The Safe Start of Drain Pumps with Single-Phase Synchronous Motor

by: Werner Hangmann, R & D Manager
Hanning Elektro-Werke GmbH, Oerlinghausen, Germany

The single-phase synchronous motor applied as drive for drain pumps has, meanwhile, almost completely replaced the shaded-pole motor which dominated this sector for decades. The decisive factors accounting for the success of this pump concept are numerous.

Figure 1: High-performance synchronous drain pump

When introducing the so-called synchronous pump to the market (shortened form for "drain pump with single-phase synchronous motor") it certainly was the lower market price in comparison to the shaded-pole motor providing the decisive impulses for its success. Moreover, a considerable advantage could be expected due to the new pump design: The dynamic sealing which constituted the weakest point of the shaded-pole pump could be eliminated. The synchronous pump enjoyed the good reputation to be absolutely leak-proof. In addition, the market expected a better resistance against foreign objects as the synchronous motor is able to change the direction of rotation in case it is overloaded by foreign objects acting on the impeller.

A lot of the ambitious expectations came indeed true. But, other problems occurred which were hardly relevant in this form regarding shaded-pole pumps. Among others, the safe start of synchronous pumps was one of the problems. In the following, this problematic subject and corresponding solutions are discussed.

Construction

Figure 2 shows the general construction of a 2-pole single-phase synchronous motor. Basically, the motor consists of a U-shaped stator on which 2 coils are installed which are connected in series. The core of the motor is a diametrically-magnetised permanent magnet. The rotor as a whole is a so-called wet-running rotor, i.e. it is located in the pumping liquid. Stator and rotor are hermetically separated from each other by a rotor chamber (not shown).

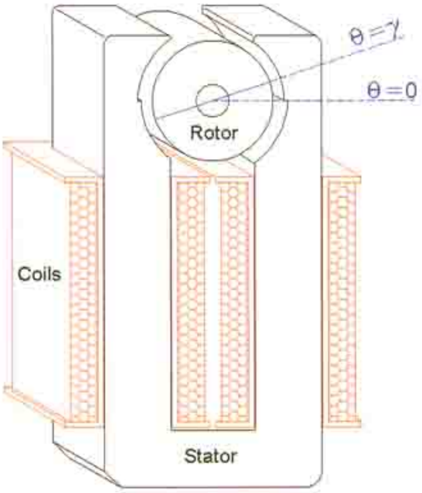

Figure 2: Construction of a single-phase synchronous motor

As it is still shown later on, one of the basic conditions for a safe start is the stator boring in form of a gradual pole. The rotor adjusts itself without stator excitation with its field axis (north-south) in that way that a maximum air gap permeance is achieved (displacement angle γ). In this position applies: $\theta = \gamma$ [1].

Theoretical model

If connected to a sinusoidal supply voltage and if the saturation of iron is neglected the system equations of a single-phase synchronous motor are [2]:

(1)

$$\hat{U} \cdot \sin[\omega_{el} \cdot t - \varphi] = i \cdot R + L \cdot \frac{di}{dt} + w \cdot \hat{\Phi} \cdot \frac{d\theta}{dt} \cdot \sin\theta$$

(2)

$$M_L = w \cdot i \cdot \hat{\Phi} \cdot \sin\theta - J \cdot \ddot{\theta} - \hat{M}_R \cdot \sin[2 \cdot [\theta - \gamma]] - M_{fr}$$

These coupled and non-linear differential equations do not permit a closed analytical solution. Therefore, it is necessary to make use of numerical solution procedures.

Definition of start-up

As it can be seen from (2), there are two angular positions (θ=0 and θ=π) per revolution the motor driving torque of which is zero. A detailed examination of the model also shows that the motor is only in a position to produce a mean torque

$$\overline{M_L} \neq 0 \text{ if } \frac{d\theta}{dt} = \omega_M = \omega_{el} .$$

If this condition is not fulfilled the motor can only develop transient torques.

This is the reason, why you cannot refer to the start-up torque of the single-phase motor as classical. Therefore, the start of a 2-pole synchronous motor after the supply voltage is switched on is described as:

transient phenomenon of the rotor measured from non-operative state until a mean angular velocity corresponding to the electrical angular velocity of the mains is achieved.

In consequence, the start duration is defined as period between switching on the supply voltage and achieving the synchronism.

Initiation of the transient phenomenon

For initiating the transient phenomenon the rotor must be able to leave its idle state. This becomes clear with the help of the following consideration: At the time t = *0* should be $\omega_M = 0$ and $\ddot{\theta} = 0$. Moreover, the rotor should be in its idle state $\theta = \gamma$. Hence, the equation (2) can be reduced to

(3)

$$M_{fr} < w \cdot i \cdot \hat{\Phi} \cdot \sin\gamma$$

The equation (3) clarifies that several conditions have to be fulfilled in order to enable the rotor to leave its idle state:

1. The idle state of the rotor must never assume the value 0 resp. π. In this case, no matter how high the current or how efficient the magnet it would not be possible to move the rotor from its "dead centre". From the constructive point of view, this problem is solved by providing the stator boring with a gradual pole so that the idle state of the rotor can achieve a value of $\gamma \approx 5°$ resp. $\gamma \approx 185°$, if it is assumed that the friction is so small that it can be neglected.

2. The sum of all frictional torques between the rotor and the firm part of the motor resp. the pump must not exceed a critical value acc. to (3). This requirement is, at first, fulfilled by a careful dimensioning of the bearing system. Apart from that, it is guaranteed by the use of a double-lip seal that foreign objects cannot enter into the bearing gap or in the mechanical air gap between rotor and rotor chamber which would create indefinable friction. Moreover, a thermoplastic encapsulation of the magnet is recommended. The injection-moulding is a protection against straying particles which could easily split from the very brittle magnet of the rotor.

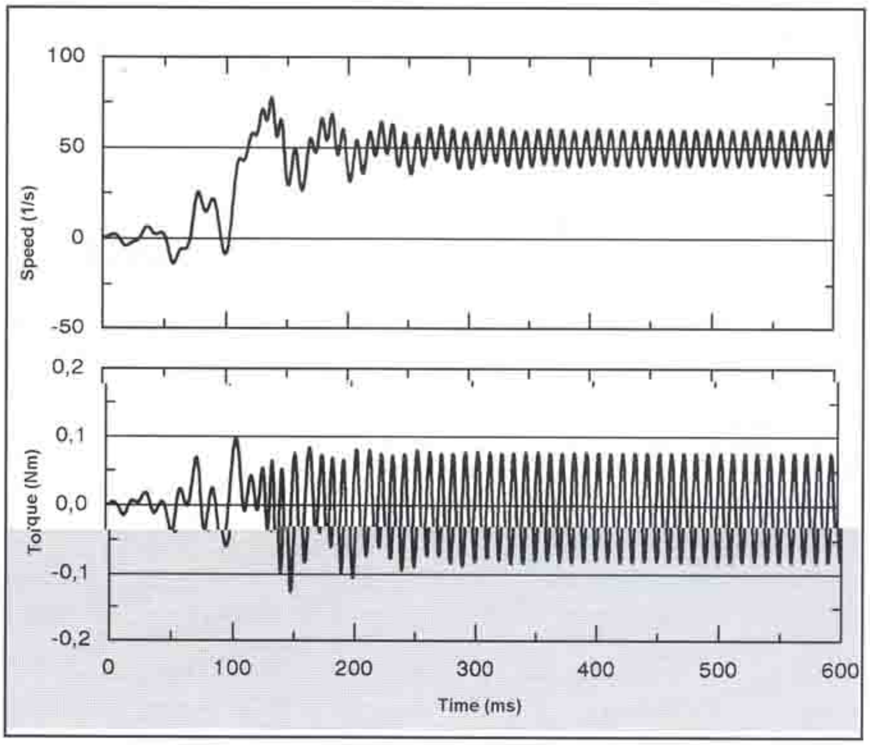

Figure 3: Start process of a single-phase synchronous motor on no-load

The transient phenomenon

After switching the motor on the transient phenomenon is beginning when the rotor left its idle state. Numerous tests have been executed in order to describe the chronological development of the start-up resp. transient phenomenon quantitatively [1], [2], [3]. It is, indeed, possible to calculate transient phenomenon by means of numerical solution procedures which, however, only make a statement about its quality (*figure* 3).

Both sensitivity analysis of the calculation processes and practical examinations have shown that the motional process of starting is instable. It is getting obvious that any small disturbance in the initial values or during the motional development would result in a completely different starting process [2]. Therefore, the starting process of a single-phase synchronous motor fulfils the decisive features of the term CHAOS. Nevertheless, qualitative statements of the starting process can be derived from the calculations:

1. The acceleration of the rotor from almost standstill $\omega_M \approx 0$ until synchronism $\omega_M \approx \omega_d$ is effected within a voltage resp. current half-wave.

2.Until the half-wave can trigger the decisive impulse for starting the motor an indeterminable number of mains cycles are necessary in order to position the motor in an advantageous angle position and to accelerate it to an advantageous angle velocity.

3.The number of the necessary mains cycles resp. the start duration mainly depends on co-ordinating the parameters of *Table 1* carefully:

4. The parameter ***i*** cannot be modified directly. It is a reaction of the interactions of all other parameters. The parameter with the largest effect on ***i*** is the voltage ***U***.

Parameter		Quantitative effects on the start duration
i resp. $\hat{U}$	↗	↘
J	↗	↗
M_L	↗	↗
w	↗	↗
$\hat{\Phi}$	↗	↘

Table 1: Parameters affecting the start duration

5. After the start-up process, only the mean value of the angular velocity of the rotor is identical with the electrical angular velocity of the sinusoidal voltage supply $\overline{\omega_M} = \omega_d$. The instantaneous value can differ considerably. This "untrue" rotation is caused by the pendulum torques acting with double mains frequency on the rotor.

The clutch system

The knowledge that the motor load M_L has a clear influence on the start duration of a single-phase synchronous motor led, at an early stage, to the development of clutches positioned between rotor and impeller. With these clutches it is possible to achieve a more or less well-developed start-up without load. It is only after the rotor passed a certain angle virtually without load that the load is engaged.

This additional component further aggravates a calculation of the start duration. A corresponding calculation could successfully be executed as the first approximation on the basis of a clutch system with torsion spring [1], [3]. However, this clutch system proved to be useless in practice as the used springs could not resist the continuous variation in stress of the motor.

Figure 4 shows a clutch system as it is used today for high-performance pumps. The life expectancy of this pump comes up to 500,000 start-ups with a probability of achieving this level of 90 % at confidence intervals of 95 %.

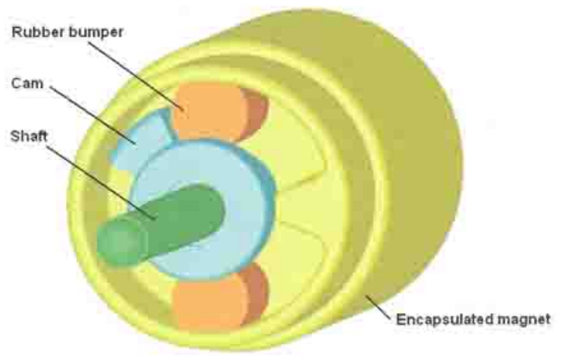

Figure 4: Resistant coupling system

It is, however, hardly possible to re-construct the mathematic model of this coupling and to integrate it in the model of the single-phase synchronous motor.

Practical method of resolution

Although the numerical calculations are very effective for the qualitative assessment of the design of a single-phase synchronous motor they are absolutely inappropriate for describing the quality of a start-up process quantitatively. After the preliminary determination of the design and the construction of corresponding prototypes it is, therefore, necessary to make reliable statements regarding the start-up of synchronous pumps by means of statistical evaluations of results of start duration tests. It is, however, essential to submit the whole system consisting of motor, clutch and load (pump including the hydraulic surrounding) to this test.

Experimental set-up

According to the definition, the indicator for a successfully completed start-up of a synchronous motor is the angular velocity. However, it can only be determined with a comparatively high expenditure. It is, therefore, recommended to make use of such indicators being easily accessible than the angular velocity.

Alternative A: Pressure measurement

The hydraulic pressure produced by a synchronous pump can be used as indicator for the starting process. A corresponding experimental set-up is shown in *figure 5*.

The synchronous pump to be qualified is installed in the application according to conditions prevailing in practice. The drain hose is laid in a way that the water which is pumped out can flow back into the machine. In addition, a pressure switch is installed at the drain hose. This pressure switch delivers a signal to the computer when the hydraulic pressure produced by the pump exceeds a certain threshold value, i.e. when the start-up of the synchronous pump was successful.

The vertical distance between the water level and the pressure switch is marked with δ. It applies: $\delta > 0$. This is required as the pump produces a certain hydraulic pressure already during the transient process. If this value δ is chosen too small the pressure switch would give a signal although the start-up is not yet completed. In practice, a value of $\delta = 0{,}2$ m proved to suitable. However, this construction causes a certain delay time if the synchronous pump should once start in a very short time $t_{S_i} \ll 0{,}5$ s.

In this case, the water column has to pass the distance δ before the pressure switch delivers a signal. The measuring result would then be tampered by the delay time. But, as long as only the "critical" cases are examined the quality of the results provided by this construction is acceptable.

The computer activates the switching element relay or triac depending on what is used in the application. The period between activating the circuit element and occurrence of the signal of the pressure switch is measured and stored by the computer as t_{S_i}.

Moreover, it is recommended to have the variable voltage source controlled by the computer and to measure the temperature of the motor coil. As it is still shown in the following, the motor temperature

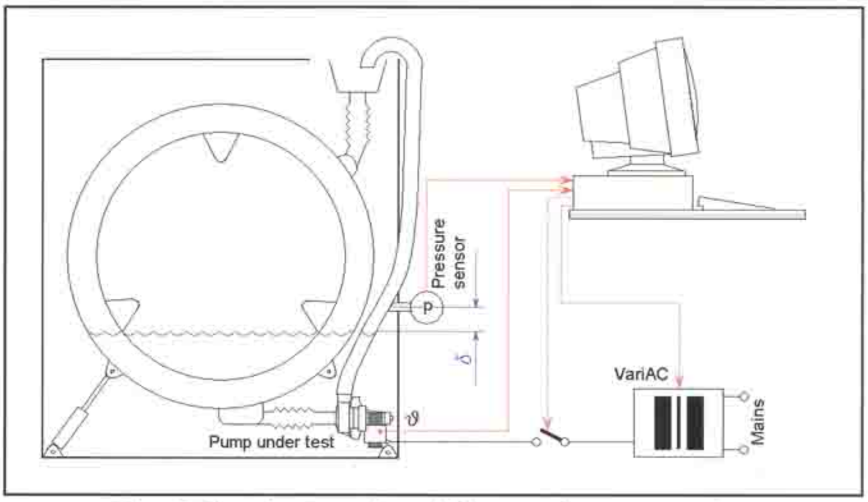

Figure 5: Measuring the starting period by means of pressure measuring

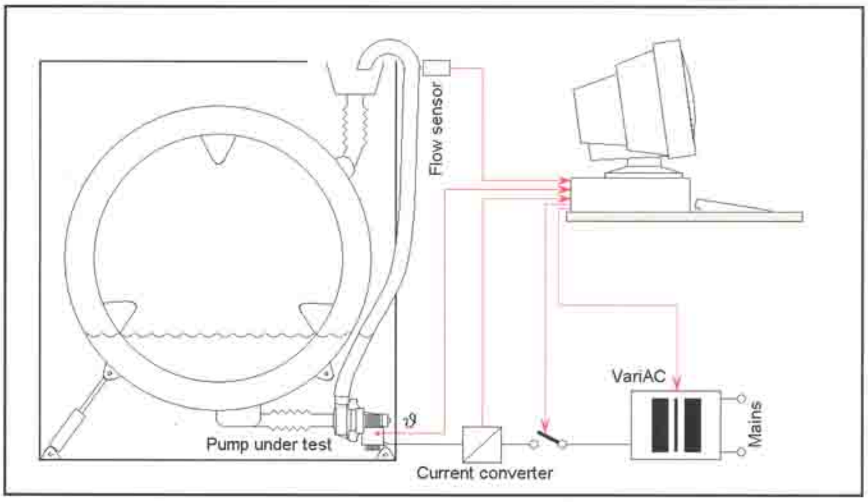

Figure 6: Measuring the start duration by current measurement

influences the starting behaviour as well.

Alternative B: Current measurement

The construction shown in figure 6 differs from the previous construction as the motor current constitutes the indicator for a successful start. With this construction, more precise measurements can be executed. But, the application of a pressure switch or a proximity switch is also necessary.

With the help of *figure 7* the process of measuring can be explained as follows:

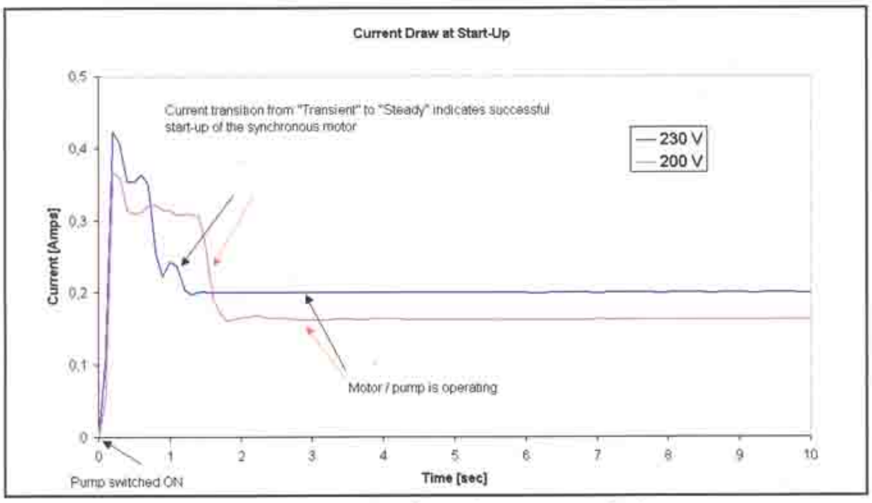

Figure 7: Current consumption of a synchronous pump during start-up

After switching the pump on the root mean square value of the pump's current consumption is measured in time intervals of 100 ms. Alternatively, it would as well be possible to record the peak values $\hat{i}$. At the end of a test period which can freely be chosen the computer controls by checking the pressure resp. the proximity switch whether a water flow has developed, i.e. if the start-up of the synchronous pump was successful.

The determination of the start duration t_{S_i} is based on the fact that the current consumption of a synchronous motor is considerably higher and more unsteady during the transient phenomenon than after the completed start-up. If the pressure resp. proximity switch has signalled at the end of the measuring period that the start-up was successful the computer determines the time of transition t_{S_i}' from transient to steady current consumption.

This value still does not constitute the exact start duration of the synchronous pump. Due to the response time τ of the current transformer the recorded current consumption lags behind the real conditions by the response time mentioned before. In case of the customary current transformers the response time amounts to τ ≡ 200 ms. In consequence, the real start duration is

(4)

$$t_{S_i} = t_{S_i}' - \tau$$

Statistical evaluation

Examining the series of measurements you will see that in spite of the same outer test conditions the results differ considerably. A general, quantitative statement regarding the start duration of the synchronous pump can, therefore, only be made after a statistical evaluation of the series of measurements.

A minimum of 50 start-up tests should have been executed with the same outer conditions. Even with this scope of random checks (n=50) and a confidence interval of 95% the standard deviation as a whole σ can differ up to -16% resp. +25% from the standard deviation s of the random check. A corresponding uncertainty regarding the determination of the parameters to be derived has to be calculated. This uncertainty can be reduced by increasing the scope of the random checks. The test expenditure is, however, increased by this means.

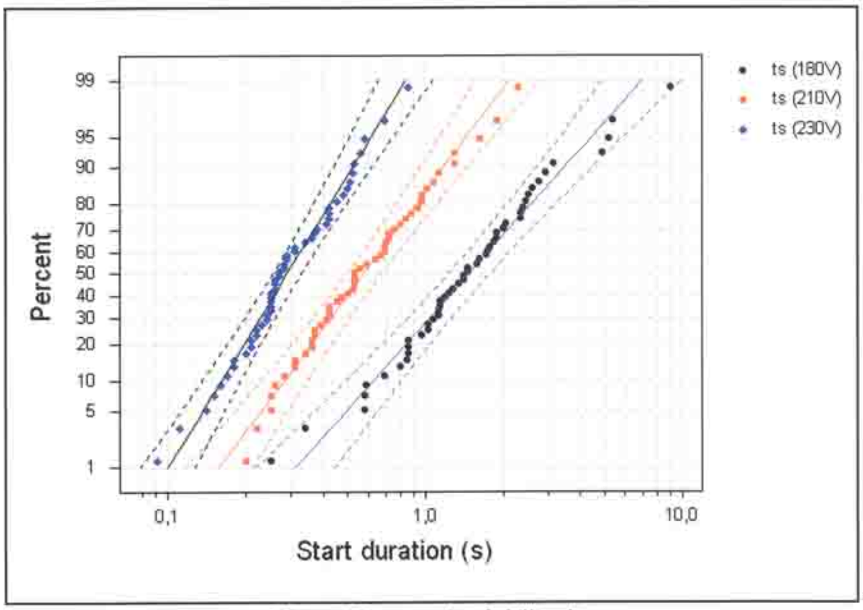

Figure 8: Lognormal probability plot

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  Voltage  |     Successful     | T_mean  | T_min  | T_max  | T_90%  | T_99%  |  T_6S
           |        starts      |  [sec]  | [sec]  | [sec]  | [sec]  | [sec]  | [sec]
 ------------------------------------------------------------------------------------
   240 V   | 50  out  of   50   |   0.3   |  0.1   |  0.7   |  0.5   |  0.8   |  2.2
   230 V   | 50  out  of   50   |   0.3   |  0.1   |  0.9   |  0.5   |  0.8   |  1.8
   220 V   | 50  out  of   50   |   0.4   |  0.1   |  0.8   |  0.6   |  1.0   |  2.6
   210 V   | 50  out  of   50   |   0.7   |  0.3   |  2.3   |  1.2   |  2.1   |  7.1
   200 V   | 50  out  of   50   |   0.8   |  0.3   |  1.9   |  1.3   |  2.1   |  6.0
   190 V   | 50  out  of   50   |   1.0   |  0.3   |  2.8   |  1.7   |  2.9   |  8.9
   180 V   | 50  out  of   50   |   1.9   |  0.3   |  9.1   |  3.5   |  7.3   | 32.6
   170 V   | 49  out  of   50   | *****   |  0.5   | *****  | *****  | *****  | *****

   U   |           Number of starts, successful within a period of ...            |
  [V]  | 1 sec | 2 sec | 3 sec | 4 sec | 5 sec | 6 sec | 7 sec | 8 sec | 9 sec | 10sec | Faults
 ---------------------------------------------------------------------------------------------
  240  |  050  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...
  230  |  050  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...
  220  |  050  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...
  210  |  043  |  005  |  002  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...
  200  |  036  |  014  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...
  190  |  032  |  015  |  003  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...  |  ...
  180  |  012  |  023  |  010  |  001  |  001  |  002  |  ...  |  ...  |  ...  |  001  |  ...
  170  |  005  |  014  |  009  |  007  |  005  |  003  |  003  |  003  |  ...  |  ...  |  001
```

Figure 9: Start duration test report

Further examinations executed with the help of a variety of a series of measurements with the statistics software MiniTab have shown that the measured values t_{S_i} correspond to the lognormal distribution. The measured values are within the confidence intervals of 95 %. As an example, this is shown in *figure 8*.

Moreover, it gets clear that a generally valid statement regarding the start duration of a synchronous pump is useless without indication of the "probability". It proved to be advantageous to determine a period (start duration $t_{S_{Y\%}}$) during which a certain percentage of all transient phenomenon is completed successfully with a confidence interval of 95 %. Suitable percentages can be 90 %, 99 % or 99,99966 % (corresponding to 6σ).

These evaluations could easily be executed with the help of a statistics software such as MiniTab. It is, however, arduous in the long term to pass the data of the computer of the test bench on to the statistics software in order to accomplish the calculations. It is easier to have the evaluation automatically executed by the computer of the test bench. The necessary algorithms read as follows:

(5)

$$\overline{t_{S_{ln}}} = \frac{1}{n}\sum_{i=1}^{n}\ln\left(t_{S_i}\right)$$

(6)

$$s_{S_{ln}} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln\left(t_{S_i}\right)-\overline{t_{S_{ln}}}\right)^2}$$

(7)

$$t_{S_{90\%}} = e^{\left(1.282\cdot s_{S_{ln}}+\overline{t_{S_{ln}}}\right)}$$

(8)

$$t_{S_{99\%}} = e^{\left(2.326\cdot s_{S_{ln}}+\overline{t_{S_{ln}}}\right)}$$

(9)

$$t_{S_{6\sigma}} = e^{\left(4.5\cdot s_{S_{ln}}+\overline{t_{S_{ln}}}\right)}$$

HANNING ELEKTRO-WERKE disposes of computer-aided test benches equipped correspondingly. All new product developments irrespective of their complexity are tested in view of the start-up safety. An extract of an automatically generated test report is shown in *figure 9*.

Outside influences

The constructional parameters which determine the start duration of a synchronous pump have already been discussed. Apart from them, there are parameters which cannot be influenced by the producer or only to a certain degree. These are:

- Mains voltage
- Power frequency
- Motor and water temperature

The frequency of most power supply systems being nowadays very stable its influence on the start duration of a synchronous pump was not examined.

The influence of the mains voltage on the start duration is, however, considerable (see *figure 9* and *figure 10*). As it is the driving force of the current flow through the motor coil it has a direct influence on the motor torque.

There is no parameter in the equations (1) and (2) referring to the motor temperature. Nevertheless, the temperature influences the starting behavior of a synchronous pump. The reason for it is its influence on the ohmic resistance **R** of the coil and the magnetic flux of the rotor $\hat{\Phi}$. With every degree C the temperature

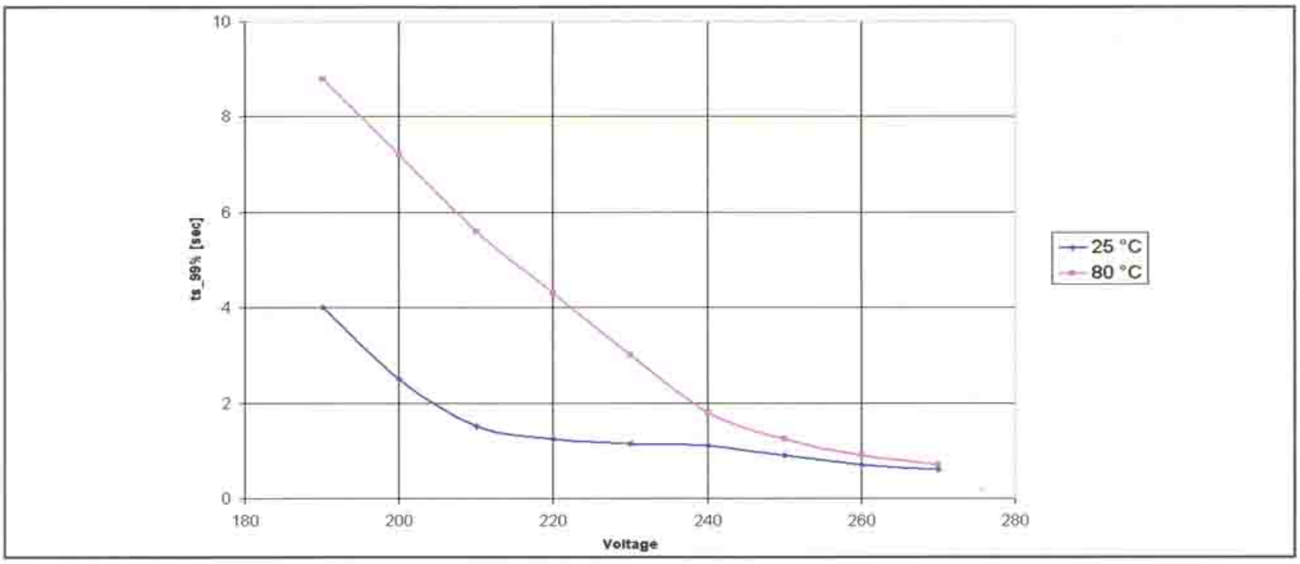

Figure 10: Influence of voltage and temperature on the start duration

rises the resistance increases by approximately 0.4 % and the magnetic flux is reduced by approximately 0.2 %. These changes directly lead to a reduction of the power reserves of the synchronous motor (*figure 10*).

Summary

As the single-phase synchronous motor is only in a position to supply a suitable torque for driving the drain pump in synchronism the start-up is very complicated. Although the introduction of a coupling system defuses this problem it would, however, aggravate the precise application of theoretical models. Finally, the qualification of the start-up process is executed by extensive tests and is followed by the statistical evaluation of the entered series of measurement.

Provided that no other agreements are made with the customer it is the target of Hanning Elektro-Werke that each pump type starts safely within 3 seconds with a probability of 99 % and a confidence interval of 95 % at an undervoltage of 15 % and a motor temperature of 25° C.

Used symbols

i	Instantaneous value of the current
J	Total mass moment of inertia
L	Inductivity
M_{fr}	Total frictional torque
M_L	Load torque
$\hat{M}_R$	Peak value of the cogging torque (reluctance)
n	Scope of random sample
R	Ohmic resistance of the winding plus iron loss resistance
$s_{S\ln}$	Logarithm of the standard deviation of the start duration in the random sample
t	Time
t_{S_i}	Single value of the start duration
$\overline{t_{S_{\ln}}}$	Logarithm of the mean value of the start duration in the random sample
$t_{S90\%}$	Time span (start duration) in which 90 % of all start-ups are securely completed
$t_{S99\%}$	Time span (start duration) in which 99 % of all start-ups are securely completed
$t_{S6\sigma}$	Time span (start duration) in which 99,99966 % of all start-ups are securely completed
$\hat{U}$	Peak value of the mains voltage
w	Number of turns of the coil
$\hat{\Phi}$	Maximum magnetic flux of the rotor interlinked with the winding of the coil
γ	Displacement angle
φ	Phase angle
θ	Instantaneous angle of the rotor position
ω_{el}	Electrical angular velocity
ω_M	Angular velocity of the motor

List of literature

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[3] Altenbernd G., Mayer J.
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Author

Werner Hangmann studied electrical engineering in Münster, Germany. From 1979 until 1996 he was responsible for the laboratory of electrical machines at HANNING ELEKTRO-WERKE GmbH in Oerlinghausen, Germany. Apart from that, he was project manager regarding the development of the synchronous pump. Since 1997, Werner Hangmann is R&D Manager of the business unit 'Appliance Applications'.