Feedback of the Input Voltage in FDTC Control Using a Three-Level NPC-VSI

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Abstract: A new control structure for sensorless induction machine dedicated to electrical drives using a three-level voltage source inverter VSI-NPC is completely analysed. The amplitude and the rotating velocity of the flux vector could be controlled freely. Both fast torque and optimal switching logic could be achieved; the selection is based on the value of the stator flux and the torque. A novel DTC scheme of induction motors is proposed in order to develop a suitable dynamic. We proposed a DTC approach based in fuzzy logic, in witch the response of torque and flux is enhanced through optimal switching strategies and torque ripple minimisation is achieved. However, the middle point voltage of the input DC voltages of the three-level NPC voltage source inverter presented serious problems caused by a fluctuation of the DC voltage sources $U_{CU}$, $U_{CL}$. As consequence to these problems, we obtained an output voltage of the inverter, which is asymmetric and with an average value different from zero. We presented one solution to minimise this fluctuation. This solution used a feedback to regulate the input voltages of a three-level inverter VSI NPC. A scheme of a fuzzy direct torque control “FDTC” with complete cascade is simulated for an induction motor. The results obtained indicate superior performance over the FOC one without need to any mechanical sensor.

Keywords: Direct torque control, fuzzy control, field oriented control, flux estimators, induction motor, multi-level inverter, neural-point clamped, sensorless vector control, switching strategy optimisation, fast torque response

INTRODUCTION

The rapid development of the capacity and switching frequency of the power semiconductor devices and the continuous advance of the power electronics technology have made many changes in static power converter systems and industrial motor drive areas. The conventional GTO inverters have limitation of their dc-link voltage. Hence, the series connections of the existing GTO thyristors have been essential in realizing high voltage and large capacity inverter configurations with the dc-link voltage $U_{dc}$. The vector control of induction motor drive has made it possible to be used in applications requiring fast torque control such as traction Nikola Tesla. In a perfect field oriented control, the decoupling characteristics of the flux and torque are affected highly by the parameter variation in the machine.

This paper describes a control scheme for direct torque and flux control of induction machines fed by a three-level inverter using a switching table. In this method, the output voltage is selected and applied sequentially to the machine through a look–up table so that the flux is kept constant and the torque is controlled by the rotating speed of the stator flux. The direct torque control (DTC) is one of the actively researched control scheme which is based on the decoupled control of flux and torque providing a very quick and robust response with a simple control construction in ac drives.[3,4]

The suggested technique is based on applying to the inverter the selected active states just enough time to achieve the torque and flux references values.

We propose a FDTC system for high voltage and high power applications. This structure lets to absorb, in network, sinusoidal currents with unity power factor. It constitutes by two-level PWM rectifier, feedback linear control using IP regulator, three-level NPC-VSI, induction motor controlled by FDTC strategy.

Three-level inverter topology: Fig. 1 shows the schematic diagram of neutral point clamped (NPC)
A two-level inverter is only able to produce six non-zero voltage vectors and two zero vectors\(^2\). The representation of the space voltage vectors of a three-level inverter for all switching states forming a two-layer hexagon centred at the origin of the (\(d\), \(q\)) plane and a zero voltage vector at the origin of the plane, as depicted in Fig. 2. According to the magnitude of the voltage vectors, we divide them into four groups: the zero voltage vectors (\(V_0\)), the small voltage vectors (\(V_1\), \(V_2\), \(V_7\), \(V_10\), \(V_11\), \(V_16\)), the middle voltage vectors (\(V_3\), \(V_6\), \(V_9\), \(V_{12}\), \(V_{15}\), \(V_{19}\)), the large voltage vectors (\(V_2\), \(V_5\), \(V_8\), \(V_{11}\), \(V_{14}\), \(V_{17}\)).

The zero voltage vector (ZVV) has three switching states, the small voltage vector (SVV) has two and both the middle voltage vector (MVV) and the large voltage vector (LVV) have only one\(^3\).

**Induction machine:** Torque control of an induction motor can be achieved on the basis of its model developed in a two axis (\(d\), \(q\)) reference frame stationary with the stator winding. In this reference frame and with conventional notations, the electrical mode is described by the following equations:

\[
\frac{di_{sd}}{dt} = -\frac{1}{\sigma L_s} \phi_{sq} + \frac{p}{\sigma L_s} \phi_{sd} + \frac{1}{\sigma L_s} (1 + \frac{1}{T_s}) i_{sd} - p \Omega i_{sq} \\
+ \frac{1}{\sigma L_s} V_{sd} \tag{1}
\]

\[
\frac{d\phi_{sq}}{dt} = -\frac{1}{\sigma L_s} \phi_{sd} + \frac{1}{\sigma L_s} \phi_{sq} - \frac{1}{\sigma L_s} (1 + \frac{1}{T_s}) i_{sq} + p \Omega i_{sd} \\
+ \frac{1}{\sigma L_s} V_{sq} \tag{2}
\]

\[
\frac{di_{sd}}{dt} = -\frac{1}{L_s} \phi_{sq} + \frac{1}{L_s} \phi_{sd} - \frac{1}{L_s} i_{sd} - R_s i_{sd} \tag{3}
\]

\[
\frac{d\phi_{sq}}{dt} = -\frac{1}{L_s} \phi_{sd} + \frac{1}{L_s} \phi_{sq} - \frac{1}{L_s} i_{sq} - R_s i_{sq} \tag{4}
\]

The mechanical mode associated to the rotor motion is described by:

\[
\frac{d\Omega}{dt} = \Gamma_{em} - \Gamma_L (\Omega) \tag{5}
\]

\(\Gamma_L (\Omega)\) and \(\Gamma_{em}\) are respectively the load torque and the electromagnetic torque developed by the machine.

**Basic dtc principles:** Fig. 3 shows a block diagram of the DTC scheme developed by I. Takahashi\(^3\). The reference values of flux, \(\phi^{*}\), and torque, \(\Gamma_{em}\), are
The stator flux angle, $\theta_s$, is calculated by:

$$\theta_s = \arctan \frac{\varphi_{sq}}{\varphi_{sd}}$$  \hspace{1cm} (6)

and quantified into 12 levels depending on which sector the flux vector falls into. Different switching strategies can be employed to control the torque according to whether the flux has to be reduced or increased.

Each strategy affects the drive behavior in terms of torque and current ripple, switching frequency and two or four-quadrant operation capability. Assuming the voltage drop ($R_s,i_s$) small, the head of the stator flux $\Phi_s$ moves in the direction of stator voltage $V_s$ at a speed proportional to the magnitude of $V_s$, according to

$$\Delta \Phi_s = V_s \cdot T_e$$  \hspace{1cm} (7)

The switching configuration is made step by step, in order to maintain the stator flux and torque within limits of two hysteresis bands. Where $T_e$ is the period in which the voltage vector is applied to stator winding. Selecting step by step the voltage vector appropriately, it is then possible to drive $\Phi_s$ along a prefixed track curve.

Assuming the stator flux vector lying in the $k$-th sector ($k=1,2,3,\ldots,12$) of the $(d, q)$ plane, in the case of three-level inverter, to improve the dynamic performance of DTC at low speed and to allow four-quadrant operation, it is necessary to involve the voltage drop ($R_s,i_s$) small, the head of the stator flux $\Phi_s$ moves in the direction of stator voltage $V_s$ at a speed proportional to the magnitude of $V_s$, according to

$$\Delta \Phi_s = V_s \cdot T_e$$  \hspace{1cm} (7)

The sensitivity coefficients $K_{\Phi}$ and $K_{\theta}$ are defined by:

$$K_{\Phi} = \frac{d \Gamma_{elm}}{d \Phi_s} = \frac{2}{\Gamma_{elm}}$$  \hspace{1cm} (11)

$$K_{\theta} = \frac{d \Gamma_{elm}}{d \theta_s} = 2 \Gamma_{\text{max} \cdot \cos 2 \gamma_o}$$  \hspace{1cm} (12)

Using equations (10), (11) and (14) leads to:

$$\Delta \Gamma_{elm} = 2 \frac{V_s \cdot T_e}{\Gamma_{elm}} \frac{\Gamma_{elm} \cdot \cos (\theta_e - \theta_m)}{\Gamma_{\text{max} \cdot \cos 2 \gamma_o}}$$  \hspace{1cm} (13)

This shows the feasibility torque control by a well selected vectors voltage $\sqrt{V_s}$. According to this strategy, the stator flux vector is required to rotate in both positive and negative directions. By this, even at very low shaft speed, large negative values of rotor angular frequency can be achieved, which are required when the torque is to be decreased very fast. Furthermore, the selection strategy represented in Table 2 allows good flux control to be obtained even in the low speed range. However, the high dynamic performance which can be obtained using voltage vectors having large components tangential to the stator vector locus implies very high switching frequency.

### Stator flux and torque estimation:

Basically, DTC schemes require the estimation of the stator flux and torque. The stator flux evaluation can be carried out by different techniques depending on whether the rotor angular speed (position) is measured or not. For sensorless application, the “voltage model” is usually employed\[6\]. The stator flux can be evaluated by integrating from the stator voltage equation.

$$\phi_s(t) = \int (V_s - R_s I_s) dt$$  \hspace{1cm} (14)

This method is very simple requiring the knowledge of the stator resistance only. The effect of an error in $R_s$ is usually quite negligible at high excitation frequency but becomes more serious as the frequency approaches zero\[6\].

Fig. 4 shows the deviation obtained at the end of the switching period $T_e$, which can be approximated by the first order Taylor Series as below.

$$\Delta \phi_s = \frac{V_s \cdot T_e \cdot \cos (\theta_e - \theta_m)}{\Gamma_{\text{max}}}$$  \hspace{1cm} (15)

$$\Delta \theta_s = \frac{V_s \cdot T_e \cdot \sin (\theta_e - \theta_m)}{\Gamma_{\text{max}}}$$  \hspace{1cm} (16)

$$\Delta T_e = \frac{V_s \cdot T_e \cdot \sin (\theta_e - \theta_m)}{\Gamma_{\text{max}}}$$  \hspace{1cm} (17)
The suitable flux level is then bounded by $E_{\phi}$. Alternative tables exist for specific operation mode. The switching table for the case of a two-level inverter is used to select the best output voltage depending on the position of the stator flux and desired action on the torque and stator flux. The electric torque is estimated from the stator flux amplitude and phase to obtain the required voltage vector selection. We can increase or decrease the flux as in fuzzy control schemes, by $E_{\phi}$.

Switching strategy for fuzzy controller: A switching Table is used to select the best output voltage depending on the position of the stator flux and desired action on the torque and stator flux. The flux position in the ($d$, $q$) plane is quantified in twelve sectors. Alternative tables exist for specific operation mode. The switching table for the case of a two-level inverter developed by I. Takahashi, permits easily to expand the optimal vector selection to include the larger number of voltage vectors produced by three-level inverter. The appropriate voltage vector is selected in the order to reduce the number of commutation and the level of steady-state ripple.

For flux control, let the variable $E_{\phi}$ ($E_{\phi}=\phi_{i}^*-\phi_{i}$) located in one of the three regions fixed by the constraints: $E_{\phi} < E_{\phi_{\text{min}}}$, $E_{\phi_{\text{min}}} \leq E_{\phi} \leq E_{\phi_{\text{max}}}$, $E_{\phi} > E_{\phi_{\text{max}}}$. The suitable flux level is then bounded by $E_{\phi_{\text{min}}}$ and $E_{\phi_{\text{max}}}$. The flux control is made by two-level hysteresis comparator. Three regions for flux location are noted, flux as in fuzzy control schemes, by $E_{\phi_{\text{norm}}}$ (negative), $E_{\phi_{\text{near}}}$ (zero) and $E_{\phi_{\text{near}}}$ (positive).

A high level performance torque control is required. To improve the torque control, let the difference $E_{\Gamma} = \Gamma_{\text{em}} - \Gamma_{s}$ belong to one of the five regions defined by the constraints:

- $E_{\Gamma} < E_{\Gamma_{\text{min2}}}$, $E_{\Gamma_{\text{min2}}} \leq E_{\Gamma} \leq E_{\Gamma_{\text{min1}}}$, $E_{\Gamma_{\text{min}}} \leq E_{\Gamma} < E_{\Gamma_{\text{max1}}}$, $E_{\Gamma_{\text{max}}} \leq E_{\Gamma} < E_{\Gamma_{\text{max2}}}$, $E_{\Gamma_{\text{max2}}} < E_{\Gamma}$.

The five regions defined for torque location are also noted, as in fuzzy control schemes, by $E_{\Gamma_{\text{nl}}}$ (negative large), $E_{\Gamma_{\text{ns}}}$ (negative small), $E_{\Gamma_{\text{z}}}$ (zero), $E_{\Gamma_{\text{ps}}}$ (positive small), $E_{\Gamma_{\text{pl}}}$ (positive large). The torque is then controlled by an hysteresis comparator built with two lower bounds and two upper bounds. The conventional DTC has been studied.

The fuzzy controller: Flux error $E_{\phi}$” torque error $E_{\Gamma}$” and flux position $\theta$” are used as inputs to the fuzzy controller, the inverter switching state “n” is the output of the controller. The three input variables are divided into their fuzzy segments. The membrane of fuzzy segments are chosen to have maximum control with a minimum number of rules. The grade of membership distribution of input variables into their fuzzy segments is shown in Fig. 5. The control rule is described by the input variables $E_{\phi}$, $E_{\Gamma}$ and $\theta_{s}$ and the control variable $n$ as:

- $R_{i}$: if $E_{\phi}$ is $A_{i}$, $E_{\Gamma}$ is $B_{i}$ and $\theta_{s}$ is $C_{i}$, $n$ is $N_{i}$

Switching strategy for fuzzy controller: The rules are formulated using the vector diagram for direct torque control and flux control of induction machine showed Fig. 4. The switching strategy in the order of the sector $\theta_{s}$, is illustrated by each table. The flux and torque control by vector voltage has in nature a desecrate behavior. In fact, we can easily verify that the same vector could be adequate for a set of value of $\theta_{s}$. The number of sectors should be as large as possible to have an adequate decision. For this reason, we propose a new approach for direct torque control using a three-level inverter based on twelve regular sectors noted by $\theta_{1}$ to $\theta_{12}$. A switching table is used to select the best output voltage depending on the position of the stator flux and desired action on the torque and stator flux. It is possible to expand the optimal vector selection to include the larger number of regular sectors and fuzzy segments of input variables.
There is a total of 180 rules, the control rule is described and developed using Mamdani’s minimum operation rule\(^9\).

\[ \mu_{N_i}(n) = \min(\alpha_1, \mu_{N_i}(n)) \]  
\[ \alpha_i = \min(\mu_A(E_\phi), \mu_B(E_r), \mu_C(\theta_i)) \]  

Where \( \mu_A, \mu_B, \mu_C \text{ and } \mu_N \) are membership function of sets A, B, C and N of the variables \( E_\phi, E_r, \theta \text{ and } n \) respectively. Thus the member function \( \mu_N \) of the output \( n \) (i.e., the \( N \)th rule) is point wise given by:

\[ \mu_{N_i}(n) = \max_{i=1}^{180} (\mu'_{N_i}(n)) \]  
\[ \mu_{Nout}(n) = \max_{N=1}^{19} (\mu_N(n)) \]  

The maximum criterion method is used for defuzzification, the outputs are crisp in this case because the flux and torque control by vector voltage has in nature a discrete behavior.

The fuzzy output which has the maximum possibility distribution, is used as control output. Then output = Nout.

Performances of the two-level current rectifier-three-level voltage inverter-induction motor cascade: We study the complete cascade composed by the induction machine fed by three-level inverter VSI-NPC controlled by FDTC strategy and two-level PWM current rectifier. In addition to solve the problem of the instability of the output DC voltages of the rectifier, we introduce in the cascade a feedback control using IP regulator, Fig. 6.

\[ \begin{align*}
\mu_{N_i}(n) & = \min(\alpha_1, \mu_{N_i}(n)) \\
\alpha_i & = \min(\mu_A(E_\phi), \mu_B(E_r), \mu_C(\theta_i))
\end{align*} \]  

Fig. 6: Two-level PWM rectifier, feedback linear control, filter, three-level inverter VSI NPC, induction motor

Fig. 7: Two-level current rectifier structure
The strategy algorithm is given as follows:

- \( F_i^{k+1} = 0 \) if \( I_{net} > I_{refi} + h \)
- \( F_i^{k+1} = 1 \) if \( I_{net} < I_{refi} - h \)

Where \( F_i^k \) : Value of \( F_i \) at \( k \)-th iteration

\( F_i^{k+1} \) : Value de \( F_i \) at \( K+1 \)-th iteration \( h \): hysteresis band width

**Voltage control loop model:** To improve the input voltages of the three-level NPC inverter, we propose to use a linear control loop with IP regulator to maintain equal the different input DC voltages of the inverter.

The modelling of this loop is based on the principle of conservation of the instantaneous power with the rectifier’s hypothesis without losses; this loop imposes the currents of network reference.

- **Input power:**
  
  \[ P_i = \sum_{k=1}^{K} \left( V_{net} \cdot I_{net} - R_i I_{net}^2 - \frac{L \cdot dI_{net}^2}{dt} \right) \]  

- **Output power:**
  
  \[ P_o = U_c \cdot I_{rect} = U_c \cdot (I_c + I_{ch}) \]

  Using the principle of instantaneous power conservation and by neglecting the Joule’s losses in the resistance, we can write:

  \[ \sum_{k=1}^{K} V_{net} I_{net} = \frac{L}{2} \frac{dI_{net}^2}{dt} + U_c I_{rect} \]  

  While supposing the currents of the network sinusoidal and in phase with their voltages, we can write then:

3. \( E_{eff} \cdot I_c = U_c \cdot I_{rect} \)

With:

- \( V_{net} = \sqrt{2} E_{eff} \cdot \sin(k \omega E_2 V) - 2 \pi \frac{2}{3} (k-1) \)
- \( I_{net} = \sqrt{2} I_c \cdot \sin(k \omega E_2 V - 2 \pi \frac{2}{3} (k-1) \)

**THE SIMULATION RESULTS**

The validity of the proposed DTC algorithm for three-level voltage source inverter is proved by the simulation results. The parameters of motors are given in the Appendix. The used flux and torque constraints
for the FDTC approach are expressed in percent with respect to the flux and torque reference values.

\[ E_{\phi_{\text{max}}} = 3\% , \quad E_{\phi_{\text{min}}} = -3\% , \quad E_{\Gamma_{\text{min1}}} = -0.8\% , \]
\[ E_{\Gamma_{\text{min2}}} = -3\% , \quad E_{\Gamma_{\text{max1}}} = 0.8\% , \quad E_{\Gamma_{\text{max2}}} = 3\% . \]

The simulation results illustrate both the steady state and the transient performance of the proposed torque control scheme. In the first part, we assume that FDTC is supplied by a battery of voltage \( V_d \). Fig. 11 shows the phase current and flux for steady state and transient operation at 9 N.m with 0.9 Wb when the input voltages are assumed constants \( (U_{c1} = U_{c2} = V_d/2) \). The waveform of the stator current is closely sinusoidal and the voltage \( V_{sd} \) is well distributed, probabilistic voltage harmonic analysis has been proposed in [10].

The trajectory of the flux is nearly a circle and answers more quickly, (7ms). Figure 12 (b) shows that the output torque reaches the new reference torque in about 2ms, fast torque response is obtained and a constant flux maintained during the torque reverse response from +9 N.m to -9 N.m and flux command at 0.9 Wb, and a well response is achieved in the other hand with a ramp reference Fig. 12 (a).

The FFT of the current waveform of phase (a) is shown in Fig. 13. The phase currents generated by the three-level inverter have low harmonic contents with FDTC system (5 % THD).

In the second part, we simulate the performances of the FDTC scheme associated to its supply for nominal references of the flux and torque without feedback control. The two-level rectifier is controlled by hysteresis technique with a band equal to \( h = 0.5 \) A, the reference input currents with nominal values at a frequency of 50 Hz, the parameters of the intermediate capacitors filter are: \( C_U = C_L = 10 \) mF, the input...
Fig. 14: The performances of the DTC drive associated to its supply with nominal references of the flux and torque.

Fig. 17: DC output voltage of the rectifier $U_{rect}$, intermediate voltage filters $U_{c1}$, $U_{c2}$ and their difference ($U_{c2} - U_{c1}$).

Fig. 18: The performances of the DTC drive associated to its supply at nominal references of the flux and torque with Feedback linear control.

voltages of the inverter are initialized to $U_{c1}= U_{c2} = 257$ V.

Fig. 14 shows that the magnitude of the voltage $V_{sd}$ increases gradually with the increase in the voltages of the intermediate filters ($U_{c1}$, $U_{c2}$). Consequently, the performances of control are degraded and the semiconductors are subjected to a commutation with high voltage; what produces failure of control, an increase in the losses due to commutation and breakdown of the semiconductors. In addition, the electromagnetic torque and stator flux oscillate around their nominal values (9 N.m and 0.9 Wb) without notable overtaking but with an important harmonic content.
It is noted in Fig. 15, that the input voltages of the three-level inverter are increasing and their difference is about 0.7V. This difference can reach the value of 10V in the case of the FOC control and then FDTC system has self-compensation by adequate selection of the vector voltages. The input currents of the three-level inverter \( I_{d1} \) and \( I_{d2} \) have the same shape, but reversed one compared to the other, the \( I_{d0} \) current has practically zero value, Fig. 16. Fig. 17 and 18 present the simulation results of the DC middle point voltage evolution and the performance of the DTC scheme when a feedback control is introduced in the cascade. The parameters of the IP regulator are: \( K_p = 700 \), \( K_p = 0.01 \). The input voltages of the inverter are initialized to \( U_{c1} = U_{c1} = 257V \) with \( C_{L} = C_{L} = 10mF \).

We note that: the difference of the input voltages of the rectifier decreases considerably, output voltages of the rectifier and intermediate filter voltages (\( U_{dc1}, U_{dc2} \)) are balanced. The progression of the magnitude of the output voltage of three-level inverter (\( V_{dc} \)) is clearly attenuated. Thus, the performances of FDTC control are highly improved with complete cascade. The electromagnetic torque and stator flux are then controlled at their nominal values with low ripple.

**CONCLUSION**

The direct torque control FDTC was introduced to give a fast and good dynamic torque and can be considered as an alternative to the field oriented control (FOC) technique. It is concluded that the proposed control produces better results for transient and the steady state operation than the conventional control.

In this study, a DTC systems using three-level GTO voltage source inverter was presented it is suitable for high-power and high-voltage applications. We enhance the DTC approach by introducing fuzzy logic controller. From analysis of these results establish the following remarks:

* The fuzzy logic approach has a fast torque and flux response as compared to the conventional DTC.
* The stator current wave form is more close to the suitable sinusoidal signal.
* Introducing a feedback linear control to solve the usual problem of unbalanced voltages input in three-level VSI-NPC can easily control the neutral point voltage. From this analysis high dynamic performance, good stability and precision are achieved; the results obtained are full of promise to use this system in high voltage and great power applications as electrical traction.

**Appendix A: Induction motors parameters:**

- Rated power: 1.5 kW
- Rated voltage: 220 V
- Rated speed: 1420 rpm
- Rated frequency: 50 Hz
- Rated current: 3.64 A (Y) and 6.31 (Δ)
- Stator resistance: 4.85 Ω
- Rotor resistance: 3.805 Ω
- Stator inductance: 0.274 H
- Rotor inductance: 0.274 H
- Magnetizing Inductance: 0.258 H
- Number of poles: 4
- Rotor inertia: 0.031 Kg.m²
- Friction Coefficient: 0.008 N.m.s/rd
- \( V_{dc} = 514V \); \( Te = 100 \mu s \)

**REFERENCES**