# Comparison of Different Motor Control Principles Using Frequency Converter


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***Abstract*—Main object of research in this paper is comparison of three different principles of induction motor control using high performance frequency converter FC-302. In the beginning principles of Scalar Control (U/f), Voltage Vector Control (VVCplus) and Flux Vector Control (FVC) are explained. Further more laboratory model for testing each method, which consists of frequency converter, induction motor and DC generator as load, is described. Measurements of load torque, current and motor speed for each method are performed during motor acceleration from zero to rated motor speed. Comparison of mentioned methods in aspect of dynamics and stability related to the load torque is given. Practical use of each method is proposed.**



***Keywords*—comparison, converter, scalar control, vector control, laboratory model**.


## I. INTRODUCTION

High performance frequency converters provide usage of different motor control principles. Basic principle of frequency converter is rectifying of AC voltage from main power supplies into DC voltage and, after that, converting DC voltage to AC voltage with variable amplitude and frequency. This enables infinitely variable speed control of three phase AC motors and permanent magnet synchronous motors. There are three kinds of motor control principles which will be presented in this paper. Scalar control, as the name indicates, is due to magnitude variation of control variables only, and disregards the coupling effect in the machine [1]. The most common control principle for induction motors is the constant volts per hertz (*U/f*) principle [2]. This principle is used in open loop volts per hertz control by frequency converter used in research. The other two observed control principles are based on vector control. Vector control simplifies motor control using d-q or Park-Transformations which convert current and voltage from a-b-c to $d^e$-$q^e$ or synchronously rotating reference frame [3]. Voltage Vector Control (VVCplus) of induction motor connects stator voltage equation, converted to field coordinates, with magnetizing current vector, which represents the rotor flux. Reference [4] gives complete mathematical model of voltage-fed induction motor in field coordinates. The last observed motor control principle is Flux Vector Control (FVC) which is used without speed sensor in open loop. The speed of an induction motor is estimated by speed estimation techniques given in [1]. Usage of these mentioned control principles depends on motor purpose and load demands. Laboratory model for testing these methods consists of frequency converter, induction motor and DC generator as load. For each method values of current, load torque, speed and power are recorded during loaded motor acceleration from zero to rated speed. Problem at motor start causes the motor current which has high amounts. The other problem is to insure sufficient moment which depends on motor load. In aspect of speed, motor needs to achieve rated speed in short time. This task is opposite to request of low current at starting of motor. Basis for understanding this dynamic behavior is mathematical model which connects physical values with time as common variable [5]. By choosing the one of mentioned control principles, in the dependency of motor load or required characteristics, motor dynamics and stability can be improved.

## II. MOTOR CONTORL PRINCIPLES

### A. *Scalar Control (U/f)*

The open loop volts/hertz control of an induction motor is by far most popular method of speed control because of its simplicity, and these types of motors are widely used in industry [4]. Voltage is required to be proportional to frequency so that stator flux ($\Phi$) remains constant. This causes maximum motor torque ($T$) to also remain constant and independent of supply frequency. Equation (1) connects these values in relative terms as in [5]:

$$T = \Phi^2 = (U / f)^2. \tag{1}$$

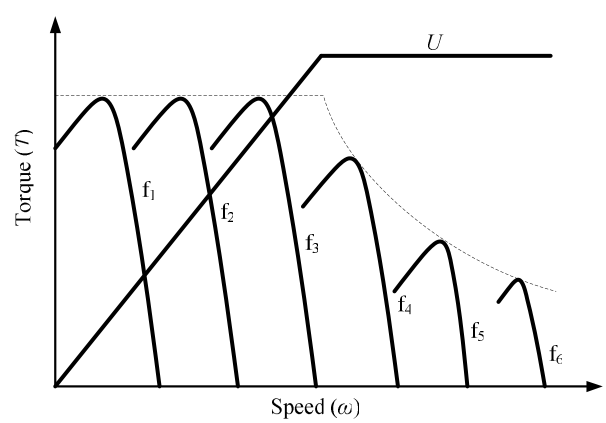


Figure 1. Torque-speed curves showing effect of frequency variation load torque and supply voltage changes [4].

Fig. 1 shows the torque-speed curves on example of fan or pump load type. Speed is increasing proportionally with frequency and maximum torque remains constant if supply voltage also increases with frequency. Scalar control is simple to implement but, because of the inherent coupling effect (i.e. both torque and flux are functions of voltage or current or frequency), gives sluggish response and the system is easily prone to instability. This is caused by high order (fifth-order) system effect.

### B. *Vector Control*

Requests of very dynamic drives can not be accomplished by using scalar control because it is slow so scalar control is replaced with vector control. Vector control of induction motor is based on torque control of separately excited DC motor. Control of DC motor is based on control of two separate circuits: field circuit an armature circuit. This means that when torque is controlled by controlling the armature current ($I_a$), the field flux ($\Phi_f$) is not affected and we get the fast transient response and high torque/ampere ratio with the rated field flux [1]. Because of decoupling, when field current ($I_f$) is controlled, it affects the field flux only, but not the armature flux ($\Phi_a$). DC-machine like performance can also be implemented to an induction motor if the machine control is considered in a synchronously rotating reference frame ($d^e$-$q^e$), where the sinusoidal variables appear as DC quantities in steady state. Fig. 2 shows induction motor with the inverter and vector control in the front, which is presented 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:

$$T = K_t\, \Phi_{rmax}\, i_{qs} = K_t^{'}\, i_{ds}\, i_{qs}\,, \tag{2}$$

where $\Phi_{rmax}$ is the peak value of flux and $K_t$ is constant value. 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. 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 two control principles of vector control are used. These control principles will be explained from usage perspective.

#### 1) *Voltage Vector Control (VVCplus)*

VVCplus control is used in open loop without feedback sensor. Control structure in VVCplus is shown on Fig. 3.

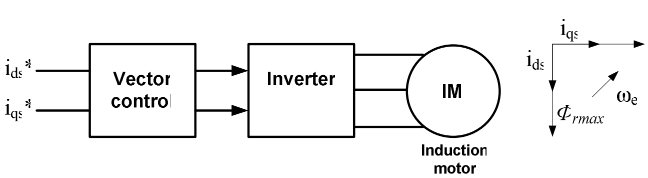


Figure 2. Vector-controlled induction motor [1].

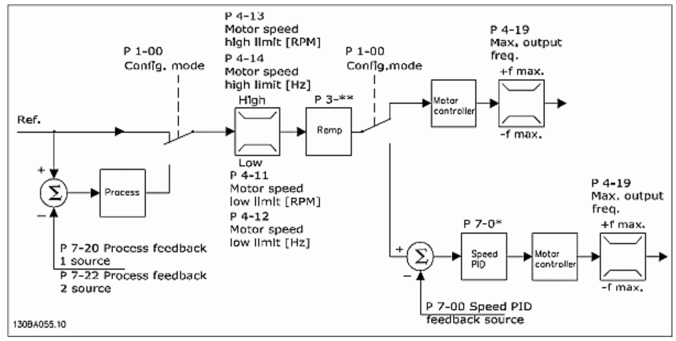


Figure 3. Control structure in VVCplus open loop and closed loop.

VVCplus improves dynamic and stability, both when speed reference is changed and in relation to the load torque [6]. This type of control is adaptive to motor load and adaptation to speed and torque changes is less then three milliseconds. Motor torque can remain constant regardless to speed changes.

#### 2) *Flux Vector Control (FVC)*

FVC is used also in open loop without a feedback sensor. In this case an estimation of speed feedback is generated to the PID regulator to control the output frequency. PID regulator must be set with its P, I and D parameters. This control principle can be used in closed loop if speed signal is available. FVC is used for high demanding motor drives. Control structure in FVC is showed on Fig. 4.

## III. LABORATORY MODEL

In Fig. 5 is shown laboratory model that 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 [6]. Direct current that excites magnetic field in DC generator is set so that, when rated speed is reached, electrical power amounts 4 kW. The reference speed value for motor acceleration is linear ramp. Motor accelerates from zero RPM to rated speed in 20 s, as it is set in frequency converter parameter for ramp up time.

### A. *Frequency converter FC-302*

FC-302 is a high performance frequency converter for various applications. Beside squirrel cage induction motors,

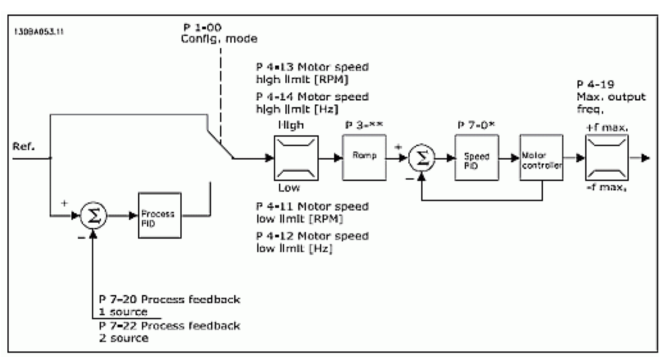


Figure 4. Control structure in FVC sensorless open loop configuration.

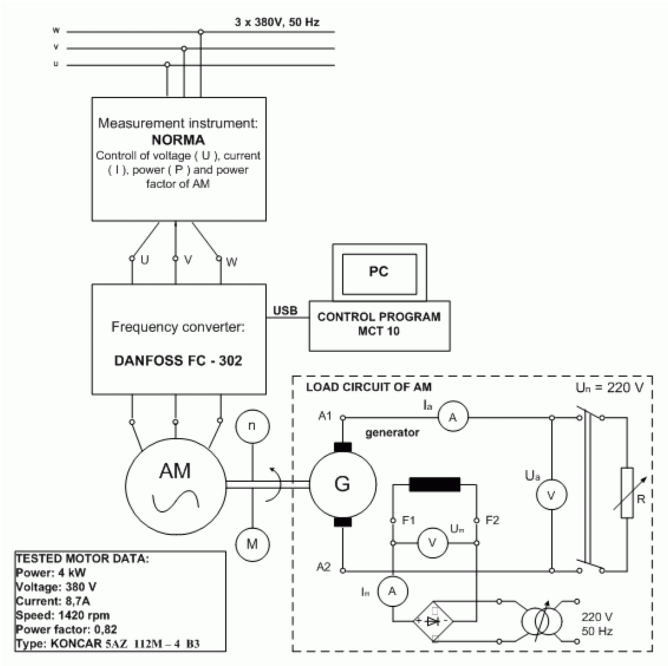


Figure 5. Block scheme of experimental model and tested motor data.

FC-302 can also handle permanent magnet synchronous motors. It consists of diode rectifier, LC filter and three-phase bridge inverter (Fig. 6).

### B. *Load characteristics*

Fig. 7 represents characteristics of DC generator used as load. Measured torque and calculated mechanical power on the motor shaft are given in correlation with motor speed. Load torque is proportional to motor speed. According to [7] mechanical power is calculated as follows:

$$P = T \cdot \omega, \tag{3}$$

where $T$ is torque and $\omega$ is mechanical angular frequency. According to (3) mechanical power is proportional to second power of motor speed. Gained load characteristics indicate that DC generator acts as Eddy-current system. This type of load corresponds to calendars with viscous friction, Eddy-current brakes, etc.

## IV. Results

To find out what benefits each control principle brings, current, torque, electrical power and speed are recorded. Measurements are preformed using frequency converter software and associated computer software. It is important to notice that current and electrical power exact values are

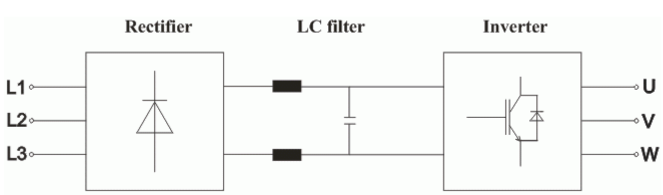


Figure 6. Power transmission part of converter.

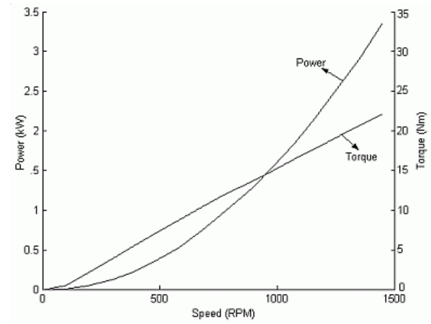


Figure 7. Load characteristics.

measured on motor phases, whereas torque on the shaft and motor speed are values estimated in internal motor model of frequency converter.

### A. *Current measurements*

Measurements of current performed during motor acceleration from zero to rated motor speed with U/f, VVCplus and FVC motor control principles are shown on the Fig. 8. The highest peak value and the fastest current respond is gained using FVC. The slowest current response is realized using U/f control principle. The lowest peak value and fast response is reached using VVCplus control principle.

### B. *Torque measurements*

Torque measurements performed during motor acceleration from zero RPM to rated motor speed with all three motor control principles are shown on the Fig. 9. The highest peak value and the slowest torque respond is realized using FVC. The fastest torque response and the lowest peak value are gained using VVCplus control principle.

### C. *Electrical power measurements*

Electrical power measurements performed during motor acceleration using all three methods are shown on the Fig. 10. The highest electrical power values and the slowest respond is realized using FVC. Measured electrical powers gained with VVCplus and U/f control principles are very similar. The difference in electrical power response between these two methods is that peak value reached with VVCplus is 90 W smaller than the peak value reached with U/f control principle.

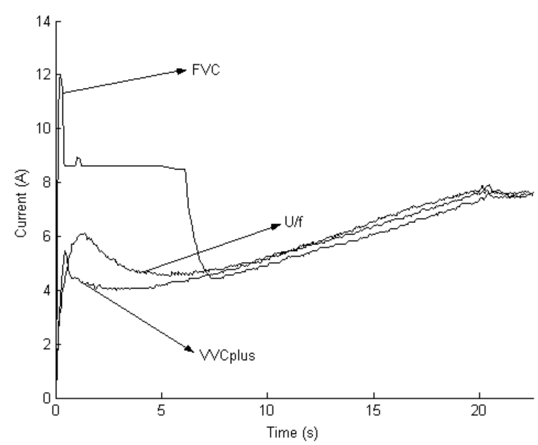


Figure 8. Current measurements.

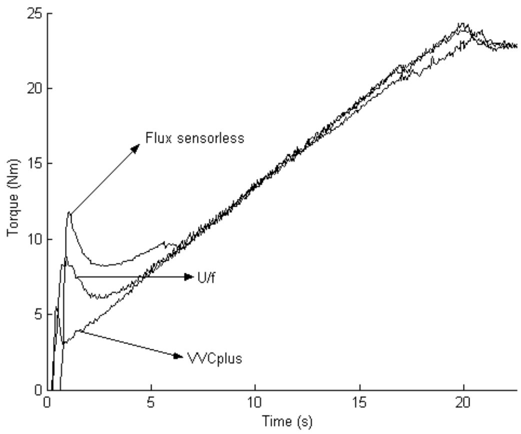


Figure 9. Torque measurements.

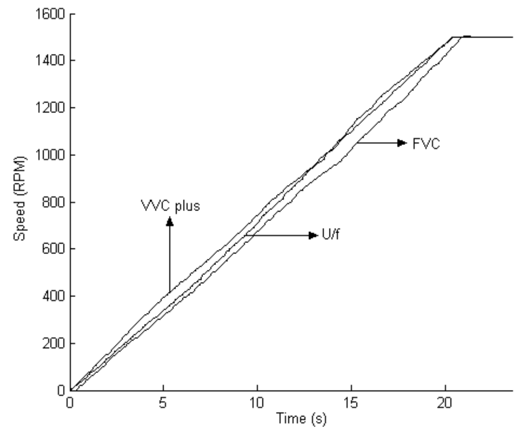


Figure 11. Speed measurements.

### *D. Speed measurements*

Speed measurements performed during motor acceleration from zero RPM to rated motor speed with all three motor control principles are shown on the Fig. 11. The highest peak value and the slowest speed respond is realized using FVC. The fastest speed response is gained using VVCplus control principle.

## V. CONCLUSION

Frequency converter FC-302 provides three different motor control principles, Scalar Control (U/f), Voltage Vector Control (VVCplus) and Flux Vector Control (FVC). These three methods are tested in laboratory system, with DC generator as load. DC generator has load characteristics analogous to those of calendars with viscous friction, Eddy-current brakes, etc. Results of taken measurements indicate that, for this type of load, VVCplus control principle is most adequate, while it provides the fastest speed and torque response, lowest current and torque peak values, as well as lowest electrical power on the motor phases. FVC gives slowest speed and torque responses, with highest peak values of all measured signals. Measured electrical power on motor phases is considerably higher than electrical power measured using other two control principles. Hence current, torque and power values at motor acceleration are higher than with other two methods.

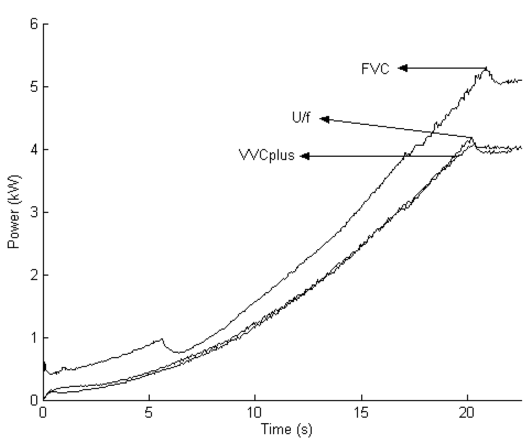


Figure 10. Electrical power measurements.

All this indicates that FVC control principle is inappropriate for used load, but would be suitable for loads with constant torque, such as belt conveyors and also for loads with constant power, that is winders, rotary cutting machines etc. Scalar Control U/f provides the most accurate speed in both static and dynamic conditions, while voltage-frequency characteristic in this control principle is fixed. Voltage-frequency characteristic can be entered manually in frequency converter software in five points, so it does not have to be linear. This makes U/f control principle suitable for special motor applications. However, scalar control in common applications is inferior to vector control, because of slower response with higher peak values.

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