Comparison of Static Characteristics between Unregulated and Regulated Electrical Drives

Case Study

Jelena Jukić Antolović
J.J. Strossmayer University of Osijek
Faculty of Electrical Engineering
Department of Electromechanical Engineering
Kneza Trpimira 2b, 31000 Osijek, Croatia
e-mail: j-jukic@hotmail.com

Vedrana Jerković Štil
J.J. Strossmayer University of Osijek
Faculty of Electrical Engineering
Department of Electromechanical Engineering
Kneza Trpimira 2b, 31000 Osijek, Croatia
e-mail: vedrana.jerkovic@etfos.hr

Željko Hederić
J.J. Strossmayer University of Osijek
Faculty of Electrical Engineering
Department of Electromechanical Engineering
Kneza Trpimira 2b, 31000 Osijek, Croatia
e-mail: zeljko.hederic@etfos.hr

Abstract *– In this paper, the difference between an unregulated and a regulated electrical drive in terms of power losses is analyzed. First, open loop scalar control, closed loop scalar control and speed estimated scalar control are explained. Then, static characteristics obtained by experimental measurements are analyzed and compared for different control principles. Finally, based on experimental results, it is proposed when and which drive is to be used.*

Keywords *– frequency converter, induction motor, power losses, scalar control, speed estimation*

1. INTRODUCTION

The induction machine is the most widely used machine in a wide variety of industrial applications as a means of converting electric power to mechanical work due to its robustness, reliability, low cost, high efficiency and good self-starting capability [1]. As pointed out in [2], development of the frequency converter in the 1960s and 1970s enabled the use of induction machines in variable speed drives. Today, energy savings and power efficiency have become very important issues in every industrial facility. In [3], it is concluded that global electricity financial savings can be carried out when variable speed drives are utilized to replace the majority of existing nonadjustable drive systems for the induction motor. In [4], it is also stated that in order to minimize power losses the induction motor should either be fed through a converter or redesigned with optimization algorithms. However, the output voltage and current waveforms of frequency converters contain numerous harmonics and these harmonics have detrimental effects on motor performance in form of derating and torque pulsation, especially at low speed [5]. This means that during normal operation motor control must ensure that motor operation is restricted to the regions of high torque per ampere. These operating points match motor and inverter ratings giving minimal system losses. Accordingly, in [6], it is shown that in the textile industry considerable energy savings can be achieved when the motor fed by a frequency converter runs at its base frequency. Also, a frequency converter improves the power factor of an electrical drive as it compensates inductive reactive power of the motor with large capacitors of the intermediate circuit [7].

The presence of any power quality disturbances in the induction motor power supply, such as frequency and voltage deviations, voltage imbalance and voltage waveform distortions, leads to additional power losses occurring in the motor and consequently to an increase in the windings temperature. A higher windings temperature means faster aging of the insulation system and, as a result, a reduction in machine's operational life [8]. In [9], it is stated that marine induction motors can be seriously overheated due to a lowered level of supply voltage quality. An analytical model of an induction case machine supplied with lower voltage quality is made in [8]. [10] deals with prediction of iron losses in case of non-sinusoidal supply in variable speed drives.

Frequency converters can be divided into direct frequency converters and frequency converters with an intermediate circuit. Direct frequency converters are used rarely and are analyzed in [11]. According to [12], the basic principle of a frequency converter with an intermediate circuit is to rectify AC voltage from the main power supplies into DC voltage and after that to convert DC voltage to AC voltage with variable amplitude and frequency. Induction motors regulated with frequency converters are called regulated electrical drives. Induction motors directly connected to the main power supply (without any device used for regulation) are unregulated electrical drives. There are two kinds of motor control principles, i.e., scalar control and vector control.

The aim of this paper is to examine how a frequency converter used with the simplest control method, i.e., scalar control, affects energy consumption of an electrical drive. As the scalar control principle will be used for experimental measurements, its principle will be explained in detail. After that, performances of unregulated and regulated drives in terms of power losses are compared using static characteristics gained in the experiment.

2. SCALAR CONTROL

Scalar control is the most common control principle for induction motors [13], and it is used for speed control of induction motors.

Fig. 1 shows the mechanical characteristics of a scalar controlled induction motor. The speed increases proportionally with frequency and the maximum torque remains constant if the supply voltage also increases with frequency [12]. The speed control principle, which keeps the ratio of voltage and frequency constant, is called scalar control. Because the supply voltage can only be increased to its nominal value, the constant ratio between the voltage and the supplied frequency can be maintained to this point. After that point, the voltage remains at the nominal value, but the frequency increases, which causes a decrease in torque.

To achieve a needed magnetic flux it is necessary to have a specific amount of supply voltage U dependent on the stator frequency f and load torque TL characteristic. Therefore, the speed is defined as a function of two control variables, i.e., voltage and frequency, and one disturbing variable, i.e., load torque [14]:

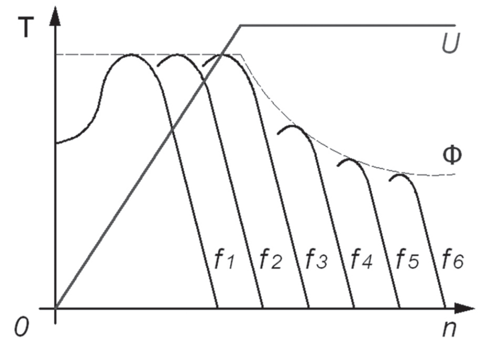

Fig. 1. Torque-speed curves showing the effect of frequency variation load torque and supply voltage changes

$$n = f(U, f, T_L) \quad (1)$$

Scalar control can be accomplished in two manners, i.e., by open loop and by closed loop [14]. Both control principles will be described in this paper.

2.1. OPEN LOOP SCALAR CONTROL

According to [15], the open loop scalar control of an induction motor is by far the most popular method of speed control because of its simplicity. Fig. 2 shows a block diagram of an open loop scalar controlled system. In this case, scalar control is applied to a frequency converter with an intermediate voltage circuit. The open loop scalar control reference value is the frequency of stator voltage. The voltage controller generates the reference value of stator voltage depending on the speed reference value. Current limitation automatically decreases the voltage in case of stator overcurrent. Every change of load torque or stator voltage amplitude causes a change in speed.

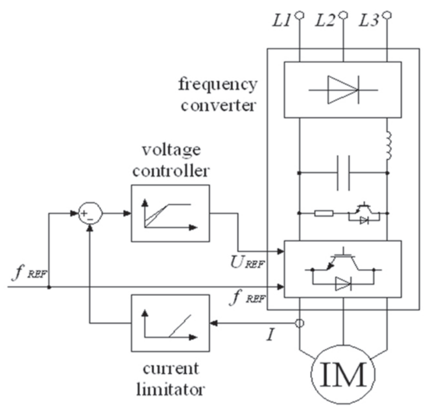

Fig. 2. Block diagram of the open loop scalar controlled system

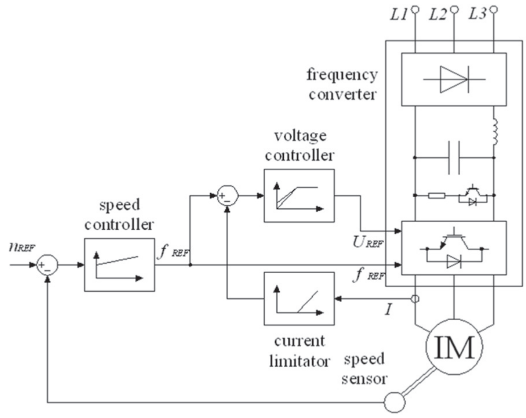

Fig. 3. Block diagram of the closed loop scalar controlled system

2.2. CLOSED LOOP SCALAR CONTROL

The difference between open loop scalar control and closed loop scalar control is that in the latter there is a speed feedback added to the open loop scalar control system. A closed loop scalar control block diagram is shown in Fig. 3. The speed of the induction motor is measured with speed sensor and compared with reference speed. The difference between these two values is then processed by a speed controller. The speed controller output value is the referent input value of the open loop scalar control system.

With closed loop scalar control constant speed regardless of load torque or stator voltage amplitude change can be achieved [14]. To enable no speed change by changing the torque or stator voltage amplitude, the supply frequency must be increased. This is called slip compensation, and it is shown in mechanical characteristics in Fig. 4. Fig. 4a) shows load increase in case there is no slip compensation. Starting operating point 1 is defined by reference speed n_0 and load torque T_{L1}. If the load torque increased from T_{L1} to larger torque load T_{L2}, an electrical drive would slow down to the speed n_1, i.e., operating point 2 would be reached.

For constant speed retaining the new operating point would have to be operating point 3, with load torque TL_2 and reference speed n_0, as shown in Fig. 4b). To retain reference speed n_0 the supply frequency at the frequency converter output must increase. The increased supply frequency value can be calculated as follows:

$$\Delta f = \frac{p(n_0 - n_1)}{60} \tag{2}$$

where Δf is an increased value of the supply frequency, p is the number of pole pairs, n_0 is the reference speed of the drive, and n_1 is the measured speed, or the output speed of the drive. The supply frequency increase leads to a change in the operating torque characteristic. The new torque characteristic (painted red in the diagram) is defined by operating points 3 and 4.

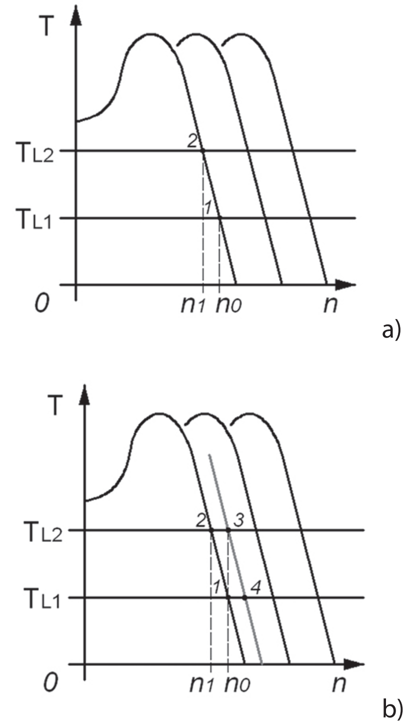

Fig. 4. Mechanical characteristics: a) no slip compensation; b) with slip compensation

According to (1), the speed can be estimated and slip compensation can be made without a speed sensor.

2.3. SENSORLESS SLIP COMPENSATION

The benefits of speed estimation control are the increased reliability of the overall system with the removal of mechanical sensors, thereby reducing sensor noise and drift effects as well as costs and size [16]. Slip compensation can also be estimated by using speed estimation. For speed estimation different algorithms have been developed over the years, some of them are analyzed in [15], [16] and [17]. They use currents and voltages from the frequency converter output (or the induction motor stator) to estimate the rotor speed of an induction motor.

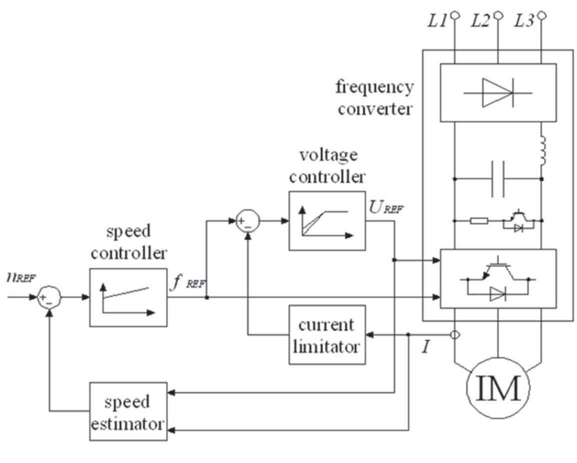

Fig. 5. Block diagram of the speed estimated scalar controlled system

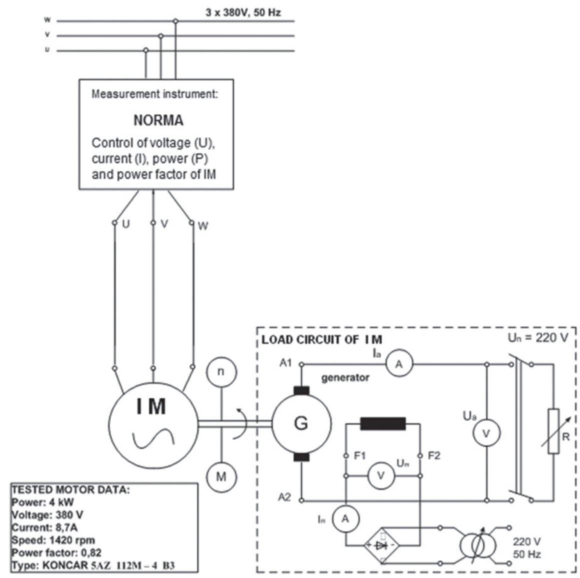

Fig. 6. Laboratory model of an unregulated electrical drive

Fig. 5 shows a speed estimation scalar controlled system. Voltage and current signals are acquired in the speed estimator, where the speed is estimated.

3. RESULTS

To compare losses of unregulated and regulated drives, measurements on two laboratory models were carried out. The first laboratory model represents an unregulated electrical drive, as shown in Fig. 6, and it consists of a 4 kW induction motor connected directly to the main power supply. The induction motor is delta connected with a DC generator as load [7]. On the power supply lines, voltage, current, and power measurement is available. The power factor can also be measured.

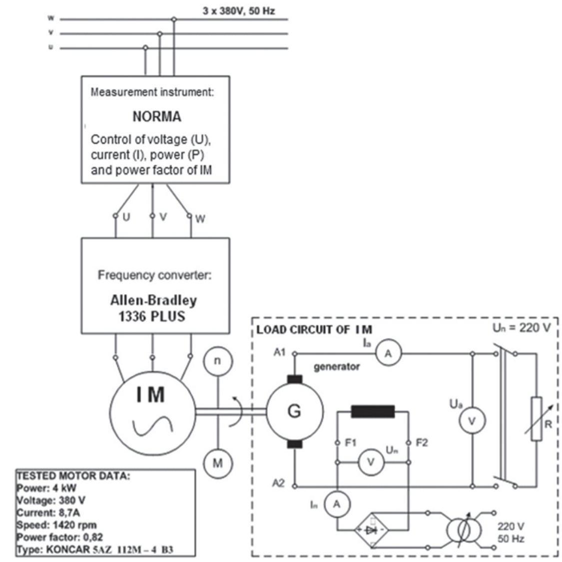

Fig. 7. Laboratory model of a regulated electrical drive

The second laboratory model is a regulated electrical drive model, and it is shown in Fig. 7. This frequency converter is used for open loop scalar control with speed estimation.

3.1. RESULTS MEASURED FOR AN UNREGULATED ELECTRICAL DRIVE

Table 1 contains results measured for the unregulated electrical drive laboratory model shown in Fig. 6. P_1 is the input power of the induction motor, measured in kilowatts. Value *n* represents the speed measured in rotations per minute; *U* is the voltage in volts; *I* is the current in amperes and f is the power supply frequency expressed in hertz. Load torque T_L is expressed in newton-meter, and output power P_2 in kilowatts.

Fig. 8 shows the power and speed dependence on the unregulated electrical drive. Input power P_1 and output power P_2 are placed on the ordinate and the measured motor speed is placed on the abscissa. It can be seen that the output power P_2 is lower than the input power P_1. The differences between these two powers are losses. It can also be seen in Fig. 8 that the speed decreases when the power (and load torque) increases.

Table 1. Results measured for an unregulated electrical drive

No	P_1 [kW]	*n* [rpm]	*U* [V]	*I* [A]	*f* [Hz]	T_L [Nm]	P_2 [kW]
1	0.30	1,497	389.0	4.93	49.98	0.00	0.00
2	1.06	1,498	388.8	5.09	49.97	3.62	0.57
3	1.55	1,484	387.4	5.32	49.99	8.24	1.28
4	2.12	1,477	387.6	5.78	49.98	11.86	1.83
5	3.16	1,464	387.8	6.85	49.98	16.94	2.60
6	3.64	1,458	386.5	7.41	49.97	20.87	3.19
7	4.30	1,450	386.9	8.26	49.99	24.49	3.72

Table 2. Results measured for open loop scalar control

No	P_1 *[kW]*	P_{FC} *[kW]*	*f* *[Hz]*	n_s *[rpm]*	*U* *[V]*	*n* *[rpm]*	T_L *[Nm]*	P_2 *[kW]*
1	0.39	0.07	47.97	1,439	360	1,438	0.00	0.00
2	1.01	0.66	47.97	1,439	360	1,430	2.93	1.15
3	1.49	1.11	47.97	1,439	361	1,423	6.47	2.30
4	2.21	1.76	47.97	1,439	361	1,415	11.70	4.00
5	2.55	2.07	47.97	1,439	361	1,410	12.81	4.36
6	3.74	3.24	47.97	1,439	362	1,392	21.25	7.10
7	4.11	3.58	47.97	1,439	362	1,387	23.41	7.80
8	4.37	3.84	47.97	1,439	362	1,382	24.33	8.10

3.2. RESULTS MEASURED FOR OPEN LOOP SCALAR CONTROL

Table 2 contains results measured for motor supplied via the frequency converter with open loop scalar control. Results are shown in Fig. 9. Adjustment of frequency converter parameters of Allen-Bradley 1336 PLUS is explained in [14]. Open loop regulation is set by setting parameter 77 (*Speed control*) to *No control*.

Considerable values for open loop scalar control can be measured at three different points: on the power supply (marked with *Supply*), on the output of the frequency converter (marked with *Frequency converter output*) and on the electrical drive output (marked with *Electrical drive output*). Supply power P_1 is measured on the power supply, that is, on the input of the frequency converter. The following values are measured on the frequency converter output: the frequency converter output power (i.e., electrical drive input power P_{FC}), frequency on the output of the frequency converter f and the output voltage of the frequency converter U. The output speed of the frequency converter n_s is calculated in [14]. Drive speed n is measured on the electrical drive output. Load torque T_L and output power P_2 are calculated in [14].

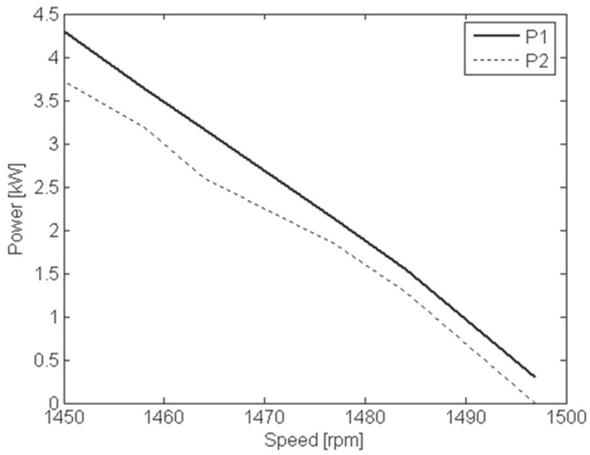

Fig. 8. Power and speed dependence on the unregulated electrical drive

Fig. 9 shows the dependence of power and speed in case of open loop scalar control. Power supply P_1, output power on the frequency converter P_{FC} and output power on the electrical drive P_2 are on the ordinate, and the measured speed is placed on the abscissa. The difference between input P_1 and output P_{FC} power on the frequency converter is equal to losses in the frequency converter, and the difference between P_{FC} and mechanical power P_2 represents losses in the induction motor. The frequency of the power supply is constant. The output frequency of the frequency converter is constant because its parameters are set to open loop scalar control.

3.3. RESULTS MEASURED IN CASE OF SPEED ESTIMATION SCALAR CONTROL

Table 3 shows measured results for a speed estimation scalar controlled laboratory model shown in Fig. 7 and Fig. 5. The values in Table 3 are analogous to the ones given in Table 2. The parameters of the frequency converter Allen-Bradley 1336 PLUS are set like in open loop scalar control, and speed estimated scalar control regulation is obtained by setting the parameter 77 (*Speed control*) to *Slip comp* .

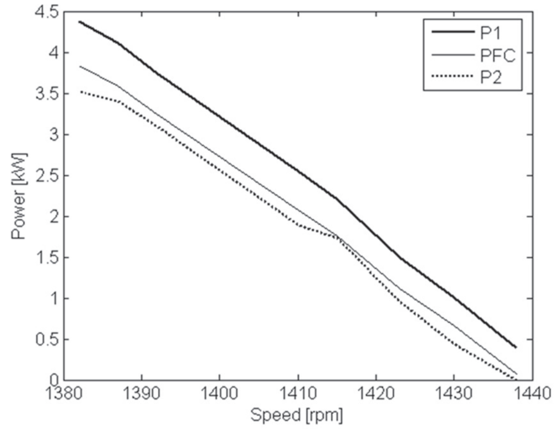

Fig. 9. Power and speed dependence in case of open loop scalar control

Table 3. Measured results by speed estimation

No	Supply	Frequency converter output				Electrical drive output		
	P_1 [kW]	P_{FC} [kW]	f [Hz]	n_s [rpm]	U [V]	n [rpm]	T_L [Nm]	P_2 [kW]
1	0.41	0.07	47.99	1,440	360	1,438	0.00	0.00
2	1.00	0.62	48.13	1,444	362	1,435	3.23	0.49
3	1.55	1.13	48.27	1,448	363	1,432	6.55	0.98
4	2.21	1.73	48.44	1,453	365	1,429	11.63	1.74
5	2.97	2.51	48.63	1,459	366	1,424	15.25	2.27
6	3.49	3.03	48.77	1,463	368	1,420	17.99	2.67
7	4.21	3.74	48.94	1,468	369	1,415	23.56	3.49
8	4.62	4.00	48.99	1,470	370	1,410	24.95	3.68

Fig. 10 shows the difference between input and output power in case of speed estimation scalar control. The input power of power supply P_1, the output power of frequency converter P_{FC} and the output power of electrical drive P_2 are placed on the ordinate and the measured speed is placed on the abscissa. The frequency of the power supply is constant. The frequency converter adjusts its output frequency to load because its parameters are set to speed estimation scalar control (slip compensation).

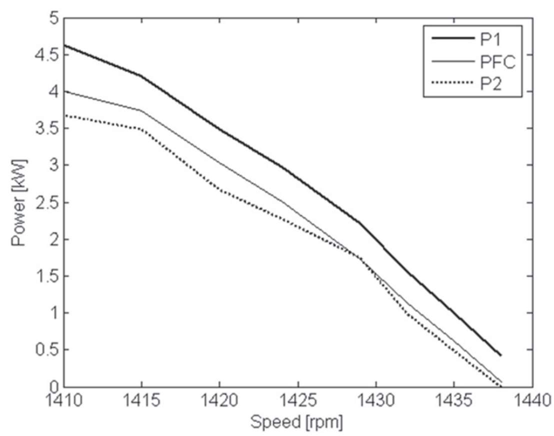

Fig. 10. Power and speed dependence in case of speed estimated scalar control

3.4. COMPARISON OF RESULTS

Fig. 11 shows the induction motor frequency dependence on load. Induction motor supply frequencies and the electrical drive input power are placed on the ordinate and the abscissa, respectively.

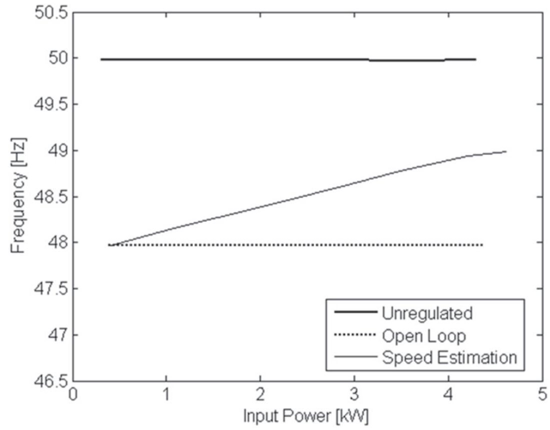

Fig. 11. Induction motor frequency dependence on load

Unregulated drive frequency is constant and equals grid frequency of 50 Hz. Open loop scalar control gives the drive frequency that corresponds to the nominal speed of the motor. This frequency is also constant. In case of speed estimation scalar control, frequency increases with drive load to obtain a constant speed of the induction motor.

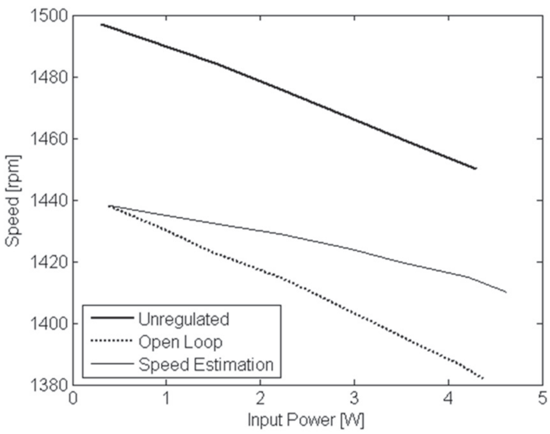

Fig. 12. Induction motor speed dependence on load

Fig. 12 shows dependence of the induction motor speed on load for an unregulated electrical drive, a regulated electrical drive in open loop scalar control and the speed estimated scalar control principle. Measured drive speeds and input power are placed on the ordinate and the abscissa, respectively. The highest speed is achieved by an unregulated electrical drive because the input frequency is the highest, which means that the drive speed is greater than the rated speed of the motor. This characteristic depends on the quality of motor construction. In case of open loop control, no slip compensation is present and the motor speed decreases with an increase in load. In this case, the motor speed is closer to the rated speed. In case of speed estimated scalar control, there is a decrease in the speed, but it is much smaller. The difference between the reference and the drive speed in this case occurs due to the estimation error.

In newer and better frequency converters, e.g., the frequency converter examined in [7] on the same induction machine, speed estimation parameters can be defined, and the frequency converter can be adapted to the induction machine so good that there is no speed change.

Fig. 13 shows the dependence of mechanical torque and input power. Calculated load torques and the input power are placed on the ordinate and the abscissa, respectively. The largest output torque by the lowest input power is achieved in case of an unregulated electrical drive due to higher frequency and drive speed. Dependence of mechanical torque and input power for open loop scalar control and for speed estimated scalar control in case of a lower input power is approximately the same. In case of a larger input power dependence of mechanical torque and the input power for open loop scalar control is almost the same as for an unregulated electrical drive. The lowest mechanical torque for the largest input power is achieved in case of speed estimated scalar control.

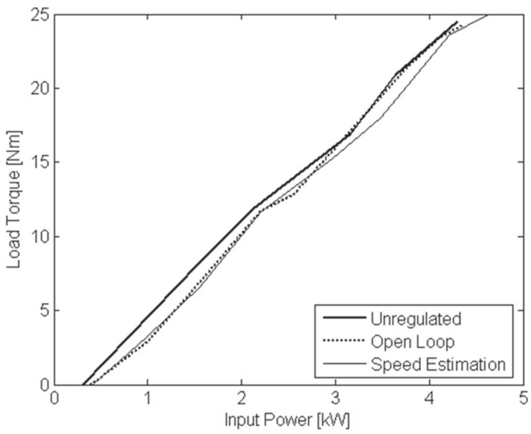

Fig. 13. Induction motor load torque dependence on the input power

Fig. 14 shows dependences of total power losses and input power of an unregulated drive, open loop scalar controlled and speed estimated scalar controlled drive. Calculated total power losses and the input power are given on the ordinate and the abscissa, respectively. The unregulated electrical drive has the lowest total power losses. Open loop scalar control and speed estimated scalar control have aproximately the same total power losses, which are larger than the total power losses by unregulated electrical drives.

It is better to have lower power losses. Therefore, in this case the unregulated electrical drive is better, because it does not have power losses on the frequency converter.

Fig. 15 shows power efficiency dependence on the input power. Calculated efficiencies and the input power are placed on the ordinate and the abscissa, respectively. The unregulated electrical drive has the highest efficiency. Open loop scalar control and the speed estimated scalar control have approximately the same efficiencies, which are lower than the efficiency of an unregulated electrical drive. It is better to have a higher efficiency and therefore the unregulated electrical drive is better.

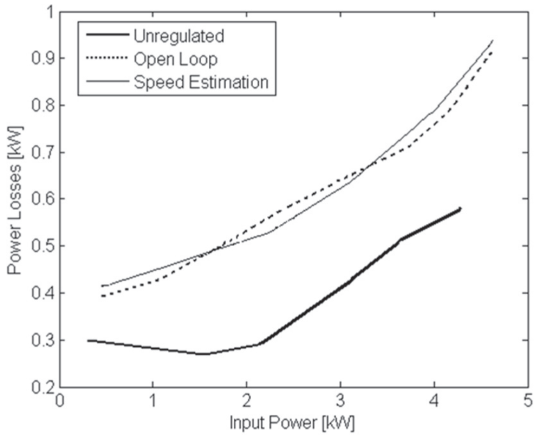

Fig. 14. Total power loss dependence on the input power

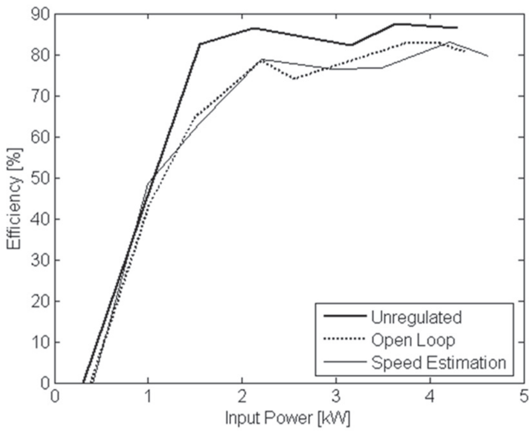

Fig. 15. Electrical drive efficiency dependence on the input power

4. CONCLUSION

Static characteristics prove that for smaller simple static electrical drives, where the accurate speed is not needed, there are no savings made by placing a frequency converter on the drive, because it increases losses. However, as proved in [7], the frequency converter improves the power factor of an electrical drive as it compensates inductive reactive power of the motor with large capacitors of an intermediate circuit. This issue is particularly important in larger electrical drives. In further research, power losses in dynamical conditions will be examined.

Speed adjustment is needed in most applications. In this case, speed estimated scalar control is an optimal choice, because it is rather cheap, as no speed sensors are needed. Newer frequency converters have better estimation algorithms and with speed estimation based control constant speed regardless of load change can be achieved. For most demanding applications, where high accuracy of speed regulation is needed, closed loop control should be used.

5. REFERENCES

[1] M. Salahat, O. Barbarawe, M. AbuZalata, S. Asad, "Modular Approach for Investigation of the Dynamic Behavior of Three-Phase Induction Machine at Load Variation", Engineering, Vol.3, No.5, June 2, 2011, pp. 525-531

[2] M. Ranta, "Dynamic induction machine models including magnetic saturation and iron losses", Doctoral Thesis, Alto University, 2013, p. 13

[3] C. M. F. S. Reza, Md. Didraul Islam, S. Mekhilef, "A review of reliable and energy sufficient direct torque controlled induction motor drives", Renewable and Sustainable Energy Reviews, Vol. 37, 2014, pp. 919-932

[4] C. Thanga Raj, S. P. Srivatsava, P. Agarval, "Energy Efficient, Control of Three-Phase Induction Motor – A Review", International Journal of Electrical Engineering, Vol. 1, No. 1, April 2009, pp. 61-70

[5] G. K. Singh, "A research survey on induction motor operation with non-sinusoidal supply wave forms", Electric Power System Research, Vol. 75, 2005, No. 2-3, pp. 200-213

[6] Y. Dhayeweswaran, L. Ashok Kumar, "A study on current characteristics of induction motor while operating at its base frequency in textile industry", Energy, Vol. 75, 2014, pp. 340-345

[7] V. Jerkovic, Z. Spoljaric, Z. Valter, "Optimal Control of Induction Motor Using High Performance Frequency Converter", 13th International Power Electronics and Motion Control Conference, EPE-PEMC, Poznan, Poland, 1-3 September 2008, pp. 705-709

[8] P. Gnacinski, “Effect of power quality on windings temperature of marine induction motors, Part I: Machine model”, Energy Conversion and Management, Vol. 50, 2009, pp. 2463-2476

[9] P. Gnacinski, “Thermal loss of life and load-carrying capacity of marine induction motors”, Energy Conversion and Management, Vol. 78, 2014, pp. 574-583

[10] E. El Karashi, “Detailed comparative study regarding different formulae of predicting the iron losses in a machine excited by nonsinusoidal supply”, Energy, Vol. 73, 2014, pp. 513-522

[11] P. Huaidong, L. XiaoFan, “Investigation of direct-frequency converter”, Proceedings of the IEEE International Conference on Power Electronics and Drive Systems, Hong Kong, China, 27-29 June 1999, pp. 229-233

[12] V. Jerkovic, Z. Spoljaric, K. Miklosevic and Z. Valter, “Comparison of Different Motor Control Principles Using Frequency Converter”, Science in Practice, Osijek, Croatia, 5-7 May 2008, pp. 53-56

[13] H.A. Toliyat, S. Campbell, “DSP – Based Electromechanical Motion Control”, CRC Press LCC, Boca Raton, Florida, USA, 2004

[14] J. Jukic, “Laboratorijski model sustava skalarnog upravljanja asinkronog motora”, Master’s thesis, Faculty of Electrical Engineering in Osijek, 2009

[15] W. Leonhard, “Control of Electrical Drivers”, Springer, Berlin, Heidelberg, New York, 2001, pp. 241-301.

[16] S. B. Bodkhe and M. V. Aware, “Speed-speed estimation, adjustable-speed induction motor drive based on DC link measurement“, International Journal of Physical Sciences Vol. 4 (4), April 2009, pp. 221-232

[17] M. Hinkkanen, “Flux Estimators For Speed-Speed estimation Induction Motor Drives“, Doctoral Thesis, Helsinki University of Technology, Department of Electrical and Communications Engineering, Power Electronics Laboratory, 2004