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A Study ofDirect Torque Control for Three-Level InverterFed Induction Motor Drive

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Abstract: This paper offers the comparative evaluation of various level of multilevel inverter for induction motor torque rippleminimization.A three-stage neutral-factor-clamped inverter-fed induction motor power is proposed in this paper. Thetraditional direct torque manipulate (DTC) switching desk fails to remember the circuit barriers, equivalent to neutralpoint-balance and gentle vector switching, brought on by using the topology of a 3-degree inverter. Two sorts of modified schemes for three-level DTC are proposed to resolve these problems. They provide performance enhancement at the same time keeping robustness and simplicity.In the present undertaking the DTC is carried out by way of using area vector pulse width modulation (SVPWM) methodin an effort to acquire gentle operation of pressure. The obstacle of big beginning present will also be investigated and solved by introducing the system of preexcitation. The effectiveness of the proposed schemes is demonstrated through simulation making use of MATLAB/SIMULINKimplementation and experimental validation.

Keywords-AC motor drives, adaptive observer, induction motor (IM) drives, three-levelinverter, torque control

I. INTRODUCTION

The direct torque control (DTC) method has emerged as analternative to Field Oriented Control (FOC) method for highperformance ac drives since it was firstly proposed in the mid-1980 [1-2]. The merits of DTC are fast torque response, simplestructure (no need of complicated coordinate transformation,current regulation or modulation block), and robustness againstmotor parameter variation [3-7].On the other hand, multi-level inverters have become avery attractive solution for high power application areas [8-11].The three-level Neutral Point Clamped (NPC) inverter is one ofthe most commonly used multi-level inverter topologies in highpower ac drives. By comparing to the standard two-levelinverter, the three-level inverter presents its superiority in termsof lower stress across the semiconductors, lower voltagedistortion, less harmonic content and lower switchingfrequency [12]. Due to the above mentioned merits, the threelevel inverter fed DTC motor drive has become an importantresearch topic in research and academic community over thepast decade [13-21].

A variety of techniques have been proposed to overcomesome of the drawbacks present in DTC [22]. Some solutionproposed are: DTC with the Space Vector Pulse WidthModulation (SVPWM)) [23]; the use of a duty-ratio controllerto introduce a modulation between active vectors chosen fromthe look-up table and the zero vectors [24-25]; use of artificialintelligence techniques, such as neuro-fuzzy controller withSVPWM [26-28]. However, the complexity of the control isconsiderably increased.Among various modulation techniques for a multi-levelinverter, SVPWM is an attractive candidate due to thefollowing merits. It directly uses the control variable given bythe control system and identifies each switching vector as apoint in complex space. It is suitable for Digital SignalProcessor (DSP) implementation and able to optimizeswitching sequences.switching.In this paper, Direct Torque Control-Space VectorModulation (DTC-SVM) with three-level NPC voltage sourceinverter is investigated. The proposed scheme is describedclearly. Simulation and experimental results are reported todemonstrate its effectiveness. The entire control scheme isimplemented using Matlab/Simulink and hardware realizationis done using dSPACE. The simulation and experimentalresults of the proposed scheme are found to be in closeagreement, thereby indicating the feasibility of the proposedscheme in giving fast control of the induction motor torque.

II. PRINCIPLE OF DTC AND THREELEVEL INVERTER

A. Three-Level Inverter

The main circuit of a three-level inverter isillustrated in Fig.1 and there are three states for onephase output: +Udc/2, 0, and−Udc/2, with the neutralpoint as reference. To be more universal, the negativedc bus voltage will be selected as reference ground,and the three states are indicated by "2," "1," and "0," for "+Udc/2," "0," and "−Udc/2," respectively. More output levels provide more freedom in vector selectionand it is possible to synthesize waveforms that aremore sinusoidal in shape. However, the complexity ofvector selection rises with the number of vectors. Inaddition, there are further problems, including neutralpoint balance and smooth vector switching, whichneed to be carefully solved.

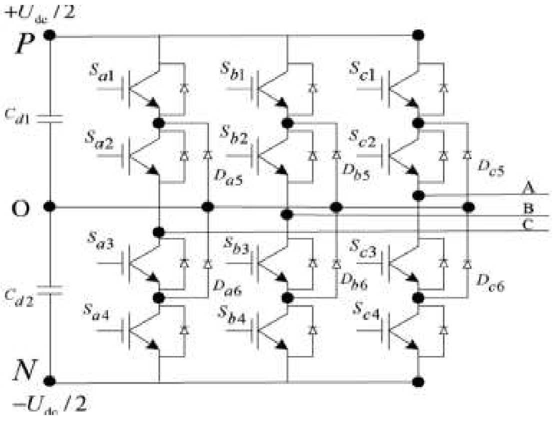


Fig.1 basic three level inverter

B. Basic Principle of DTC

A mathematical model of an IM described byspace vectors in a stationary frame can be expressed asfollows

$u_s = R_s\ i_s + p\ \psi_s$……………………………2.1

$0 = R_r i_r + p\ \psi_r - j\omega_r \psi_r$………………… 2.2

$\psi_s = L_s\ i_s + L_m i_r$………………………2.3

$\psi_r = L_m i_s + L_r i_r$……………………….2.4

where u_s , is, i_r , ψ_s , and ψ_r are the statorvoltage vector, stator current vector, rotor currentvector, stator flux linkage vector, and rotor fluxlinkage vector, respectively; R_s , R_r , L_s, L_r , andL_m are the stator resistance, rotor resistance, statorinductance, rotor inductance, and mutual inductance,espectively; and ωr is the rotor speed and p = d/dtisthe differential operator.From the stator voltage equation (2.1), it canbe seen that, by omitting the stator resistance voltagedrop, the stator flux can be controlled directly fromthe stator voltage. The electromagnetic torque can beobtainedfromwhereδsr is the spatial angle between thestator and rotor fluxes, Np is the motor pole-pairnumber, and T_e is the electromagnetic torque. In DTC,the amplitude of the stator flux is kept constant and afast torque response is obtained by changing angle δsrquickly. From (2.1)–(2.4), the relationship betweenthe stator and rotor fluxes can be obtained aswhere $\sigma = 1 - L_2\ m/(L_s L_r\ )$ and $T_r = L_r/R_r$.

$$P\ \psi r + \left(\frac{1}{\sigma\ Tr} - jWr\right)\psi r = \frac{Lm}{\sigma\ LsTr}\ \psi s \qquad \text{….(2.5)}$$

Equation(2.5) indicates that the dynamic response of the rotorflux is a first-order lag with respect to the stator flux,so the torque can be changed quickly by changing theangle of stator flux.

III. TORQUE AND FLUX RIPPLEREDUCTION IN DTC

The conventional switching table for twolevel DTC cannot be directly extended to three-levelDTC. This is because it is not only the performancethat is of concern, the limitation caused by thetopology of three-level inverter also should beconsidered. Two kinds of scheme for three-level DTCare proposed in this paper to solve these problems.

A. DTC Method – I:

The first DTC scheme utilizes the vectors ofthe three-level inverter directly and inserts appropriateintermediate vectors to meet the demand of neutralpoint balance and smoothed vector switching.Theswitching principle is described in detail in thefollowing. First, the vector is selected according to thedemand of the flux and torque; vector switching andneutral point balance will be considered later. Fig.2shows the space vector diagram for a three-level DTCcontrol strategy and its sector division. The 27 vectorsare marked by V1,V2 . . .V27. There are 12 sectorsand the shadowed area is the first sector, which isdifferent from that of the conventional two-level DTC.The basic principles of the vector selection are shownin Table.1 and these meet the demands of the fluxand torque; k represents the stator flux located in kthsector. In addition, "↑" means increase, "↓"means decrease, and "="means no change is needed.

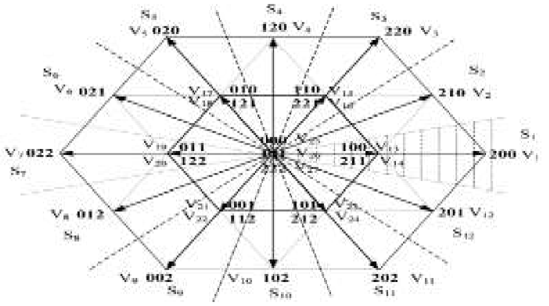


Fig.2 Space vectordiagram for thethree-level DTC

Table.1 Vector selection table for threelevelDTC

Flux	Torque	Selected vector number
↑	↑	k+2
	=	26
	↓	k-2
↓	↑	k+4
	=	26
	↓	k-4
↑	↑	k+3
	=	26
	↓	k-3

It should be noted that there may exist morethan two vectors to meet the demands of the flux, andthe one which meets the torque response better ispreferred. However, in many cases, the selected vectorusually cannot meet the requirements of the vectorswitching and neutral point balance, which means thatthe selected vector cannot be applied to the three-levelinverter directly.

For example, suppose the stator flux islocated in the first sector, and the working voltagevector at the moment is V_1(200). To increase the statorflux and torque, according to Table.1,V_3(220)would be selected. But there is a high-voltage jump inphase B from 0 to 2, which should be avoided. In thiscase, V_2(210) will be inserted as an intermediatevector to smooth the high-voltage jump.

There are three aspects with respect tovoltage jumps: 1) phase voltage jump, 2) line voltagejump, and 3) three-phase jump at the same time.High-voltage jump increases harmoniccontent and the stress across power semiconductors,which negates the advantages of the three-levelinverter. To overcome this problem, an appropriateintermediate vector should be inserted to meet therequirement of the voltage jump.

Another issue is the problem of neutral pointbalance, which is inherited from the topology of threelevel inverter. Neutral point balance is mainlycontrolled by selecting appropriate small vectors; thisis because of the opposite effects of redundant vectors.In this paper, we also adopt the redundantstates of small vectors to keep the neutral pointbalance.The final vector selection rules are obtainedby considering the aspects introduced earlier, and theprinciples are summarized as follows.

Step I: Select vector according to the demands forflux and torque, which are listed in Table.1.

Step II: If the selected vector cannot meet therequirement of the voltage jump and neutral pointbalance, an appropriate intermediate vectorwill be inserted.

The principles for selecting the intermediate vectorsare as follows.

1) Large vectors or middle vectors should be selectedpreferably to increase the utilization ratio ofthe dc bus.

2) Middle vectors can switch to adjacent smallvectors and large vectors freely.

3) Large vectors can switch to the small vectors inthe same spatial orientation.

4) Small vectors can switch to zero vectors freely.

5) When small vectors are available, select the one,which can meet the requirement of neutralPoint balance. Using the steps earlier, anappropriate vector can be selected to meet thedemand of the flux and torque, as well as therequirement of voltage jump and neutral pointbalance, which ensures the safe operation of thethree-level inverter.

B. DTC Method - II

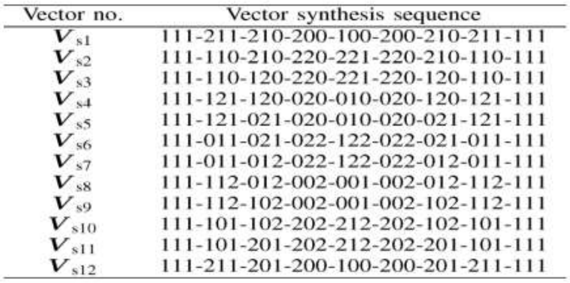
In DTC method-I, by inserting theappropriate intermediate vector, the problems ofneutral point balance and smooth vector switchingwere solved. However, it may degrade theperformance of torque and increase the complexity ofvector selection, so anotherscheme is proposed here.

Method - II makes use of synthesizingvectors, which is termed discrete space vectormodulation (SVPWM). This was first proposed intwo-level DTC. The two-level SVPWM-DTCincorporates a more complicated and accurateswitching table by dividing one sampling period intotwo or three intervals, and thus, more vectors areobtained.

Speed is also taken into account and morelevels of hysteresis are adopted to make the switchingtable more accurate. The benefits of SVPWM-DTCare reduced torque and flux ripple at a little extraexpense of computational time.This paper extends SVPWM to three-levelDTC by using synthesizing vectors and the main aimof introducing SVPWM is to solve the problems ofneutral point balance and smooth vector switching. Toreduce the complexity of the algorithm, the samestructure as Table.1 is adopted and the speed was nottaken into account in the switching table. First, weshould synthesize some vectors, which are expected tosolve the problems of neutral point balance andsmooth switching between any two vectorssimultaneously.This means that the vector selection,according to the need of the torque and flux, isdecoupled from the circuit limitation introduced by thethree-level topology. A series of novel synthesizingvectors are produced, which are illustrated in Fig.3and marked by Vs1, Vs2, . . . , Vs12.Take Vs1 , for example, it is synthesized bythe nearest three vectors, namely, V1(200), V2 (210),and V13/V14 (100/211). The duration time of eachvector can be calculated easily by utilizing theprinciple of volt-second balance. To smooth the vectorswitching, zero vector V26(111) is incorporated at thebeginning and ending of each synthesize sequence,taking up 10% or less duty of the whole period.

The 12 synthesizing vectors are distributeduniformly in the fixed-angle space (15° for Vs1) withconstant or variable amplitude.In this paper, constant amplitude for thesynthesis vector is selected for simplicity, so theduration of each vector in Vs1 ,Vs2 , . . . ,Vs12 can beobtained offline and stored in a look-up table for realtime implementation. The final synthesizing vectorsare listed in Table.2 and the sector division for threelevel DTC is presented in Fig.3, which has a 15°shift compared to that in Fig.2

Table.2novel vector synthesis



Vector no.	Vector synthesis sequence
V_{s1}	111-211-210-200-100-200-210-211-111
V_{s2}	111-110-210-220-221-220-210-110-111
V_{s3}	111-110-120-220-221-220-120-110-111
V_{s4}	111-121-120-020-010-020-120-121-111
V_{s5}	111-121-021-020-010-020-021-121-111
V_{s6}	111-011-021-022-122-022-021-011-111
V_{s7}	111-011-012-022-122-022-012-011-111
V_{s8}	111-112-012-002-001-002-012-112-111
V_{s9}	111-112-102-002-001-002-102-112-111
V_{s10}	111-101-102-202-212-202-102-101-111
V_{s11}	111-101-201-202-212-202-201-101-111
V_{s12}	111-211-201-200-100-200-201-211-111

From Table.1, it isseen that the switching between any arbitrary twovectors or adjacent vectors in a synthesis sequence aresmooth. The neutral point balance can be solved byadjusting the “lasting time” of the small vectors in onesampling period. Taking Vs1 as an example, 211 and100 are a pair of small vectors and their total "lasting time" is fixed during one sampling period, but their individual working time can be arranged according tothe requirement of neutral point balance.

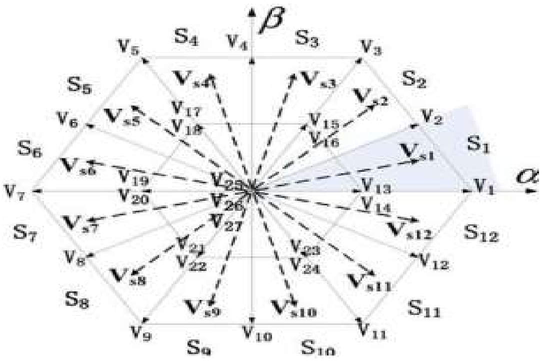


Fig.3 synthesis vector diagram

DTC method-II employs the same switchingtable, as shown in Table.1, except that the selectedvector is replaced by the novel synthesis vector listed in Table.2. For example, if the selected vector number is k according to Table.1, the synthesizedvectorVsk will be selected as the output vector, andnumber 26 means the zero vector 111.For DTC method-I, a further step-II shouldbe taken before the final vector is selected; however,this process is not needed in method-II, whichsimplifies the selection of vector. An example ofswitching pattern for the two kinds of DTC method isillustrated in Fig.4. It is seen that for DTC methodI, there is only one vector in one sampling period,while there is a sequence of vectors for DTC method -II, with 111 as the beginning and ending.

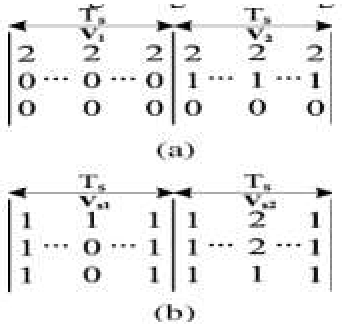


Fig.4 Example of switching pattern.(a) DTCmethod I. (b) DTC method II.

IV. SIMULATION AND RESULTS

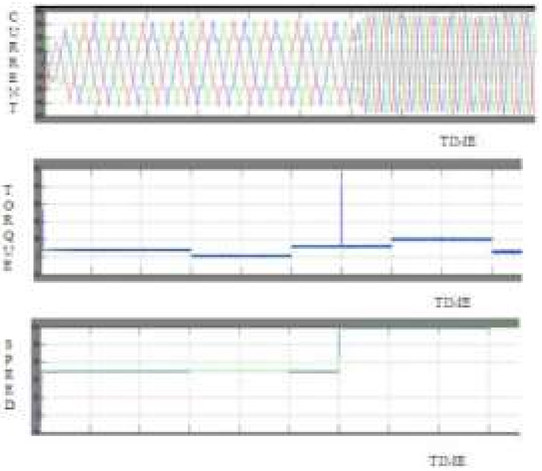


Fig.4Starting response of DTC method I with pre excitation.

In Fig.4, the stator fluxis first established by using the pre excitationtechnique, which can be seen from the upper half in Fig.4. The motor then accelerates up to 1200 r/minwith the permitted maximum torque. The maximumstarting current is restricted to 7.5 A; this valuereaches almost 27A without pre excitation. The statorflux is established with current limitation beforestarting the motor, so sufficient torque can beproduced, which may result better dynamicperformance. However, the dynamic responsedifference between the one with and without preexcitation is not significant, if the pre excitation timeis excluded; this is because the stator flux can beestablished in several milliseconds,unfortunately, at the expense of large current.

V. CONCLUSION

Two types of modified DTC schemes havebeen proposed in this paper and both achieve highperformance control of a three-level inverter-fedmotor drive. They both work over a wide speed rangeand overcome the limitations caused by the topologyof the three-level inverter. By using appropriateintermediate vectors, the problems of neutral pointbalance and smooth vector switching are solved.Furthermore, a novel vector synthesis sequence wasproposed and this decoupled the performance controlfrom the circuit limitation.

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