Implementation of Slip-Controller for Induction Motor Drive Employing Indirect Matrix Converter

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Abstract: A new scheme to design the proportional integral (PI) type controller for speed control of a constant Volts/Hz (V/F) three phase induction motor drive employing a matrix converter has been presented. An approximate linear model of induction motor operating in constant Volts/Hz scheme is derived and a design example of a slip controller for a three phase motor is presented. Performance of the designed controller is verified with results from simulation using Matlab.

Keywords— Constant Volt/Hz, Matrix converter, Space vector PWM, VVVF, Induction motor drive.

I. INTRODUCTION

Recent advances in power electronics and microprocessor technology have made it possible to commercialize sophisticated sensor-less Vector-Control and Direct Torque Control (DTC) schemes of induction motor speed control for low and medium power drive requirement. However Variable Voltage Variable Frequency (VVVF) drives using constant V/F principle remain a predominant choice over Field Oriented Control (FOC) and DTC drives for induction motor speed control in applications where the need of fast and smooth response to speed/torque change is not required, such as pumps, washing machines, ventilation blowers, etc. Using constant V/F control in these applications reduce the cost of extra current sensors and computational resources compared to FOC or DTC drives, while achieving the expected speed-torque control. The constant volts/Hz based VVVF drive principle is extensively documented in text-books and literature; however a method of designing slip-regulator using analytical approach is not described. Analytical approach for design of PI controllers for Field Oriented Control with parameter variations are presented in which can be used for design of slip controller for constant V/F drive but they are very complex and require accurate information of motor parameters. In this paper a step-wise design method is presented which is very simple and requires only the name-plate data of the motor. The design is verified with results from simulation using Matlab.

The control scheme of a typical constant V/F drive as shown in Fig. 1 relies on a PI-controller for regulating slip speed to compensate for the change in load torque at any operating speed. The design of PI-regulator is based on the gain constants, namely proportional gain, \( K_p \), and integral gain, \( K_i \), which are generalized by the drive manufacturer for a given rating of motor drive. However the optimum values of the controller gains are based on the actual rating of the motor, which is sometimes different than the rating of the drive. Hence re-tuning the PI controller to motor ratings justifies a better transient control capability and marginal improvement in efficiency.

MATRIX CONVERTER

A. Overview of a Matrix Converter

A general block diagram of a three-phase induction motor drive based on a matrix converter is shown in Fig. 2. The heart of this system is an array of nine bidirectional power switches (Fig. 3) which constitute the matrix converter itself, an input LC filter (with damping resistors connected in series or parallel with the inductors), and the induction motor. The power switches of the converter are controlled according to the commands given by the implemented modulation and commutation strategies. In this way, the voltage and frequency of the output voltages of the converter are continuously adjusted according to the requirements of the V/F which controls the induction machine.

B. Control of the Matrix Converter

The matrix converter is controlled with the aid of a modulation strategy. The one adopted in this work is the well known indirect space vector modulation. According to it, the matrix converter is viewed as a virtual system consisting of a rectifier stage
connected to an inverter stage. The rectifier is controlled like a
current source and the inverter is controlled like a voltage
source. In both stages (rectifier and inverter), the switches are
controlled using the classic Space Vector Modulation technique.
Taking into account the constraints imposed by the modulation
strategy and safe operation of the matrix converter, each output
line of the converter must be connected to a single input line at
time, that is:
\[ S_{a} + S_{b} + S_{c} = 1, \quad j \in \{A, B, C\} \]

C. Indirect modulation principle

The object of the modulation strategy is to synthesize the output
voltages from the input voltages and the input currents from the
output currents. The three phase matrix converter can be
represented by a 3 by 3 matrix form because the nine
bidirectional switches can connect one input phase to one output
phase directly without any intermediate energy storage elements.
Therefore, the output voltages and input currents of the matrix
converter can be represented by the transfer function \( T \) and the
transposed \( T^T \) such as
\[
V_0 = T \ast V_1
\]
\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
S_{ad} & S_{bd} & S_{cd} \\
S_{bd} & S_{bd} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd}
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

\[
I_1 = T^T \ast I_0
\]
\[
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix} =
\begin{bmatrix}
S_{ad} & S_{bd} & S_{cd} \\
S_{bd} & S_{bd} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd}
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b \\
I_c
\end{bmatrix}
\]

Where \( V_a, V_b \) and \( V_c \) are input phase voltages, and \( V_a, V_b \) are \( V_c \)
output phase voltages, \( I_a, I_b \) and \( I_c \) are input currents and
\( I_{a}, I_{b} \) and \( I_{c} \) are output currents. The elements in the transfer
matrix \( TI/j \) represent the switch function from the instantaneous
input voltage \( V_i \) to the instantaneous output voltage \( V_j \) and have
to be assigned values that assure output voltages and input currents
to follow their reference values. Defining a modulation
strategy is actually filling in the elements of the transfer matrix.
Although several Modulation strategies have been proposed
since Venturini announced a closed mathematical solution for
the transfer function \( T \) in early 1980, the indirect space vector
modulation is gaining as a standard technique in the matrix
converter modulations.

The indirect space vector modulation (indirect SVM) was first
proposed by Borojevic et al in 1989 where matrix converter was
described to an equivalent circuit combining current source
rectifier and voltage source inverter connected through virtual dc
link as shown in Fig. 4. Inverter stage has a standard 3φ voltage
source inverter topology consisting of six switches, \( S7 \sim S8 \) and
rectifier stage has the same power topology with another six
switches, \( S1 \sim S6 \). Both power stages are directly connected
through virtual dc-link and inherently provide bidirectional
power flow capability because of its symmetrical topology.
Although this equivalent circuit has provided a strong platform
to analyze and derive several extended PWM strategies specified
in a certain application since then, it is still ambiguous for a
beginner to grasp its operating principle. The operating principle
of the indirect SVM will be illustrated with graphical approach.
The basic idea of the indirect modulation technique is to
decouple the control of the input current and the control of the
output voltage. This is done by splitting the transfer function \( T \)
for the matrix converter in (2) into the product of a rectifier and
an inverter transfer function.
\[
T = I^T R
\]

Where the matrix \( I \) is the inverter transfer function and the
matrix \( R \) is the rectifier transfer function. This way to model the
matrix converter provides the basis to regard the matrix
converter as a back-to-back PWM converter without any dc-link
energy storage. This means the well know space vector PWM
strategies for voltage source inverter (VSI) or PWM rectifier can
be applied to the matrix converter.

Substituting (5) in (2),
\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
S_{ad} & S_{bd} & S_{cd} \\
S_{bd} & S_{bd} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd}
\end{bmatrix}
\begin{bmatrix}
S_{ad} & S_{bd} & S_{cd} \\
S_{bd} & S_{bd} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd}
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
S_{ad} & S_{bd} & S_{cd} \\
S_{bd} & S_{bd} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd}
\end{bmatrix}
\begin{bmatrix}
S_{ad} & S_{bd} & S_{cd} \\
S_{bd} & S_{bd} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd}
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]

The above transfer matrix exhibits that the output phases are
compounded by the product and sum of the input phases through
inverter switches \( S7 \sim S12 \) and rectifier switches \( S1 \sim S6 \). The
first row of (6) represents how output phase \( A \) is built from the
input phase \( a, b \) and \( c \) and this mathematical expression can be
interpreted again in the graphical viewpoint. If the equivalent
circuit is seen from the inverter output phase \( A \), two switches \( S7 
and S8 \) of phase \( A \) half bridge is directly connected to input
phases \( a, b \) and \( c \) through six rectifier switches \( S1 \sim S6 \). Fig.5
shows how the switch set of equivalent circuit can be
transformed into the relevant switch set of the nine bidirectional
switched matrix converter in the case of phase \( A \) and gives an
basic idea that the duty cycles of the matrix converter branch can
be derived by multiplying the duty cycles of the corresponding
rectifier and inverter switches in the equivalent circuit. Therefore

![Equivalent circuit of indirect matrix converter](image-url)
the indirect modulation technique enables well-known space vector PWM to be applied for a rectifier as well as an inverter stage.

Fig 5 Transformation from equivalent circuit to matrix converter phase A.

SLIP REGULATOR DESIGN

A. Slip Control Scheme
Constant Volts/Hz or scalar control of induction motor refers to the scheme of controlling the motor torque and speed by proportionally varying the voltage with supply frequency to maintain air-gap flux constant and achieve up to rated torque at any speed by controlling the slip-speed.

Neglecting magnetizing inductance, torque developed in an induction motor can be expressed as:

\[ T_\text{s} = \frac{V^2}{\omega_1 R_2} \left( \frac{R_1 + R_2}{s} \right) + (X_1 + X_2)^2 \]

Where, \( V \) = per phase voltage applied to the stator, \( \omega_1 = 2 \pi f_1 \), \( f_1 \) is the supply frequency, \( p \) = pole pairs, \( R_1 \) and \( R_2 \) = stator and rotor resistance and \( X_1 \) and \( X_2 \) = stator and rotor reactance, \( s \) = slip. Under normal operating conditions, the slip is small implying

\[ \frac{R_2}{s} \gg R_1 \Rightarrow \frac{R_2}{s} \gg (X_1 + X_2) \]

Hence the developed torque can be approximated as:

\[ T_\text{s} \approx \frac{|V|^2 \cdot s \cdot \omega_1}{R_2} \]

From (2) it can be seen that

\[ T_\text{s} \propto s \cdot \omega_1 \text{ if } \frac{V}{\omega_1} \text{ is kept constant, torque developed could be controlled by controlling the slip speed } s \cdot \omega_1 \]

The constant volts/Hz control scheme is shown in fig 18. The speed reference \( \omega_1 \text{ rad/sec} \). The output of the PI controller is the commanded slip speed \( s \cdot \omega_1 \text{ which is summed up with the actual speed of the motor } \omega \text{ to generate the synchronous speed } \omega_2 \text{ frequency command. The voltage command to the inverter is fed through a V/Hz profile graph to keep the V/F ratio constant. The error difference of reference and actual speed is processed through the slip regulator defined by the proportional gain, } K_p \text{ and integral gain, } K_i \text{ to generate slip speed. The values of these gain constants determine the performance of drive.}

Fig. 18 Schematic of speed controller.

B. Linearised model of induction machine constant V/F drive using PI slip regulator.

From (21), it can be deduced that to control the torque developed by motor, the slip speed needs to be controlled. An Induction motor drive system using a PI-controller to regulate speed can be modeled as shown in figure 20.

The rotor speed is

\[ \omega_2 = (T_2 - T_1) / J \cdot s \]

Where \( J \) is the moment of inertia of the motor.

The open loop transfer function of the system assuming the load torque is zero, can be given by

\[ A(s) = \frac{K(1 + T_1 \cdot s) \cdot K_f}{(T_1 \cdot s) \cdot (J \cdot s)} \]

\[ K_f = \frac{T_{\text{rated}}}{s \cdot \omega_1} \]

Where, 

PI controller constants \( K \) and \( Ti \) can be calculated using conditions
\[ |A(f\omega_c)| = 1 \]
\[ \phi_e = 180^\circ + \tan^{-1}(\omega_c \cdot T_c) - 90^\circ - 90^\circ \]
\[ K = \frac{T_i \cdot J \cdot (\alpha e)^2}{K_f \cdot \sqrt{1 + (T_i \cdot \alpha_e)}} \]
\[ T_i = \frac{\tan(\phi_e)}{2 \cdot \pi \cdot f_c} \]

Where \( \phi_e \) is the phase margin and \( \omega_c = 2\pi f_c \), where \( f_c \) is cross over frequency. Assume ideal phase margin of the system \( \phi_e = 60 \) degree and cross over frequency is 1/3 of speed sensor frequency. The PI controller gains \( K_p \) and \( K_i \) can be calculated as

\[ K_p = K \quad \text{and} \quad K_i = \frac{K}{T_i} \]

II. SIMULATION RESULTS

Simulation of the Drive was made using Matlab-Simulink and SimPowerSystems Toolbox. The scheme of the drive simulated is shown in figure 22. Back-propagation method is used to realize the digital PI controller.

Fig. 21 Matrix converter output voltage for the reference speed of 800rpm.

A reference speed of 800 rpm is set and the rated load torque is applied. Fig 21 shows the voltage that is available at the machine terminals to run the machine at this speed.

Fig. 22 Reference voltage available at the converter terminals.

Fig. 23 Stator currents of the machine.

Fig. 24 Torque

Fig. 25 Machine speed.

From fig 25 it can be seen that the machine speed is settling at the reference speed set externally.

The controller performance is also verified by applying a step change in the reference speed. For a step change in the reference
speed from 800 rpm to 1000 rpm at time t=5sec, the various waveforms are shown with rated torque applied.

**Fig.26** Three phase converter output voltage.

From fig 27 it can be seen that the reference voltage changes for the change in the reference speed set. The reference voltage at 800 rpm is 214V whereas at 1000 rpm it is 350V. The frequency is also changed to maintain constant V/F.

**Fig.27** Reference voltage variation.

The rated torque of 27Nm is applied constant throughout the speed variations. The variation of machine speed is shown in the fig.29. The speed settles at the desired value because of the controller action.

**Fig.28** Torque

**Fig.29** Machine speed

**CONCLUSION**

An analytical method of designing PI-controller using the motor name-plate details for speed control of a constant V/F controlled induction motor drive has been presented and an approximate linear model of induction motor drive when operating under constant V/F control has been derived. The drive response with the designed PI-controller has been successfully verified with simulation results. Satisfactory performance is observed at low-speed and high speed operation of the drive during load transients. The designed PI-controller demonstrated effective control of the motor speed at start-up and speed-reversals without causing any undesired over-shoot of speed. It is felt that with lower speed sensor cut-off frequency the design procedure can be extended to even lower operating speeds of the motor.

**III. APPENDIX**

The ratings of the three phase 50 Hz, 400 V, 4 kW, delta connected, 1,430 rpm squirrel cage induction motor are:

- \( R_s = 1.4050 \ \Omega \)
- \( R'_s = 1.3950 \ \Omega \)
- \( L_d = 0.005839 \ H \)
- \( L'_d = 0.005839 \ H \)
- \( J = 0.0131 \ Kgm^2 \)
- \( F = 0.002985 Nms \)
- Poles = 4

**IV. REFERENCES**


**V. BIOGRAPHIES**

**K.Ganesan** is working as Assistant professor in the department of Electrical and Electronics engineering in Vel Tech University, Chennai. His areas of interests include Power electronics for renewable energy, Flexible AC transmission and Drives.