ARCHIVES OF ELECTRICAL ENGINEERING **VOL. 62(2), pp. 217-225 (2013)**

DOI 10.2478/aee-2013-0017

Sensorless and energy-efficient PMSM drive for fan application

STEFAN BROCK, TOMASZ PAJCHROWSKI

Poznań University of Technology
Piotrowo 3a, 60-965 Poznań, Poland
tel.48-616652385
e-mail: {stefan.brock/tomasz.pajchrowski}@put.poznan.pl

(Received: 17.06.2012, revised: 15.01.2013)

Abstract: The paper presents the problem of sensorless control of a permanent magnets synchronous motor (PMSM) without a damping cage for fan applications. Frequency control was used according to the principle of *v/f* = const. In order to reduce the power consumption of the drive system, the optimal voltage to the motor frequency characteristics was tested in the laboratory. The experimental studies was performed on a laboratory set of a drive consisting of two coupled PMSM machines, where one machine was supplied by a transistor inverter and the other was a passive load. A new criterion based on minimizing the module of stator current vector was proposed and an optimization algorithm in steady states was tested. The results of laboratory tests confirmed the validity of the applied solution for the fan drive.

Key words: energy losses, *v/f* control, PMSM, fan applications

1. Introduction

Due to their excellent dynamic properties, Permanent Magnet Synchronous Motors (PMSMs) are widely used in drive systems requiring high-precision control, such as industrial robots and machine tools. Many of the current researches present the use of PMSM motors without a damping cage for the pump and fan drives, which are much less demanding dynamically [1-5]. Due to the long connection cable between the motor and inverter in the pump and fan drives, direct measurement of the rotor position is difficult. In addition, it increases the costs and reduces the reliability of the drive. The use of the block observer is difficult because of the filters often used in these solutions between the inverter and the motor.

An alternative control for the PMSM for fan application is open loop control. Such a system is controlled by a frequency, according to the principle of *v/f* = const [1, 2, 4-6]. In [6-8], the authors carried out extensive simulation studies of PMSM drives without the damping cage, controlled by a frequency. The authors showed that, in order to reduce the power consumption of the drive, optimization of the supply voltage should be performed and a loop stabilizing the motor should be introduced. This paper presents the laboratory results of such a drive. In addition, a new criterion to minimize the power supply consumption was proposed based on measurement of the module of stator current vector. The optimization was performed on-line. The results of laboratory tests confirm the validity of the applied solution for the fan drive.

2. Power losses minimization in PMSM drive

Control techniques designed to obtaining the loss minimization have been extensively investigated in the literature [5, 9-12]. They can strictly be divided into three main categories: papers that deal with the “loss-model control” technique, papers that apply the “search control” algorithm, and papers that use the simple state control.

The “loss-model control” technique is based on the derivation of a mathematical model, which allows describing the energy losses occurring during motor operation. This approach can be easy used if the losses in the machine model depend on the value of input signals or measurement signals. In a PMSM with no core loss a drive that operates at maximum torque per current principle will be optimally efficient. It has been shown [5] that a PMSM operating at a constant speed and torque has a single optimum voltage value that will minimize the total electrical loss. The existence of core loss will cause this optimum to deviate from the maximum torque per current principle. Evidently, key issues in this case are the good knowledge of a system model, a correct identification of its parameters [11]. It should also be taken into account and modelled variation of the parameters with the temperature, current, etc.

The “search-based control” algorithms, in contrast to previous methods, are not based on a power loss model. In this method, the power supplied to the drive system is measured [9, 10]. The search algorithm is used to adjust a control variable until it detects a minimum in the power. The approach mainly consists of changing step by step the value of a control variable, then measuring for each operating point the input power. In conclusion, by comparing the measurement power with the previous one at the same operating conditions (with the same output power), the minimum power losses of the drive is searched. This kind of controller has the advantage that it does not depend on a model of the drive and therefore is insensitive to variations in the motor parameters, such as the temperature change in resistance. This method does not require accurate modelling of complicated phenomena such as core loss. The same method has been used in an optimum efficiency control of a field-oriented induction motor drive in which the magnetizing component of current was used as the control variable. Implementation of the optimizing control on a PMSM drive is simpler than with an induction motor drive because the control variable, in this case the voltage amplitude, does not affect the motor speed as it does with the induction machine, and so the slip calculations of the field-oriented induction motor drive are not needed in the PMSM drive.

By simple state control is meant that one parameter of the drive is measured and controlled in a simple way, usually by PID type controller. This includes for example constant slip frequency or constant displacement power factor cos(φ) for induction motor [12]. The best dynamic performance is obtained if the cos(φ) is calculated in every sample step.

For the effective operation of search mechanism it is essential, that the losses are related to the control variable by a single minimum function. In presented paper the choice of control variable for the PMSM is the voltage amplitude. Because the selected control method is based on the *v/f*, it is chosen as the search value the stator voltage difference in relation to the characteristics of the theoretical *v/f* = const. On the other hand, the minimum in the loss-versus-voltage curve for the PMSM is relatively flat. As consequence the search algorithm will have some difficulty finding the true minimum. At the same time, the flatness of the minimum power characteristic reduces the negative effects of error in the voltage. Any suboptimal voltage near the optimum will give up nearly the same power losses.

3. The laboratory stand

The laboratory tests were performed on the drive system consisting of two permanent magnet synchronous machines coupled by a common shaft. The first motor was supplied by the IGBT inverter, which was controlled by the microprocessor. The second machine, connected to a bridge rectifier and a resistor, was working as a load machine. Figure 1 shows a block diagram of the laboratory stand.

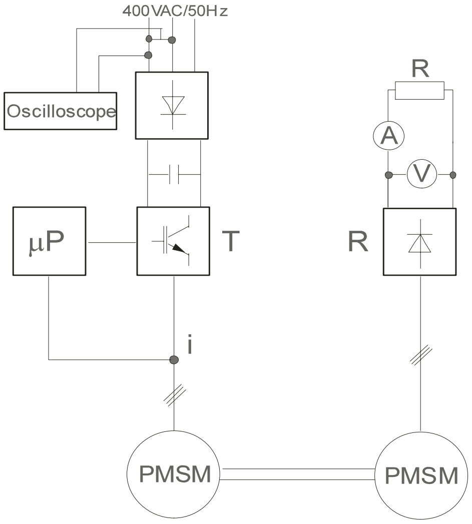
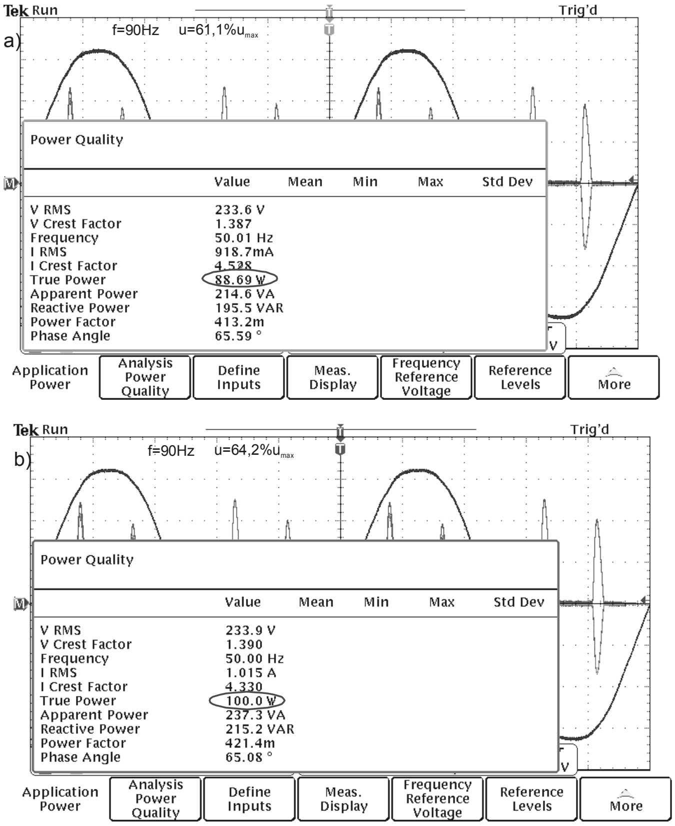


Fig. 1. Block diagram of the laboratory set-up

Measurement of the input power of converter devices with a diode bridge rectifier is a difficult problem, mainly due to the pulse shape of the supply current. The active input power in one phase was measured using a measuring system consisting of a DPO3014 digital oscilloscope equipped with a power measurement module DPO3PWR and current and voltage probes. It is assumed that the supply voltage of the grid is symmetrical. On this basis, the total power consumed from the power grid can be determined. Figure 2 shows sample results of the analysis of input power supply.



Power Quality

	Value	Mean	Min	Max	Std Dev
V RMS	233.6 V				
V Crest Factor	1.387				
Frequency	50.01 Hz				
I RMS	918.7mA				
I Crest Factor	4.528				
True Power	88.69 W				
Apparent Power	214.6 VA				
Reactive Power	195.5 VAR				
Power Factor	413.2m				
Phase Angle	65.59 °				

Power Quality

	Value	Mean	Min	Max	Std Dev
V RMS	233.9 V				
V Crest Factor	1.390				
Frequency	50.00 Hz				
I RMS	1.015 A				
I Crest Factor	4.330				
True Power	100.0 W				
Apparent Power	237.3 VA				
Reactive Power	215.2 VAR				
Power Factor	421.4m				
Phase Angle	65.08 °				

Fig. 2. Analysis of the input power supply for the drive system, (one phase):
a) $f = 90$ Hz, $u = 61{,}1\% u_{\max}$, $P_{we} = 89$ W, b) $f = 90$ Hz, $u = 64{,}1\% u_{\max}$, $P_{WE} = 100$ W

4. Energy optimal *v/f* characteristics for the frequency control

The aim of this study was to develop a sensorless control system to minimize active power consumption by the drive in a steady state. The drive system should operate within a given output frequency range of 0 to 90 Hz. The tested inverter is controlled to get a sinusoidal output voltage with a frequency f and amplitude u_{out} according to the characteristics

$$u_{\text{out}} = \left(u_o + m \cdot f\right) + \Delta u, \tag{1}$$

where u_o and m are the parameters describing the characteristics and Δu is the value of the correction voltage amplitude. The parameters u_o and m were chosen to ensure stable operation over a range of speeds. The correction voltage Δu was adjusted individually for different speeds in order to minimize the active power consumption by the drive system from the power grid. The load torque is linearly dependent on the velocity according to the equation

$$T_L = k \cdot \omega, \tag{2}$$

where T_L is the load torque, ω is the rotational speed, and k is the proportionality factor. Due to the synchronous rotation speed the correction voltage value does not influence the power transmitted into the load machine. A too small value of the correction voltage may cause the system to fall out of synchronous mode and crash.

In the first stage of the research work an off-line study was performed. During these studies the correction voltage was sought for each speed to minimize the active power consumption indicated on the oscilloscope.

The results are shown in Figure 3a. For each operating frequency there is a modest input power minimum. Figure 3b shows the relationship between the value of voltage correction and the synchronous speed. Due to the flatness of optimum voltage relative to speed function, the voltage correction varies significantly between neighbouring measurement points. These results indicate that the search for the optimum operation will adversely determined. Exemplary results for the output frequency of 90 Hz are shown in Figure 2: for the basic *v/f* characteristic the power consumption is 300 W; when the voltage correction is taken into account the input power is reduced to 266 W.

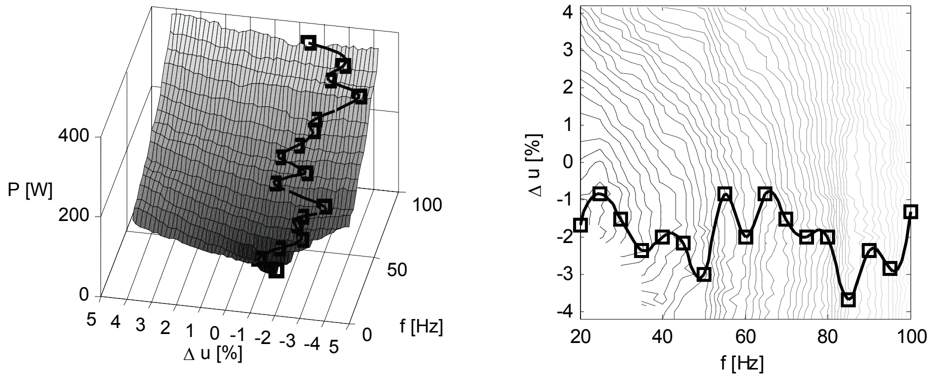


Fig. 3. Characteristics of input power of the converter as a function of frequency and voltage correction

Due to technical complication, the input power is not measured in the inverter control system, but the output currents i_a, i_b, and i_c are measured. It is therefore proposed to minimize output current instead of minimizing the input power. During the occurrence of transient states caused, for example, by change of the reference speed, determine the amplitude of the phase current on-line is not possible. Therefore, to minimize the motor current, the module of output current vector $|\mathbf{i}|$, defined by the equation (3), has been selected:

$$|\mathbf{i}| = \sqrt{i_a^2 + \frac{(i_b - i_c)^2}{3}}. \tag{3}$$

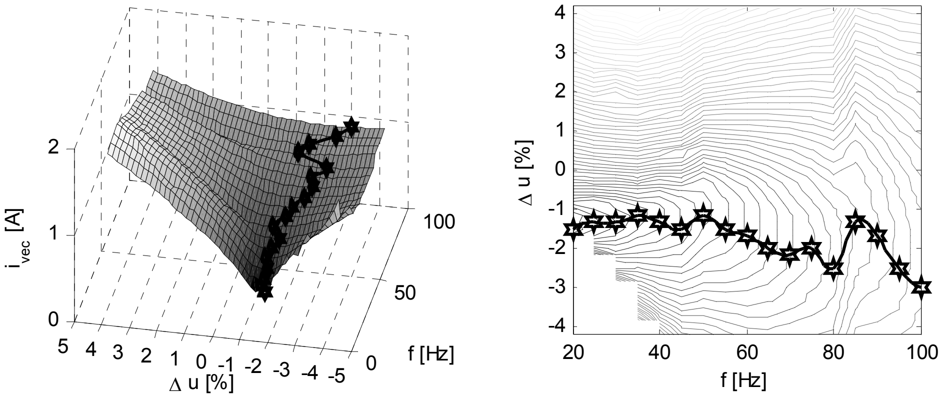


Fig. 4. Characteristics of output current of the converter as a function of frequency and voltage correction

The results of comparison of the two criteria of minimizing: the input power and the module of the output current vector are shown in Figures 4a and 4b. In the second case, the resulting surface has a clear extreme, making it easier to search for the optimal solution. To assess whether the criterion of minimizing the module of the current vector can replace the criterion of minimizing the input power consumption, the efficiencies achieved by the drive system in both cases were compared. The efficiency of the drive system for the voltage correction determined by the criterion of minimizing the module of output current is only slightly lower than in the case of minimizing the input power consumption (Fig. 5). It should be emphasized that the presented efficiency ratio represented the whole drive system: the controlled inverter ac/dc/ac, two PMSM machines, and the load inverter ac/dc. The final characteristics of output voltage amplitude versus output frequency are shown in Figure 6.

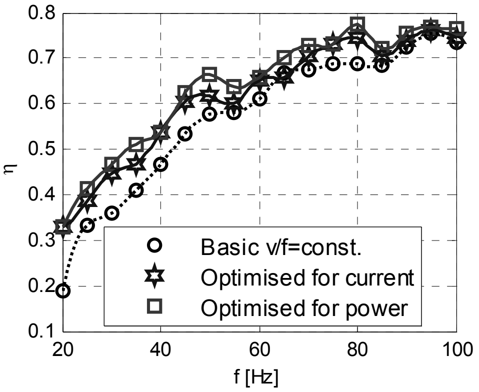


Fig. 5. Efficiency of the drive set as a function of output frequency

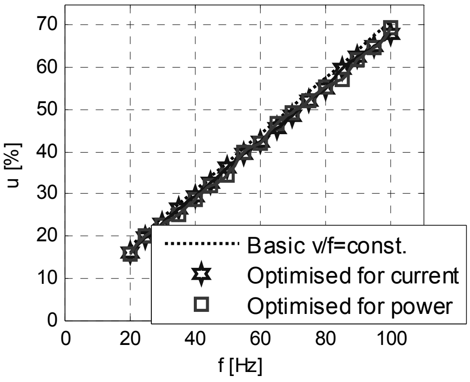


Fig. 6. Output voltage as a function of frequency

5. On-line optimization for running drive

Analytical determination of the characteristics presented in the previous section would require the precise identification of machine parameters, and obtaining them by the measurement method is a time-consuming task. Therefore, a simple algorithm operating under the normal drive condition was proposed and was used for selection of the voltage correction. The algorithm is used only for the static optimization tasks carried out at a steady state operating point. This assumption is motivated by the fact that in the case of a fan drive the load torque does not change rapidly. A hill climbing algorithm with a variable step was used, operated according to the formulas

$$\Delta u(n+1) = \Delta u(n) + z\cdot\left(\delta + \eta\cdot\big\| i(n)\right| - \left| i(n-1)\big\|\right), \tag{4}$$

$$z(n) = \begin{cases} z(n-1) & \text{for } |i(n)| < |i(n-1)| \\ -z(n-1) & \text{for } |i(n)| \geq |i(n-1)|, \\ 1 & \text{for } \quad n = 1 \end{cases} \tag{5}$$

The parameters δ and η have been chosen empirically in order to ensure the stability of the search algorithm. The algorithm runs in steady state mode, where the reference speed does not change. During the reference speed changes, to ensure the safe operation of the drive the voltage correction is preset to the secure value $\Delta u = 0$. The experimental results, summarized in Figures 7 and 8, confirm the correct operation of the drive. Figure 7 shows the change of inverter output frequency from 90 Hz to 85 Hz and its return to 90 Hz. After the end of the dynamic transition state the voltage correction is reduced to the optimum value, simultaneously, during a time of about 60 s, at the same time as the motor current is reduced too. Figure 8 shows the start-up of the drive to the output frequency of 90 Hz. As a result of the applied frequency increase limiter, the start-up takes 90 seconds, and during that time the correction voltage is preset to 0. After the start-up, the process begins searching for the optimal voltage correction.

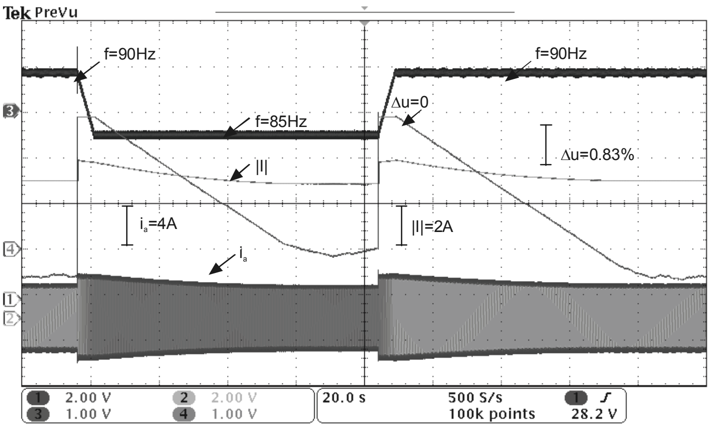


Fig. 7. Operation of the optimize algorithm during the frequency change

6. Summary

In this paper a "search-based control" strategy for selection of the voltage correction to modify the characteristics of the *v/f,* has been analyzed and implemented in a DSP-controlled PMSM drive. The acceptability of replacing the criterion of minimum input power consumed from the mains by the criterion of minimizing the module of motor current was assessed. In particular, it has been verified by experimental tests that the control based on search for minimum output current for fixed operating point can suboptimal minimize the controllable electrical losses occurring in a PM synchronous motor drive. The main results of the experimental tests carried out demonstrated how, in comparison to traditional control methods, the proposed algorithm increments the efficiency of a PMSM drive without influence of the dynamic performance This drive is more suited to applications where efficiency and simplicity are more important than high dynamic performance, notably in pump, fan, and compressor drives. The control does not require accurate knowledge of the motor parameters.

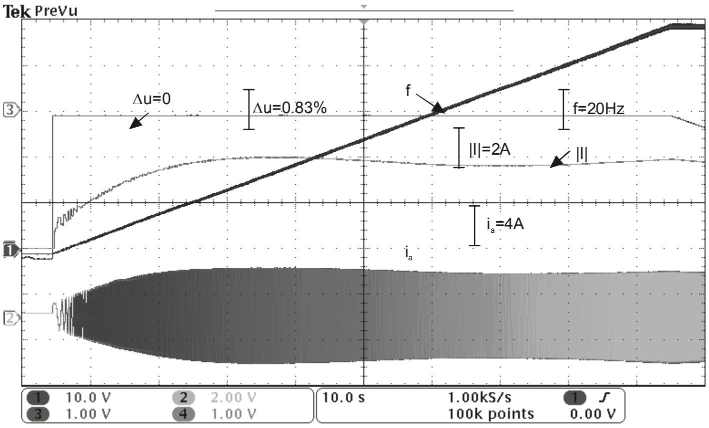


Fig. 8. Startup the drive from 0 to 90 Hz

Acknowledgements
This work was partly supported by grant POIG.01.01.02-00-113/09: "The new generation of energy-efficient electric drives for pumps and fans".

References

[1] Kiuchi M. et al., *V/f control of permanent magnet synchronous motors suitable for home appliances by DC-link peak current control method*. International Power Electronics Conference (IPEC), pp. 567-573 (2010).

[2] Perera P.D.C. et al., *A sensorless, stable v/f control method for permanent-magnet synchronous motor drives*. IEEE Transactions on Industry Applications 39(3): 783-791 (2003).

[3] Kshirsagar P. et al., *Implementation and Sensorless Vector-Control Design and Tuning Strategy for SMPM Machines in Fan-Type Applications*. 41st IEEE IAS Annual Meeting and Industry Applications Conference, pp. 2062-2069 (2006).

[4] Itoh J.I., Nomura N., Ohsawa H., *A comparison between V/f control and position-sensorless vector control for the permanent magnet synchronous motor*. Power Conversion Conference, Osaka, pp. 1310-1315 (2002).

[5] Colby R.S., Novotny D.W., *An efficiency-optimizing permanent-magnet synchronous motor drive.* IEEE Transactions on Industry Applications 24(3): 462-469 (2002).

[6] Brock S., Pajchrowski T., *Energy-optimal V/f control of permanent magnet synchronous motors for fan applications*. Maszyny Elektryczne: zeszyty problemowe 92 (2011).

[7] Brock S., Pajchrowski T., *Reducing Energy Losses for Fan Applications with V/f control of PMSMs*. Przegląd Elektrotechniczny (Electrical Review) 87(11): 89-94 (2011).

[8] Brock S. *The study of the stability of the fan drive with permanent magnets synchronous motor operated in an open control loop.* Studia z Automatyki i Informatyki (Studies in Automation and Information) 35: 7-16 (2010) (in Polish).

[9] Morimoto S., Takeda Y., Hirasa T., *Current phase control methods for permanent magnet synchronous motors.* IEEE Trans. Ind. Electron. 5(2): 133-139 (1990).

[10] Mademlis C., Xypteras J., Margaris N., *Loss minimization in surface permanent-magnet synchronous motor drives.* IEEE Trans. Ind. Electron. 47(1): 115-122 (2000).

[11] Fernandèz-Bernal F., Cerrada A.G., Faure R., *Model-based loss minimization for DC and AC vector controlled motors including core saturation.* IEEE Trans. Ind. Appl. 36(3): 755-763 (2000).

[12] Abrahamsen F., Blaabjerg F., Pedersen J.K., Thøgersen P.B., *Efficiency-optimized control of medium-size induction motor drives.* IEEE Trans. Ind. Appl. 37(6): 1761-1767 (2001).