{n,k}=\int_0^\infty \tau\alpha_{n,k}(\tau)d\tau. \tag{17}$$

Frequency $\bar{\mu}_{n,1}$ for the case of performance of at least one component from n is calculated by the planned preventive fault times:

$$\frac{1}{\theta_{n,1}}=\frac{1}{\theta_1}+\frac{1}{\theta_2}+\frac{1}{\theta_3}+\ldots+\frac{1}{\theta_n}. \tag{18}$$

When two components perform the same functions in parallel, then

$$\bar{\theta}_{2,1}=\frac{\bar{\theta}_1\bar{\theta}_2}{\bar{\theta}_1+\bar{\theta}_2}. \tag{19}$$

For three components

$$\bar{\theta}_{3,1}=\frac{\bar{\theta}_1\bar{\theta}_2\bar{\theta}_3}{\bar{\theta}_1\bar{\theta}_2+\bar{\theta}_1\bar{\theta}_2+\bar{\theta}_2\bar{\theta}_3}. \tag{20}$$

Considering (1.14) and (1.19) the frequency of the performance of at least one of the two components

$$\bar{\mu}_{2,1}=\frac{\bar{p}_1\bar{p}_2\left(\bar{\theta}_1+\bar{\theta}_2\right)}{\bar{\theta}_1\bar{\theta}_2}=\bar{\mu}_1\bar{\mu}_2\left(\bar{\theta}_1+\bar{\theta}_2\right). \tag{21}$$

When three components perform in parallel

$$\bar{\mu}_{3,1}=\bar{\mu}_1\bar{\mu}_2\bar{\mu}_3\left(\bar{\theta}_1\bar{\theta}_2+\bar{\theta}_1\bar{\theta}_3+\bar{\theta}_2\bar{\theta}_3\right). \tag{22}$$

The proposed approach can help calculate similar dependencies for any number of parallel performing components. In this case the dependencies become more complicated with the increase in the simultaneous component performance. So, in case of two units out of three, the analysis must already be carried out according to concrete coincidences. The calculation is simpler if it is performed with respect to the periodicity of the planned equipment repair. In the considered case the coincidence of the simultaneous maintenance of all three units of equipment is provided by the probability of the planned fault time in the following way

$$\bar{P}^0_{3,2}=\bar{p}_1\bar{p}_2\bar{p}_3.$$

Average time of these events $\bar{\theta}^0_{3,2}$ and their frequency $\bar{\mu}^0_{3,2}$ are:

$$\bar{\theta}^0_{3,2}=\frac{\bar{\theta}_1\bar{\theta}_2\bar{\theta}_3}{\bar{\theta}_1\bar{\theta}_2+\bar{\theta}_1\bar{\theta}_3+\bar{\theta}_2\bar{\theta}_3};\quad \bar{\mu}^0_{3,2}=\bar{P}^0_{3,2}\left(\bar{\theta}^0_{3,2}\right)^{-1}. \tag{23}$$

When only one component performs and two components are subject to maintenance (repair), then there are three such similar coincidences. Their probabilities are determined by the formulas

$$\bar{P}^1_{3,2}=p_1\bar{p}_2\bar{p}_3;\quad \bar{P}^2_{3,2}=\bar{p}_1p_2\bar{p}_3;\quad \bar{P}^3_{3,2}=\bar{p}_1\bar{p}_2p_3,$$

and average periodicities of the planned fault times are expressed by the equations:

$$\bar{\theta}^1_{3,2}=\frac{\bar{\tau}_1\bar{\theta}_2\bar{\theta}_3}{\tau_1\bar{\theta}_2+\tau_1\bar{\theta}_3+\bar{\theta}_2\bar{\theta}_3};\bar{\theta}^2_{3,2}=\frac{\bar{\theta}_1\bar{\tau}_2\bar{\theta}_3}{\bar{\theta}_1\tau_2+\bar{\theta}_1\bar{\theta}_3+\tau_2\bar{\theta}_3};\ \bar{\theta}^3_{3,2}=\frac{\bar{\theta}_1\bar{\theta}_2\bar{\tau}_3}{\bar{\theta}_1\bar{\theta}_2+\bar{\theta}_1\tau_3+\bar{\theta}_2\tau_3}.$$

Frequencies of these coincidences

$$\bar{\mu}^1_{3,2}=\bar{P}^1_{3,2}\left(\bar{\theta}^1_{3,2}\right)^{-1};\ \bar{\mu}^2_{3,2}=\bar{P}^2_{3,2}\left(\bar{\theta}^2_{3,2}\right)^{-1};\ \bar{\mu}^3_{3,2}=\bar{P}^3_{3,2}\left(\bar{\theta}^3_{3,2}\right)^{-1}. \tag{24}$$

If the considered events don`t overlap each other in time, then their frequency is calculated by the sum of the frequencies (23) and (24):

$$\bar{\mu}_{3,2}=\bar{\mu}^0_{3,2}+\bar{\mu}^1_{3,2}+\bar{\mu}^2_{3,2}+\bar{\mu}^3_{3,2}. \tag{25}$$

Inputting the frequency in (16) the density of probability of the corresponding number of simultaneously performing components. For at least two out of three simultaneously performing components, the density of probability

$$\alpha_{3,2}(\tau)=\frac{1}{\bar{\mu}_{3,2}}\frac{d^2}{d\tau^2}p_{3,2}(\tau). \tag{26}$$

Average time between failures $\bar{\tau}_{3,2}$ is calculated via analogous equation (17). The frequency $\bar{\mu}_{3,2}$ and time between failures $\bar{\tau}_{3,2}$ determine the probability of at least two simultaneously performing units of the equipment:

$$P_{3,2}=\bar{\mu}_{3,2}\bar{\tau}_{3,2}. \tag{27}$$

4. Discussion of the results

Any system, if necessary, can be presented in the form of a scheme that reflects the functional reliability of its components. In order not to eliminate, but to prevent the occurrence of failures in the system, it is necessary to carry out the maintenance of its components in time. You need to know the frequency of its maintenance, determine the necessary time between failures. When solving this task, which was considered using the example of the power-supply system of the steelmaking plant of PJSC "NLMK", series connections of electrical equipment of the concrete levels were substituted by equivalent components. Equivalent components on the similar levels with respect to each other are connected in parallel. The number of equivalent components on one level grows with the decrease in the number of the level. The function of distribution of time between failures allows to calculate the average value of the time between failures for each equivalent component via planned probability of trouble-free performance. It determines the frequency of maintenance of the series connection equipment. In accordance with the above, the considered power-supply system was complemented with the table reflecting the structure of the considered system. The second table demonstrates the probability of trouble-free of electrical equipment and equivalent components, as well as their mathematical expectations of time between failures with the current probability of electrical equipment performance. Using the law of distribution of the time between failures of equivalent components τ_2 with the accepted probability P^* in accordance with (23)-(27) and formula

$$\tau_1 = \frac{\tau_2 (1-P^*)}{(1-P)}$$

times between failures τ_1 are calculated. After that it is necessary to carry out preventive maintenance of electrical equipment. As a result, the considered system and the corresponding values of the probabilities of trouble-free performance of the equipment got the frequencies of preventive maintenance of the equipment (table). The planned probability of electrical equipment maintenance is pretty high. For the first level it amounts 0.999999. Every kind of reservation reduces the possibility of rejection of receivers, but it does not affect the frequency of stops in the workflow. The replacement of less reliable equipment with a more reliable and more precise equipment practically excludes this factor, therefore, the number of possible failures and their impact on the operation of technical machines is reduced. Especially relevant is the production of hazardous gases and dust, for example, for coal mines of milling plants, cement plants, failures in such systems are not allowable due to the dangers of the explosion and subsequent human casualties, thus only from the position of safety it is more advantageous to use equipment with a greater degree of reliability.

5. Conclusion

As a result of the analysis performed, it can be concluded that ensuring absolute reliability of power-supply to receivers (accumulators) when servicing electrical equipment by repair personnel, is impossible both practically and theoretically. It is caused by the fact that with increasing probability of trouble-free performance of equipment, the frequency of its maintenance increases, it becomes more frequent. It goes especially clear at the first level, while the similar result extends to all levels of the system. Thus for the first level with the accepted value of the probability of the time between failures, ranging from hours to several days. With the probability increase, the periodicity for the concrete equipment can be reduced to minutes even within the thousandth. That is typical for all system levels, but depends on the accepted probability of trouble-free performance of the equipment. This phenomenon is traced at lower levels with lower probability values, as well as at higher levels in case of large probabilities. The solution is the following: either use equipment of higher reliability, which increases the frequency of its maintenance, or use systems of automatic equipment control and maintenance.

Table 1. Values for the periodicity of maintenance of electrical equipment at system levels

Electrical engines of technological equipment	Power-supply system levels					
	First	Second	Third	Fourth	Fifth	Sixth
	Values of time between failures in hours					
1	2	3	4	5	6	7
Tilting furnace engines	9,95	62,8	129,0	1546	95724	1852915
Portal rotation engines	9,90					
Roof pitch engines	4,30	53,5				
Door engines	8,80					
Water pumps	5,50	61,8				
Fans	88,04					
Lance engines	17,3					
Smoke exhausters	14,2					
Gate drive	4,8	70,1	153,0			
Smoke exhausters BAVOV	8,5					
Gas cleaning engines	5,2					
Electromagnetic metal stirring device	3,3	53,1				
Gas-blower	26,3					
Fan	14,1					
Mold end milling machine	14.1	67,6	145,7	2240	70024	

End of the table

1	2	3	4	5	6	7
Bucket elevator	17,7	73,2	134,0			
Rotoblast barrel	68,3	77,7				
Belt conveyor	25,8	64,7				
Tumbling-barrel	34.6					
Quench tank pump	11,4					
Press	15,5					
Apron casting transportation conveyor	10,9					
Snagging grinder	29,7	62,7				
Screw-cutting lathe	52,6					
Drainage pump	13,1					
The average periodicity of preventive maintenance of equipment at the levels of the power-supply system in hours with the probability of its trouble-free performance 0.999999						
	19	65	$1,4\cdot10^2$	$19\cdot10^2$	$83\cdot10^3$	$185\cdot10^4$

The approach considered within the research and the usage of the required time between failures of components allows to reduce complex multilevel systems to series. That is why the simplest dependencies from the theory of random pulsed stream is available to analyze systems and provide the required level of reliability. This approach also lets determine the number of attendants by the periodicity of the planned fault time of the components, that is important result for the reliability of the considered systems. The use of equipment with a high degree of reliability will reduce the cost of stopping the production cycle, which is economically feasible for any type of production.

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