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OPTIMIZATION OF THE PLATE HEAT EXCHANGER USED FOR MILK PRECOOLING

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The article deals with the adjustment of the flow rate of milk and water by a plate heat exchanger, which is used for precooling milk. First, measurements of the parameters of the device in the stable were carried out. Subsequently, the plate heat exchanger was measured in the laboratory. Water at 35 °C was used instead of milk. Different flow ratios of cooling water and cooled water (instead of milk) were set. From the measured values, changes in the temperature of cooled water were calculated depending on its flow rate at a constant ratio of cooling water and cooled water. It was found that in the measured range, there are flow values at which temperature change is maximal. This dependence applies to all selected cooling water and cooled water flow ratios: (0.8, 0.9, 1.0, 1.1, 1.2.). The results show that with the same amount of cooling water, it is possible to achieve greater cooling of milk by 0.7 to 1.6 °C, or to achieve a reduction in water consumption. The device on the farm was modified to allow the flow of milk and cooling water to be changed. The optimal values found were set, and verification measurements were performed. The saving of 4.8% of cooling water was confirmed.

Keywords: animal husbandry; milk production; milk cooling; energy consumption

Currently, there is an effort to reduce energy consumption in all areas of human activity. Electrical energy produced is still largely generated by burning fossil fuels. At the same time, there is also an economic reason. The price of energy is rising rapidly, which increases production costs. This also applies to livestock and milk production. One of the highly energy-intensive operations is milk cooling (Gaworski, 2021; Shine et al., 2018; Upton et al., 2015). As part of energy savings, it is possible to use the heat from the condenser of the cooling device to heat the water, or to remove part of the heat using a precooler. Precoolers have an energetic effect (Murphy et al., 2013) but at the same time accelerate milk cooling. The use of precoolers was shown to help reduce the growth rate of bacteria in milk and milk composition was not affected (Paludetti et al., 2018).

Precoolers can be designed as pipe or plate heat exchangers. The advantage of plate heat exchangers is the possibility to easily change the heat exchange surface by changing the number of plates. For precooling, a large amount of water is necessary, which is approximately the same as the amount of cooled milk.

In most cases, there is no other option than to use water from the water supply pipeline. Many years ago, water from precoolers was discharged into waste. At present, we are facing a lack of water in many places (Trnka et al., 2018). A whole range of scientific papers deals with the issue of water consumption in milk production (Shine et al., 2020; Vaculík et al., 2021). The price of water is gradually increasing and releasing it into waste would be an economic loss, which can be almost as big as the savings in milk cooling. The water that passes through the precooler must be captured and reused. Therefore, it is necessary to have a sufficiently large water tank and pump available for its further transport to the place of consumption.

The aim of our work was to optimize the operation of the precooler used on the farm. Since the performance of the milk pump is significantly higher than the flow rate of milk into the receiver jar, the pump is in operation for a short time. This is followed by the receiver jar filling interval when the pump is switched off. Our assumption was that by reducing the flow rate of milk and water, the time during which heat energy can be transferred from milk to water will be extended. On the other hand, a decrease in the flow rate will result in a decrease in heat transfer coefficient (Ibler et al., 2002; Baláš, 2013). These two quantities act in opposite way, so we decided to verify the effect of flow experimentally.

Material and methods

Measurements were carried out on a farm where a 2 × 3 tandem milking parlor was installed. The milking device was from S. A. Christensen company and included a plate precooler. A flexible impeller milk pump with a performance of 3000 $l\cdot h^{-1}$ was used. The plate heat exchanger had 42 plates and a heat exchange surface of 2.1 m^2. The original state was according to Fig. 1A.

The milk pump was controlled by using of a float in a reciever jar. A permanent magnet is pressed into the float, which switches the magnetic sensors located inside the stainless-steel small pipe along which the float moves. In total, there are three sensors in the small pipe. In the bottom part, there is a sensor that turns off the operation of the pump. In the middle, there is a sensor switching

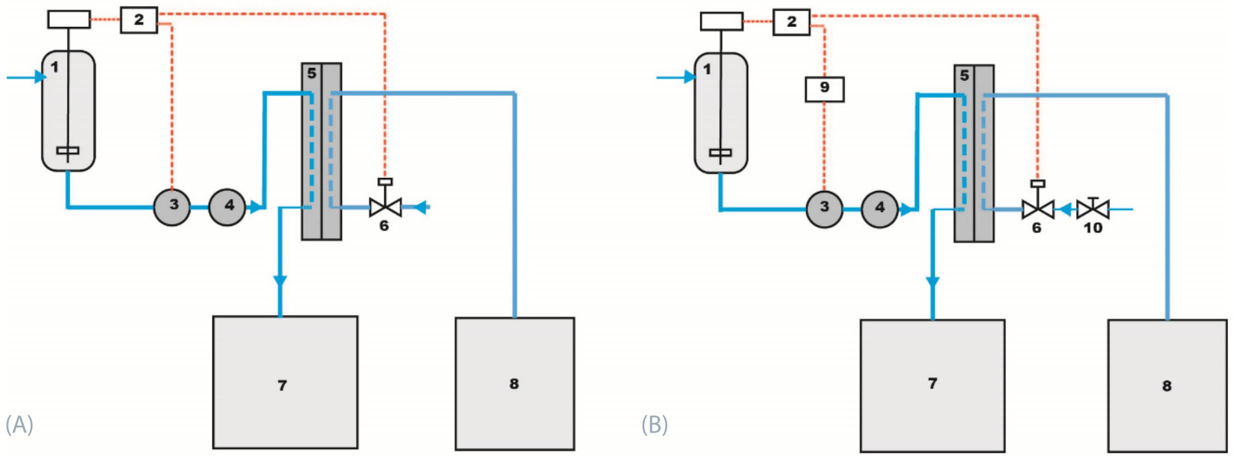

Fig. 1 Cooling device on the farm
A – the original state; B – the modified device; 1– receiver jar, 2 – contactor, 3 – milk pump, 4 – milking filter, 5 – plate heat exchanger, 6 – solenoid valve, 7 – milk cooling tank, 8 – water tank, 9 –frequency converter, 10 – adjustment valve

on the pump, and in the upper part, there is a sensor that switches off the vacuum for milking when the receiver jar is overfilled. The signals from magnetic sensors control the operation of the contactor, which switches the pump and at the same time the solenoid valve that opens the water inlet to the cooler. The times when the pump was in operation and when it was switched off were measured. At the same time, the amount and temperature of individual doses of milk and cooling water were also measured. Temperature was measured at both the t_1 inlet and the t_2 outlet of the plate heat exchanger. The m total amount of water and milk for the entire measurement period was calculated. The flow rate of water and milk and the δ ratio of the flow rates of cooling water and milk, respectively cooling water and cooled water when measured in the laboratory, was determined according to Eq. (1).

$$\delta = \frac{Q_1}{Q_2} \tag{1}$$

where: Q_1 – cooling water flow rate (kg·s^{-1}); Q_2 – flow rate of milk or cooled water (kg·s^{-1})

Furthermore, the values of the average inflow of milk into the receiver jar were calculated in such a way that the amount of milk pumped out in one cycle was divided by the cycle time (filling time + pumping time).

After taking measurements on the farm, the heat exchanger was placed in the laboratory and connected according to the diagram in Fig. 2. Instead of milk, water, having a slightly higher specific heat capacity, was used. The average specific heat capacity of milk is 3936 J·kg^{-1}·K^{-1}. With the previous measurements, we have verified that the use of water instead of milk is possible. Due to the lower specific heat capacity of milk, temperature change is a little higher than that of water. To verify the correctness of the results, the experiment was cerried out in the stable. Temperatures were chosen similar to the measurements in the stable. In two storage tanks, there was water at a temperature of 13 °C and 35 °C. Water from both storage tanks was pumped by milk pumps through the plate heat exchanger to the collection tanks. The same pumps as the milk pump were used on the farm.

The actual measurements were carried out in such a way that after starting the pumps, the water from both parts of the heat exchanger first flowed into the drain for 10 seconds to replace the water inside the heat exchanger. Then, the water was collected in collection tanks for 30 s. Subsequently, the water was again directed to the drain, and the pumps were turned off. The pumps were driven by frequency converters. Frequency was set to 20, 30, 40, and 50 Hz. All possible combinations were set (50–50, 50–40, 50–30, 50–20, 40–50, 40–40, 40–30, 40–20, 30–50, 30–40, 30–30, 30–20, 20–50, 20–40, 20–30, 20–20). A total of 16 different measurements were carried out and each measurement was repeated 5 times. The temperature and weight of the water in the collection containers were measured.

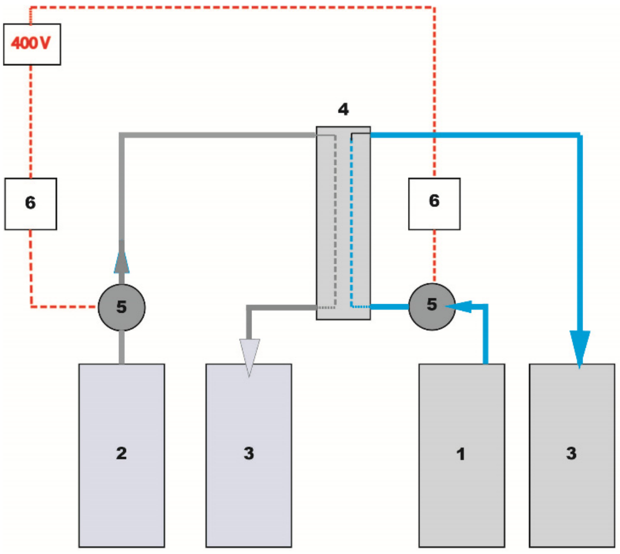

Fig. 2 Laboratory device
1– cooling water tank (13 °C); 2 – cooled water tank (35 °C); 3 – colecting tank; 4 – plate heat exchanger; 5 – pump; 6 – frequency converter

After evaluating the laboratory measurement, a modification of the flow control with the plate heat exchanger was proposed according to Fig. 1B. The switching of the milk pump and the cooling water valve by means of a float in the reiciver jar was maintained. The milk pump electric motor was connected to a frequency converter. The speed of the milk pump was set so that the flow corresponded to the determined optimal value (0.5 kg·s^{-1}). Cooling water was supplied by means of a selenoid valve which was supplemented with a control valve. The amount of cooling water flow was adjusted by the control valve (0.5 kg·s^{-1}). Measurement was carried out on the modified device.

Measurement variability was evaluated using standard deviation. The weighing error was verified experimentally due to incomplete emptying of the collection tanks.

Results and discussion

Measurement in the stable

The measurement of the original device took place in the summertime. Air temperature in the milking parlour ranged from 27 °C to 30 °C. The final temperature of the milk after cooling was 4.2 °C. The measured values are shown in Table 1.

The δ flow ratio was 0.98. The average milk flow at the inlet to the receiver jar in each pumping cycle is shown in Fig. 3. The average value for the entire milking period was 0.16 kg·s^{-1}. The maximum measured value was 0.34 kg·s^{-1}. If the pump performance is above this value, it should not lead to overfilling of the receiver jar.

Measurement in the laboratory

First, the pumps were tested. Measurements were carried out with a plate heat exchanger attached. The dependence of flow rate on the frequency of the power supply is shown in Fig. 4.

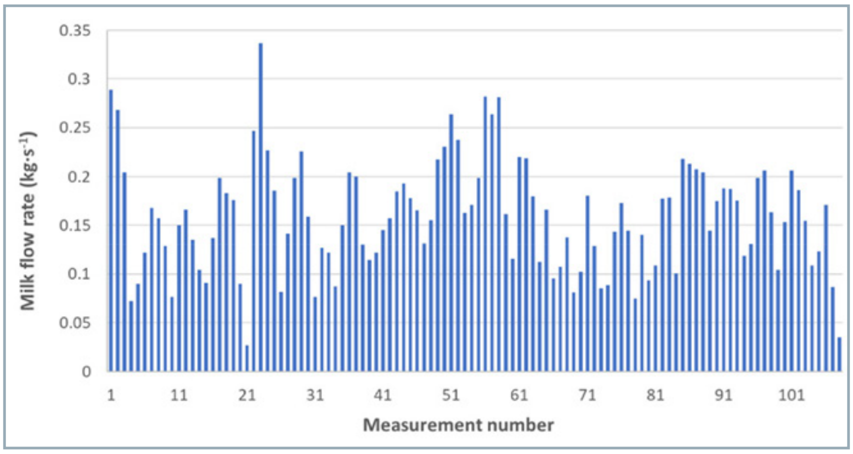

Fig. 3 Milk flow rate at the inlet to the receiver jar

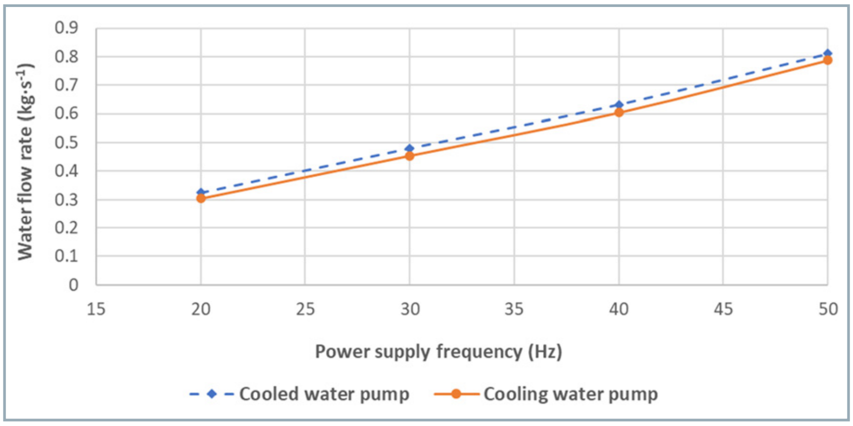

Fig. 4 Water flow rate of pumps depending on power supply frequency

Table 1 Plate heat exchanger data measured in the stable – original state

	t_1 (°C)	SD (°C)	t_2 (°C)	SD (°C)	Q (kg·s^{-1})	SD (kg·s^{-1})	m (kg)
Water	12.9	0.02	28.6	0.76	0.745	0.054	1263.6 ±2.7
Milk	35.2	0.68	18.6	0.58	0.761	0.066	1294.6 ±2.7

t_1 – inlet temperature, t_2 – outlet temperature, m – total amount, SD – standard deviation, Q – flow rate

Table 2 Change in cooled water temperature (°C) depending on the pump power supply frequency

		Power supply frequency of cooled water pump (Hz)							
		20		**30**		**40**		**50**	
		average	**SD**	**average**	**SD**	**average**	**SD**	**average**	**SD**
Power supply frequency of cooling water pump (Hz)	**20**	16.1	0.41	13.5	0.26	10.9	0.61	8.7	0.19
	30	19.5	0.07	16.8	0.07	14.4	0.30	11.7	0.28
	40	20.1	0.15	18.4	0.17	16.4	0.04	14.3	0.38
	50	20.0	0.45	19.1	0.15	18.0	0.17	15.9	0.38

SD – standard deviation

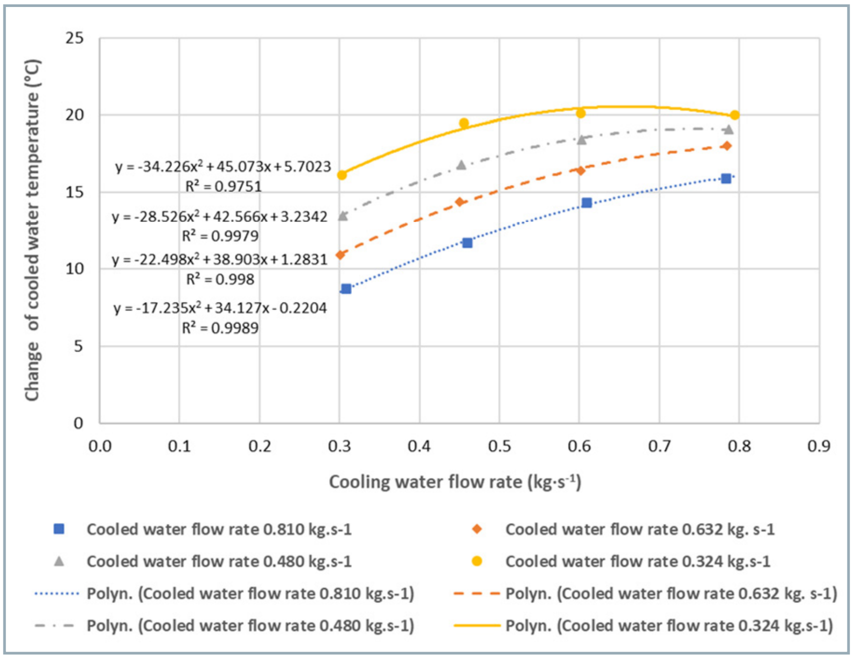

Fig. 5 Temperature changes of cooled water depending on cooling water flow rate at a constant value of cooled water flow

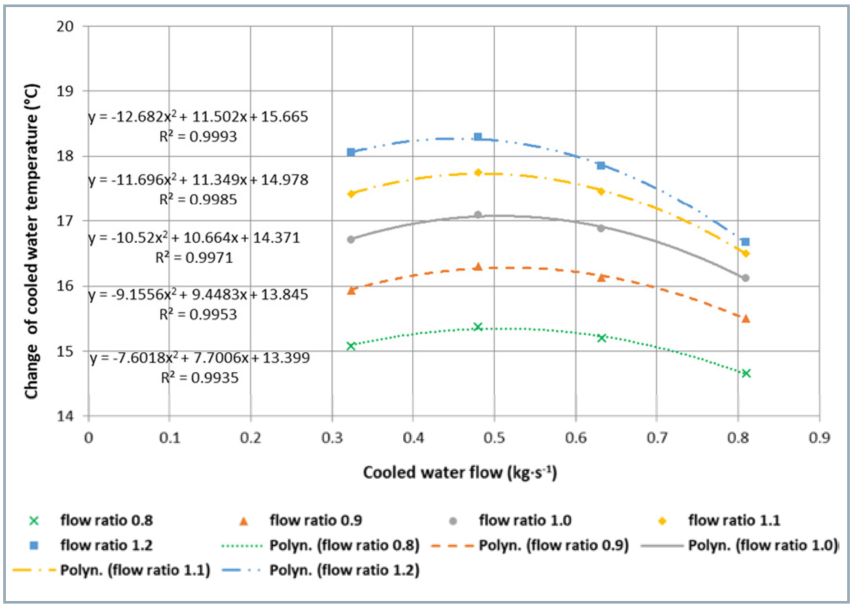

Fig. 6 Temperature changes of cooled water depending on its flow rate at constant δ flow ratios

These were flexible impeller pumps, so the amount of water pumped changed almost linearly. Both pumps worked similarly. The cooled water pump had a slightly higher performance.

This was followed by the measurement of the plate heat exchanger. In the laboratory, a measuring device was assembled according to Fig. 2. The average values of the measured quantities are shown in Table 2.

In Fig. 5, the values of the temperature change of coolled water depending on the flow rate of cooling water at a constant value of coolled water flow rate were plotted. Using MS Excel, trend lines were inserted, and their equations were determined. From these equations, the values of coolled water temperature change for 5 different cooling water flow rates were calculated. Cooling water flow rates were calculated from the δ flow ratio. The following δ values were chosen: 0.8, 0.9, 1.0, 1.1, and 1.2.

Values of the temperature change of coolled water depending on its flow rate at a constant δ flow ratio were plotted in Fig. 6. Using MS Excel, trend lines were inserted again, and their equations were determined. For these equations, the maxima were determined so that the derivative of these functions was equal to zero (Table 3).

For all values of the δ flow ratio, the maximum temperature change of cooled water at a flow rate of approximately 0.5 kg·s^{-1} was calculated. The temperature change is greater for higher values of the δ flow ratio (Fig. 6). With a flow ratio value of δ = 0.8, the theoretical difference in temperature change between the maximum value and the value without pump control

Table 3 Determination of the maximum value of curve equations

Flow ratio	Curve equation	Derivative	Maximum
0.8	$y = -7.602x^2 + 7.701x + 13.399$	$y' = -15.204x + 7.701$	$x = 0.506$
0.9	$y = -9.156x^2 + 9.448x + 13.845$	$y' = -18.321x + 9.448$	$x = 0.516$
1.0	$y = -10.520x^2 + 10.664x + 14.371$	$y' = -21.040x + 10.664$	$x = 0.507$
1.1	$y = -11.696x^2 + 11.349x + 14.978$	$y' = -23.392x + 11.349$	$x = 0.485$
1.2	$y = -12.682x^2 + 11.502x + 15.665$	$y' = -25.364x + 11.502$	$x = 0.453$

Table 4 Plate heat exchanger data measured in stable after plant adjustment

	t_1 (°C)	SD (°C)	t_2 (°C)	SD (°C)	Q (kg·s^{-1})	SD (kg·s^{-1})	m (kg)
Water	13.2	0.05	29.7	0.7	0.472	0.036	1261.1±2.4
Milk	35.6	0.46	19.1	0.54	0.508	0.064	1357.8±2.4

t_1 – inlet temperature, t_2 – outlet temperature, m – total amount, SD – standard deviation, Q – flow rate

is 0.74 °C. It represents a 5.0% increase in heat exchange. With a flow ratio value of $\delta = 1.2$, the theoretical difference in temperature change between the maximum value and the value without pump control is 1.62 °C. It represents a 9.7% increase in heat exchange. Figure 6 also shows that the same cooling effect can be achieved with less amount of cooling water.

This was followed by control measurements in the stable. The device was modified as shown in Fig. 1B. The flow rate of the milk pump was set at 0.5 kg·s^{-1}. The measurement of the dependence of flow rate on power supply frequency was carried out. The flow rate of 0.5 kg·s^{-1} corresponded to a frequency of 36.4 Hz. Cooling water flow was also set to 0.5 kg·s^{-1} by the control valve. Air temperature in the milking parlour ranged from 28 °C to 32 °C. The measured values are shown in Table 4. The final temperature of milk after cooling was 4.4 °C. The average water flow rate value was somewhat lower than the set value. This was probably due to pressure fluctuations in the water pipeline. The real value of flow ratio was $\delta = 0.93$. Inlet temperatures were almost the same as the original device (Table 1 and Table 4). The average decrease in milk temperature was 16.6 °C for the original device and 16.5 °C for the modified device. The amount of cooling water consumed was almost the same, but a significantly lager amount of milk was cooled. The difference in values was 63.2 kg. When converted to 1 kg of cooled milk, the cooling water saving is 4.8%.

Precoolers are used for a very long time. The first works were published 40 years ago (Parkinson and Fisher, 1982; Fleming and O'Keeffe, 1982). The use of precoolers is beneficial because up to 50% of heat energy is taken from milk. This was confirmed by our measurements and corresponds to the results of other authors (Paludetti et al., 2018; Parkinson and Fisher, 1982). However, the result is surprising that the system of double precooling with tap water and subsequently with ice water is more energy-demanding than a system without precooling (Paludetti et al., 2018). The proposed optimization makes it possible to reduce water consumption by 4.8% while maintaining cooling parameters which was experimentally confirmed, or to achieve a lower milk temperature by 0.7–1.6 °C with the same water consumption which was theoretically calculated. The optimization of precooler parameters is dealt with by Murphy et al. (2013). It deals mainly with the economic aspect, and considered prices for water and electricity are very low. It is not realistic to carry out an economic assessment now, given the unstable prices, especially of energy. In any case, the water used for precooling of milk must be further used, for example, as drinking water for dairy cows. Currently, water consumption on farms is around 7 l per litre of milk (Shine et al., 2018). A further increase in consumption is not desirable.

Another possible solution is to use a ground exchanger (Strpić et al., 2020) This system does not need water from the water pipeline, since the cooling water circulates in the device. On the other hand, the initial investment in the construction of earth heat exchangers is considerable. A similar solution was proposed as early as 1982 (Parkinson and Fisher, 1982). The system also works with water which does not change. The disadvantage of this solution is that the water storage tank has a volume three times compared to that of milk. Water is cooled at night in a heat exchanger on the roof of the stable. The expected cooling of water to 12 °C is unlikely to be achievable in the hottest period of year.

Conclusion

Considering that the prices of energy and water have been rising significantly recently, it is appropriate to deal with the issue of optimising milk cooling. The overall effect of modifying the plate heat exchanger system appears to be small, but it must be taken into account that the experiment took place on a small farm. Whether the modification of the device is worth at 4.8% water savings, or to achieve a lower milk temperature by 0.7–1.6 °C with the same water consumption, must be decided in specific economic conditions. Adjustment is simple and requires minimal additional costs. Some milking devices are already supplied with a milk pump, which is supplemented with a frequency converter. In this case, it is only a matter of setting the parameters of the frequency inverter.

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