

Optimal Control of Induction Motor Using High Performance Frequency Converter

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Abstract—This paper discusses optimal configuring and commissioning of laboratory system that consists of FC-302 high performance frequency converter and induction motor. In the beginning frequency converter control of induction motor is explained. Furthermore, the measurements of slip compensation parameter change influence on motor speed and motor load dependence are performed, as well as measurements of power factor correction attained by frequency converter. It is possible to compensate slip completely, so that motor speed is constant, regardless of motor load, which provides optimal control. Frequency converter partially compensates power factor of converter – motor system with capacitors of passive filter.

Keywords—converter control, induction motor, power factor correction, optimal control.

I. INTRODUCTION

Latest development of high performance frequency converters opens more possibilities for optimal control of induction and synchronous motors. In this paper optimal control of induction motor is considered. Induction motors have wide spread application in industry because of their variable speed and power range. The control and estimation of AC drives in general are considerably more complex than those of DC drives, and this complexity increases substantially if high performances are demanded [1]. Speed of induction motor can be economically controlled if source voltage has variable frequency [2]. The operating speed of induction motor can be determined by relation:

$$n = \frac{60f}{p}(1-s) \quad (1)$$

where n is shaft speed in revolutions per minute, f is the supplied frequency in Hertz, p is the number of pole pairs and s is the operating slip. Speed of induction motor depends upon applied frequency, number of pole pairs and load torque. The most common control principle for induction motors is the constant volts per hertz (V/Hz) principle [3]. If the ratio (V/Hz) remains constant with the change of frequency than stator flux (Φ) also remains constant and the torque (T) is independent of the supply frequency. Relation that connects these values in relative terms is:

$$\bar{T} = \bar{\Phi}^2 = \left(\frac{\bar{U}}{\bar{f}}\right)^2 \quad (2)$$

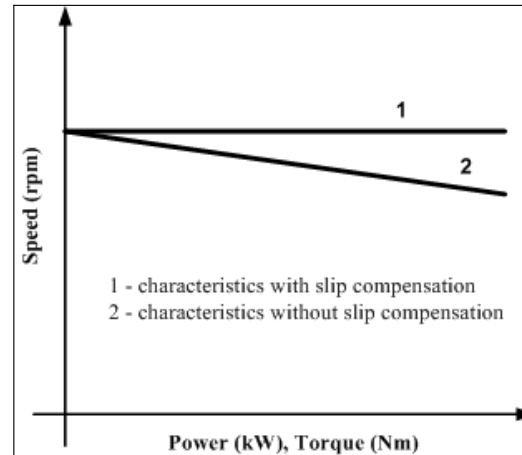


Fig. 1. Dependence of speed, load power and torque with and without slip compensation.

More advanced control principle from standard volts per hertz ratio control is voltage vector control (VVCplus) which uses frequency converter considered in this paper.

Voltage vector control improves the dynamics and stability, both when the speed reference is changed and in relation to the load torque. Vector control simplifies motor control using d-q or Park-Transformations which convert current and voltage from a-b-c to d^c-q^c or synchronously rotating reference frame [4]. The main problem that occurs in induction motor drives is drop of speed because the speed depends on motor load. This can be solved by slip compensation which will be shown further. With slip compensation speed of induction motor remains constant regardless to load power or load moment change, as it is shown in Fig. 1. Influence of frequency converter on power factor is also considered in paper. It will be proved that using high performance frequency converter improves power factor and efficiency of used power source.

II. VECTOR CONTROL

Vector or field oriented control is based on control of magnitude and phase alignment of vector variables. Requests of very dynamic drives can only be accomplished by using vector control because the scalar control is too slow. Vector control of induction motor is based on torque control of separately excited DC motor [5]. DC motor can be controlled by controlling field or

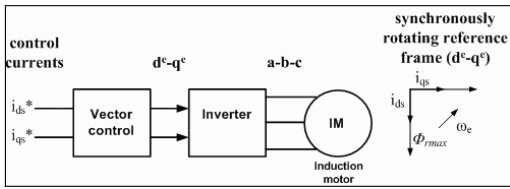


Fig. 2. Vector-controlled induction motor [1].

armature circuit. These two circuits of DC motor are completely separate. This means that, when torque is controlled by controlling the armature current (I_a), the field flux (Φ_f) is not affected and we get the fast transient response and high torque/ampere ratio with the rated field flux [1]. When field current (I_f) is controlled, it affects the field flux only, but not the armature flux (Φ_a) because of decoupling. DC-machine like performance can also be implemented to an induction motor if the machine control is considered in a synchronously rotating reference frame (d^c-q^c), where the sinusoidal variables appear as DC quantities in steady state [5]. Fig. 2. shows the simplified scheme of vector controlled induction motor which consists of inverter and vector control in the front. Vector control is shown with two control current inputs, i_{ds}^* and i_{qs}^* . These currents are the direct axis component and quadrature axis component of the stator current, respectively, in synchronously rotating reference frame [1]. Field current is analogous to i_{ds} and armature current is analogous to i_{qs} . Torque can be expressed as given in [1]:

$$T = K_t \Phi_{rmax} i_{qs} = K_t' i_{ds} i_{qs}, \quad (2)$$

where Φ_{rmax} is the peak value of flux, K_t and K_t' are constant values. Current i_{ds} is oriented in direction of flux and i_{qs} is established perpendicular to it, as shown in space-vector diagram on the right of Fig. 2. This means that when i_{qs}^* is controlled, it affects the actual i_{qs} current only, but does not affect the flux [5]. Also, when i_{ds}^* is controlled, it controls the flux only and does not affect the i_{qs} component of current. As mentioned before in paper, voltage vector control principle is used for motor control.

A. Voltage Vector Control (VVCplus)

Voltage vector control will be explained from usage perspective. VVCplus control is used in open loop without feedback sensor. Control structure in VVCplus is shown on Fig. 3. This type of control is adaptive to

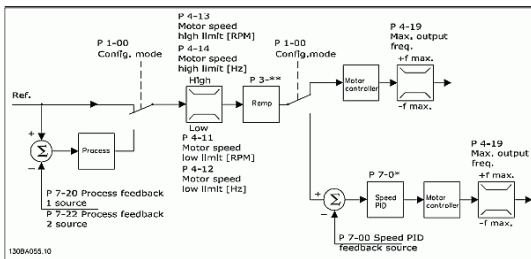


Fig. 3. Control structure in VVCplus.

motor load and adaptation to speed and torque changes is less than three milliseconds [5]. Motor torque can remain constant regardless to speed changes. VVCplus control principle is suitable for most applications. The main benefit of this control principle is robust motor model. This control principle can be used with or without slip compensation which will be described in the next chapter.

III. SLIP COMPENSATION

Relative difference between synchronous speed and rotor speed of induction motor is given in [2] with slip parameter s :

$$s = \frac{n_s - n}{n_s}, \quad (3)$$

where n_s is synchronous speed and n is rotor speed. Hence, slip is equal to ratio of relative speed between rotating stator field and rotor winding, and synchronous speed. Induction motor has two limits of speed: motor standstill (short circuit) and synchronism (ideal idle motion). At motor standstill rotor speed is zero revolutions per minute and slip factor equals one. On the other hand, at ideal idle motion, rotor speed equals synchronous speed, and slip is zero. Synchronism is not possible as stationary state, because there would be no current induced in rotor and, therefore, there would be no torque to support this state. In real idle motion there is a weak current induced in the rotor to overcome the friction resistance and iron loss, so slip is small, but greater than zero. Open loop control of induction motor can be improved by slip regulation.

A. Slip Compensation in Scalar Control

To regulate slip, the slip command ω_{sl} is needed. Slip command is yielded from speed loop error, processed in PI controller and brought through limiter. The estimated slip is then added to the feedback speed signal and frequency command is generated. For the Volts per Herz control principle, voltage command is derived from frequency command and processed in Volts per Herz function generator, which incorporates low-frequency

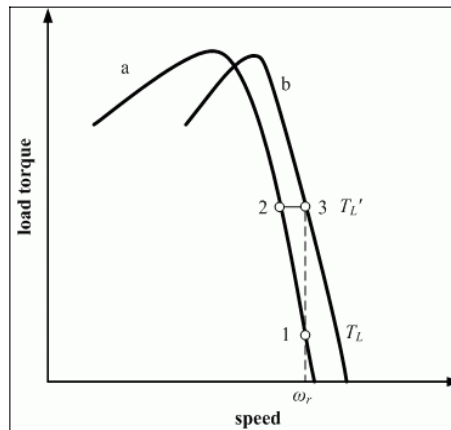


Fig. 4. Effects of load torque variation and speed compensation.

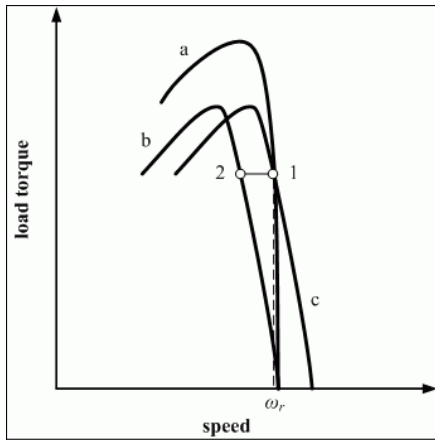


Fig. 5. Effects of supply voltage variation and speed compensation.

voltage drop compensation. At low frequencies voltage drop is present due to the resistance of stator windings. Since slip is proportional to developed torque at constant flux, slip compensation can be considered as an open loop torque control within a speed control loop. The effect of load torque variation is explained on the fig. 4. With the torque increase, speed will tend to drop. However, the speed control loop will increase the frequency until the original speed is restored. If the line voltage changes, the flux does also change. The line voltage drop is considered on the fig. 5. Decrease of line voltage leads to flux reduction and therefore to the drop of speed. Resulting speed drop will act on the speed loop to raise frequency and restore the original speed.

B. Slip compensation in vector control

There are several methods used to estimate speed of induction motor, such as: direct synthesis from state equations, model referencing adaptive system (MRAS), speed adaptive flux observer (Lienberger observer), extended Kalman filter and slip calculation. If slip calculation is chosen as a method for speed estimation, speed is calculated from slip frequency ω_{sl} . As given in [1], slip frequency can be calculated in stator flux-oriented direct vector control:

$$\omega_{sl} = \frac{(1 + \sigma s T_r) L_s i_{qs}}{T_r (\psi_{ds} - \sigma L_s i_{ds})}, \quad (4)$$

where $T_r = L_r / R_r$ is rotor electrical time constant given as ratio of rotor inductance L_r and rotor resistance R_r , and i_{ds} , i_{qs} , ψ_{ds} are the signals corresponding to stator flux orientation. σ represents following expression:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad (5)$$

where L_m is magnetizing inductance, L_s stator inductance, and L_r rotor inductance. For sensorless vector control, synchronous angular frequency ω_e is control variable. Hence, actual speed of induction motor can be derived from rotor angular frequency given with the following relation in [1]:

$$\omega_r = \omega_e - \omega_{sl}. \quad (6)$$

An accurate calculation of slip frequency for high-efficiency machines, especially near synchronous speed, is difficult because the signal magnitude is small and highly dependent on machine parameters. There is also problem of direct integration of machine terminal voltages at low speed, which are used to synthesize ω_e and ω_{sl} signals.

IV. EXPERIMENTAL MODEL

Experimental model (Fig. 6) consists of induction motor (4 kW) and frequency converter FC-302, which controls motor performance. Induction motor is configured in delta connection, with DC generator as load. Direct current that excites magnetic field in DC generator is variable.

A. Frequency converter FC-302

FC-302 is a high performance frequency converter for demanding applications. It can handle various kinds of motor control principles. Beside normal squirrel cage induction motors, FC-302 can also handle permanent magnet synchronous motors. In Fig. 7. scheme of FC-302 power transmission part is shown. Converter consists of diode rectifier, LC filter and three-phase bridge inverter. Short circuit behaviour on converter depends on the 3 current transducers in motor phases. LC filter indicates that FC-302 is voltage-fed converter. FC-302 is capable of controlling either the speed or the torque on the motor shaft. There are two types of speed control: speed open loop (does not require any feedback) and speed closed loop (needs feedback to an input). There are four control principles that FC-302 can operate with: U/f (a special motor mode), VVCplus (Voltage Vector Control principle), Flux sensorless (i. e. Flux Vector Control without encoder feedback) and Flux with encoder feedback. FC-302 supply voltage range is 380-500 volts, supply frequency 50 Hertz, output voltage can reach

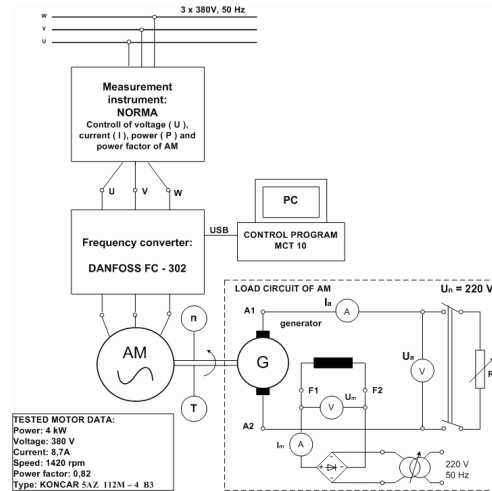


Fig. 6. Block scheme of experimental model and tested motor data.

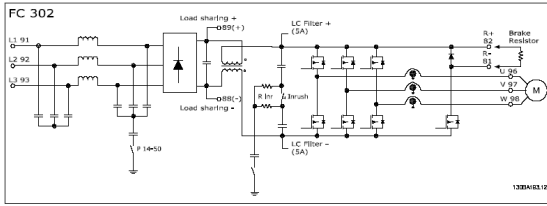


Fig. 7. Power transmission part of FC-302.

amount 0 – 100 % of supply voltage and its power size is 5.50 kilowatts. Control of induction motor is without mechanical sensor. Controlled AC drives without a mechanical sensor have in common that only terminal quantities, i.e. stator voltages and currents are measured from which the information on flux and speed of the motor must be derived, based on the nominal knowledge of the important motor parameters [6].

B. Measurements

Frequency converter can compensate motor slip by giving frequency supplement that follows the measured motor load. Slip compensation can be performed by changing values of parameter 1-62 of frequency converter. Value for slip compensation is entered in percentages. Slip compensation is calculated automatically, on the basis of rated motor speed (speed given on the nameplate data). User can enter values of this parameter in range -500 to 500% in order to compensate tolerances in the value of motor rated speed. To find an optimal value of parameter 1-62 for the specified motor, series of measurements are made. Speed reference is kept constant and motor load varied from motor nominal load to idle motion. Value of parameter 1-62 is altered manually. Motor load is changed by changing current that excites magnetic field in DC generator. Measured values are motor speed and motor power.

Since FC-302 is a voltage-fed inverter, it is expected that it alters power factor of laboratory system. To find out how frequency converter influences on power factor of laboratory system, another series of measurements are made. Again, speed reference is kept constant and motor load varied from 6.3 kilowatts to idle motion. Motor load is changed by changing current that excites magnetic field in DC generator. Measured values are power factor, motor power and frequency. Measurements were taken first on motor without frequency converter, than on frequency converter – motor system.

V. RESULTS

A. Slip Compensation

Results of taken measurements are given on the Fig. 8. As shown in Fig. 8. value of converter parameter 1-62 must be 70% to keep motor speed constant and independent of motor load. Accordingly, it is possible to compensate slip completely and achieve induction motor performance equal to performance of synchronous motor.

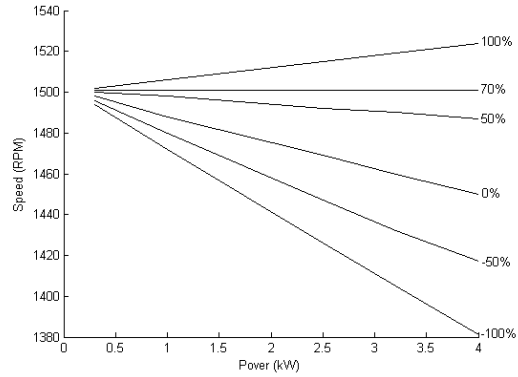


Fig. 8. Slip compensation.

As mentioned before, speed compensation principle is based on giving frequency supplement that follows the measured motor load. To find out how the frequency increases with motor load at optimal value of parameter 1-62, frequency was also measured. The result of this measurement is shown on fig. 9. Fig. 9. indicates that, when slip is totally compensated, frequency supplement is proportional to motor power. At motor nominal power, that is 4 kilowatts, frequency supplement reaches 1.7 Hertz.

B. Power Factor Corection

Results of taken measurements are given on the Fig. 10. As shown in Fig. 10. power factor of frequency converter – motor system is closer to value 1 in all power range than power factor of motor alone. Power factor of frequency converter – motor system is therefore better, because the use efficiency of mains power is greater. Frequency converter partially compensates power factor of converter – motor system. This is achieved with capacitors of passive filter placed in DC circuit. It is important to mention that power factor is equal to phase shift ($\cos\phi$) only if voltage and current wave form is sinus. If voltage and current waves are not sinus, relation between power factor (λ) and $\cos\phi$ is determined by relation [7]:

$$\lambda = \cos\phi_1 (I_1 / I) \quad (7)$$

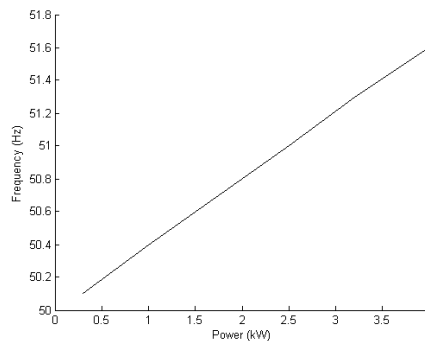


Fig. 9. Frequency supplement due to the slip compensation.

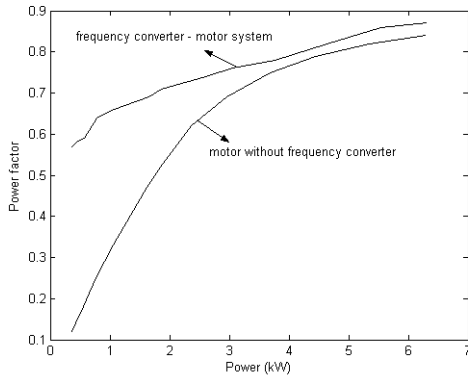


Fig. 10. Power factor correction.

where I_1 is effective value of basic current harmonic and I is total effective current.

VI. CONCLUSION

High performance frequency converters enable very effective motor control. In this paper two benefits of using such frequency converter for control of motor are described.

First benefit is possibility of slip compensation. It is proved that frequency converter can compensate motor slip completely, so that induction motor controlled with frequency converter behaves as synchronous motor. This is convenient because synchronous motors have narrow operation array comparing to induction motors, which is limited with nominal frequency at which they still can provide motor nominal torque. Slip compensation intensity is set manually, because accurate calculation of slip for high-efficiency machines is difficult since the signal magnitude is small and highly dependent on machine parameters. However, manual adjustment also means that motor can even be overcompensated or undercompensated purposely, what can be used in some special

applications. Slip compensation is gained with frequency change, that is, frequency increases with motor load. The relation between frequency supplement of slip compensation and motor power for used frequency converter is proved to be linear.

Second benefit is improvement of power factor of the system. It is proved that frequency converter compensates inductive reactive power of motor with large capacitors of DC circuit. The use of energy from power supply is therefore greater. Fig. 10. shows that the maximal improvement of power factor is gained at motor idle motion. Power factor of motor alone is than 0.12, and power factor of frequency converter – motor system is 0.57. This is especially important for drives which are not constantly loaded, as chain mortisers and so on.

All these benefits together with use of vector control enable optimal control of induction motor. Other benefits and possible imperfections of high performance frequency converters should be subject of further research.

REFERENCES

- [1] B.K. Bose, *Modern Power Electronics and AC Drivers*. Prentice Hall, Upper Saddle River, New Jersey, USA, 2002, pp. 333-435.
- [2] B. Skalicki, J. Grilec, *Electrical Machines and Drivers*. FSB, University of Zagreb, Zagreb, Croatia, 2005, pp. 337-407.
- [3] H.A. Toliyat, S. Campbell, *DSP – Based Electromechanical Motion Control*. CRC Press LCC, Boca Raton, Florida, USA, 2004
- [4] Z. Spoljaric, J. Jelesanin and Z. Valter, "Supervisory Control of EC Synchronous Motor Using LabView program", *DAAAM International*, Vienna, Austria, pp. 699-700, October 2007 [Proceedings of 18-th International DAAAM Symposium, Zadar, Croatia]
- [5] V. Jerkovic, Z. Spoljaric, K. Miklosevic and Z. Valter, "Comparison of Different Motor Control Principles Using Frequency Converter", *International Conference Science in Practice, SIP 2008*, Osijek, Croatia, May 2008, in press
- [6] W. Leonhard, *Control of Electrical Drivers*. Springer, Berlin, Heidelberg, NewYork, 2001, pp. 241-301.
- [7] V. Siladi, "Frequency Converters and Power Factor", *Elektro*, vol. 4/98, pp. 30-33, June/July 1998.