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Direct Torque Control of Induction Motor Drive Fed from a Photovoltaic Multilevel Inverter

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Abstract:
This paper presents Direct Torque Control (DTC) using Space Vector Modulation (SVM) for an induction motor drive fed from a photovoltaic multilevel inverter (PV-MLI). The system consists of two main parts PV DC power supply (PVDC) and MLI. The PVDC is used to generate DC isolated sources with certain ratios suitable for the adopted MLI. Beside the hardware system, the control system which uses the torque and speed estimation to control the load angle and to obtain the appropriate flux vector trajectory from which the voltage vector is directly derived based on direct torque control methods. The voltage vector is then generated by a hybrid multilevel inverter by employing space vector modulation (SVM). The inverter high quality output voltage which leads to a high quality IM performances. Besides, the MLI switching losses is very low due to most of the power cell switches are operating at nearly fundamental frequency. Some selected simulation results are presented for system validation.
KEY WORDS: Direct Torque Control, Induction Motor drive, hybrid multilevel inverter, PVDC power supply, SVM.

I. INTRODUCTION

After the invention of DC motor controller for speed and torque control, DC machine again back in action till development in power electronics for induction motor. Because of power electronics drive technology, induction motor becomes main workhorse of industry. Those were scalar control methods which has good steady state response but poor dynamic response. To achieve good dynamic response as well as good steady state response, vector control was introduced. But it has complexity in construction and control. In recent years several studies have been carried out for the purpose to find out alternative solution of field oriented control drive to achieve accurate and fast response of flux and torque and also to reduce the complexity of the control system of the drive. This was "direct torque control" or "direct torque and flux control" drive.

Since, DTC (direct torque control) introduced in 1985, the DTC was widely use for Induction Motor Drives with fast dynamics. Despite its simplicity, DTC is able to produce very fast torque and flux control, if the torque and the flux are correctly estimated, is robust with respect to motor parameters and perturbations [1], [2], [3]. Unlike FOC (field oriented control), DTC does not require any current regulator, coordinate transformation and PWM signals generator. In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. The problem is to quantify how good the torque control is with respect to FOC. In addition, this controller is very little sensible to the parameters variations in comparison with FOC [4], [5]. FOC makes decoupling of stator current to produce independent control of torque and flux. FOC is very sensitive to flux variations, which is mainly affected by parameter variations. It is greatly influenced on the performance of induction motor. Instead of FOC, DTC directly control flux and torque without depending on parameter variation [6].

In recent years, there has been great interest in multilevel inverters (MLIs) technology. Special attention has been paid for cascaded H-bridge inverter [7] – [11]. Generally, there are many advantages in the applications of MLIs inverters over conventional two-level inverters. The series connection of power converter modules reduces the voltage stress of each converter module (or increases the voltage capability of the overall converter structure). Besides, the resolution of the staircase waveform of the output voltage increases with the number of voltage steps of capacitor voltage sources available in the multilevel inverter. As a result of the improved resolution in the voltage harmonic content, filtering efforts and the level of the electromagnetic interference (EM) generated by the switching operation of the converter can be reduced.

The use of photovoltaic (PV) modules as a source of renewable energy is gaining attention nowadays. PV modules may be operated as isolated system (standalone system) or grid connected, in both cases it must be connected to an inverter to convert the generated dc power into ac power. The dc voltage of the PV is low which requires a pre-stage boost dc-dc converter to generate a suitable high input voltage for the inverter. Looking to the background, the PV can be used to feed the induction motor as [12] – [14]. Therefore FOC and DTC can be applied for multilevel inverter-fed from PV systems. Only the modulation method has to be upgraded to multilevel pulse width modulation (PWM) (with multiple carrier arrangements) or multilevel space vector modulation (SVM).

In this paper DTC drive for an IM based hybrid multi level inverter (HMLI) fed from PV panels has been developed using MATLAB SIMULINK. Stator current, rotor speed, electromagnetic torque and flux plot which show the performance of DTC with HMLI. DTC has also track the required speed and torque successfully which represents the successful design of the DTC drive.

II. The PVDC Power Supply

Figure 1 shows the PVDC, it consists of a PV module BP485 [15] type, MPPT control, high frequency transformer (HFT). The dc source of the main inverter unit is generated from the PV module as shown in figure 1. It consists of PV module which is the main unregulated dc source, dc-dc converter accompany with maximum power point tracking control required for catching the maximum available power from the PV module. To catch the maximum power from the PV module, the conventional perturb and observe (P&O) control method [16] – [17] has been adopted in this work. 2.3 kW PV module composed of string of about 30 units of BP485 connected in series has been chosen with nominal values for single unit is given in table I.

Figure (2) shows the (HFT) transform [8] which is a step down with 2/1 turn ratios which are suitable for this specific application and MLI. The main task of this HFT is to generate the dc source of the auxiliary inverter units from the main transformer unit dc source. By this method, an inherit voltage balancing between the main and auxiliary inverter units is obtained which is very important. This balancing will result in simplifying the control system.

Figure 2 shows the MATLAB/SIMULINK photovoltaic performances, current, voltage and power.

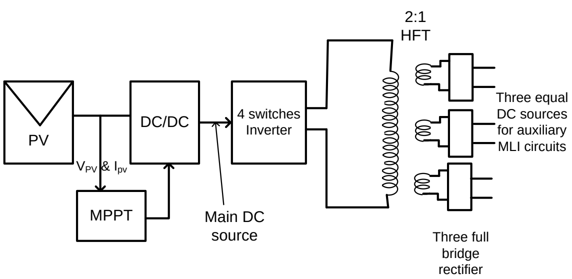

Figure 1 the PVDC power supply

Table I. PV module BP485 specifications

Rated Power (P_{max})	85W
Voltage at P_{max} (V_{mp})	17.4V
Current at P_{max} (I_{mp})	4.9A
Short circuit current (I_{sc})	5.48A
Open circuit voltage (V_{oc})	22V

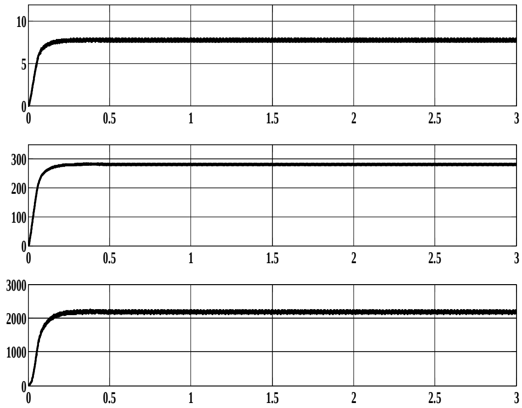

Figure 2 PV current, voltage and power

III. The Hybrid MLI Power Circuit

Figure 3 shows the general three phase configuration of the hybrid multilevel inverter topology with lower power component elements for 4 levels [7]. This inverter is composed of single unit of main stage, 3 units of auxiliary stages, '12' switches and '4' isolated dc voltage sources. The auxiliary stages are connected in series with the main stage. The main stage is a conventional two-level three-phase six switch inverter. Each auxiliary cell consists of two switches and single dc input voltage. The basic auxiliary cell of the proposed inverter includes two switches are always operating in a complementary mode and single input dc voltage to generate two levels output voltage waveform 0 and its input dc source. Therefore the auxiliary cell gives $V_o = 0$, when the switch S_1 is ON and it gives its input voltage when S_1 is OFF. To avoid short circuit condition, it should be kept in mind that both of the switches (S_1 and S_2) never be switched on at a time.

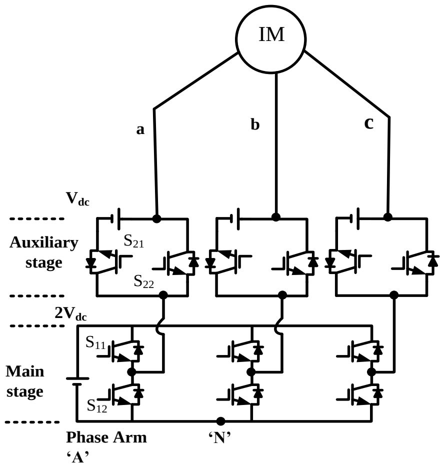

Figure 3 Four level line-to-line hybrid MLI

Using three auxiliary cells with the main cell results in generating 4 levels output pole voltage and 7 levels for the line-to-line-voltage. It can be noted that the main cell dc source is 2 V_{dc} and the auxiliary cell dc source is V_{dc}, respectively, therefore V_{aN} has 4 states (0, V_{dc}, $2V_{dc}$, $3V_{dc}$). The load line-to-line voltages can be calculated as follows

$$v_{ab} = v_{aN} - v_{bN} \tag{1}$$

Therefore the load line-to-line voltages can have ($3V_{dc}$, $2V_{dc}$, $1V_{dc}$, 0, $-1V_{dc}$, $-2V_{dc}$, $-3V_{dc}$). And the load phase voltages $V_{an,}$ V_{bn} and V_{cn} can be calculated as in (2)

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} v_{aN} \\ v_{bN} \\ v_{cN} \end{bmatrix} \tag{2}$$

Table II summarizes the output voltage levels for 4 levels using only single auxiliary cell with the main cell. The space vector as described in [7] will be employed which is the convenient modulation control to DTC.

TABLE II
Switching States of phase V_{aN}

MLI Pole voltage	**Switches of arm 'A'**					
v_{aN}	**Sa11**	**Sa12**	**Sa21**	**Sa22**	**Sa31**	**Sa32**
$0V_{dc}$	0	1	0	1	0	1
$1V_{dc}$	0	1	0	1	1	0
$2V_{dc}$	0	1	1	0	0	1
$3V_{dc}$	0	1	1	0	1	0

IV. DIRECT TORQUE CONTROL PRINCIPLES

Direct torque control principles were first introduced by Depenbrock and Takahashi. In this method, Stator voltage vectors are selected according to the differences between the reference and actual torque; reference and actual stator flux linkage. The DTC method is characterized by its simple implementation and fast dynamic response. Furthermore, the inverter is directly controlled by the algorithm, i.e. a modulation technique for the inverter is not needed. The main advantages of DTC are absence of coordinate transformation and current regulator; absence of separate voltage modulation block. Common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up.

Figure 4 shows the schematic of the basic functional blocks used to implement the DTC of induction motor drive. A MLI supplies the motor and it is possible to control directly the stator flux and the electromagnetic torque by the selection of optimum inverter switching modes. This control strategy uses two level inverter suggested by Takahashi, to control the stator flux and the electromagnetic torque of the induction motor.

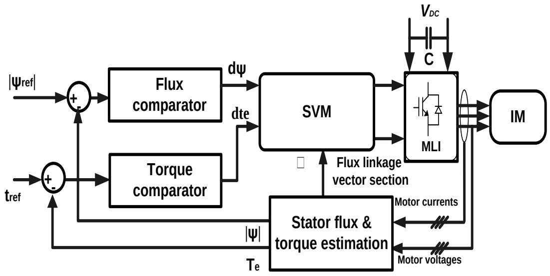

Figure 4 Block diagram of basic DTC drive

The DTC scheme consists of torque and flux comparator (hysteresis controllers), torque and flux estimator and a switching table. It is much simpler than the vector control system due to the absence of coordinate transformation between stationary frame and synchronous frame and PI regulators. DTC does not need a pulse width modulator and a position encoder, which introduce delays and requires mechanical transducers respectively. DTC based drives are controlled in the manner of a closed loop system without using the current regulation loop. DTC scheme uses a stationary d-q reference frame having its d-axis aligned with the stator q-axis. Torque and flux are controlled by the stator voltage space vector defined in this reference frame [18]. The basic concept of DTC is to control directly both the stator flux linkage and electromagnetic torque of machine simultaneously by the selection of optimum inverter switching modes. The DTC controller consists of two hysteresis comparator (flux and torque) to select the switching voltage vector in order to maintain flux and torque between upper and lower limit. DTC explained in this paper is closed loop drive. Here flux and torque measured from the induction motor using proper electrical transducer.

Then flux and torque errors are found out by equation (3) and (4).

$d\Psi = \Psi ref - \Psi$ (3)

$dte = tref - te$ (4)

Using flux and torque comparator flux and torque command obtained respectively therefore the stator voltage reference vector can be obtained too [2] as follows.

$$v_{REF} = \frac{d\psi}{dt} \quad (5)$$

The reference voltage (5) can be used helpfully to generate switches pulses of inverter [7].

V. Determination of Switching Times of Inverter Switches

Generally, every switching state creates specific three-phase voltages v_{aN}, v_{bN} and v_{cN} with respect to the neutral of the dc bus voltage, which can be defined by the equation (4):

$$\begin{aligned} v_{aN} &= k_a V_{dc} \\ v_{bN} &= k_b V_{dc} \\ v_{cN} &= k_c V_{dc} \end{aligned} \quad (6)$$

Where k_a, k_b and k_c $\in$ [0, 1, 2, 3, …, $+(2^k - 1)$] and switching states of inverter line-to-line voltages v_{ab}, v_{bc} and v_{ca} can be calculated by equation (7).

$$\begin{aligned} v_{ab} &= (k_a - k_b)\, V_{dc} = k_{ab} V_{dc} \\ v_{bc} &= (k_b - k_c)\, V_{dc} = k_{bc} V_{dc} \\ v_{ca} &= (k_c - k_a)\, V_{dc} = k_{ca} V_{dc} \end{aligned} \quad (7)$$

Equation (7) can be expressed in a matrix form as follows

$$\begin{aligned} V_{l-l(k_{ab}, k_{bc}, k_{ca})} &= [v_{ab} \quad v_{bc} \quad v_{ca}]^T = \\ &= V_{dc} \quad [(k_a - k_b) \quad (k_b - k_c) \quad (k_c - k_a)]^T \end{aligned} \quad (8)$$

Where k_{bc}, k_{bc} and k_{ca} $\in$ [- $(2^k - 1)$, …, -3, -2, -1, 0 , 1, 2, 3, ……, $(2^k - 1)$]. The vector form of the line-to-line reference voltage vector in steady state is

The inverter line-to-line reference voltage vector demanded by the control algorithm in equation (5) is ampled at the low rate of switching frequency f_s. The sampling interval $T_S = \frac{1}{f_S}$ extends over three subcycles t_1, t_2 and t_3. V^*_{REF} is an arbitrary complex quantity and it cannot be generated by the inverter. Therefore it is approximated by the available voltage space vectors given by equation (8), where during each modulation subcycle a switching sequence is generated. Consequently the inverter pole voltages v_{an}, v_{bn} and v_{cn} can be evaluated as well as switches states. Looking to equation (6), it can be noted that k_a has a direct relationship with the inverter pole voltage and therefore the lookup table II is used to generate switches pulses for this MLI. The detailed analyses is provided in [7].

VI. Simulation Results

In this paper for case study, 3HP, 220V, 50 Hz, 3-phase induction motor used for simulating DTC drive. Induction motor parameters are given in table III.

The required speed is 1500 rpm and required torque is 12 N.m to which drive has to track. DTC of induction motor is simulated for the sample time of 2e-6 second. Simulation time is 5 second. A step change with two case studies has been done in speed and in torque individually.

Table III induction motor parameters

Stator resistance (Ohms)	0.435
Stator inductance (Henry)	2.0e-3
Rotor resistance (Ohms)	0.816
Rotor inductance (Henry)	2.0e-3
Mutual inductance (Henry)	69.31e-3
Inertia	0.089
Friction Factor	0
Pairs of poles	2

The simulation results are done at rotor speed 1500 rpm and load torque changed from no load to full load torque at time instant t= 3 sec.

In this configuration, main objective is to design DTC controller for hybrid multilevel inverter fed IM drive. Required signal for this controller is obtained from the speed controller. First the stator flux magnitude and angle is obtained from the measurement. Torque and flux error is obtained, from which drive can decide either flux has to increase or decrease, also torque has to increase, decrease or remains constant. From the stator flux angle, sector will decided.

Figure 5 shows the d-q stator flux in the stationary reference frame. Figures 6 and 7 show the IM speed and torque profiles due to this specific loading condition. They give the conventional and well-know profiles, the torque tracks its reference with a very good performance. On the other hand, the speed builds up with a good performance.

Figure 8 and 9 show the hybrid MLI performances, they show the line-to-line voltages and the IM currents, respectively. The dc voltages of isolated batteries for the inverter have been chosen

150V and 300V, therefore their dc sum is 450 V. As mentioned before the load line-to-line voltages has ($3V_{dc}$, $2V_{dc}$, $1V_{dc}$, 0, $-1V_{dc}$, $-2V_{dc}$, $-3V_{dc}$). Figure 9 shows the motor currents which are very almost sinusoidal due to the high quality of the hybrid MLI output voltage and the natural low-pass load filter of the motor.

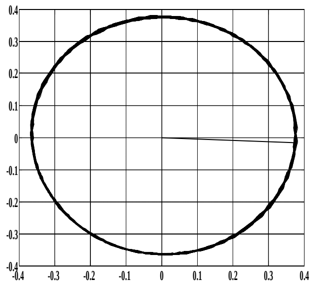

Figure 5 d-q plot Stator flux

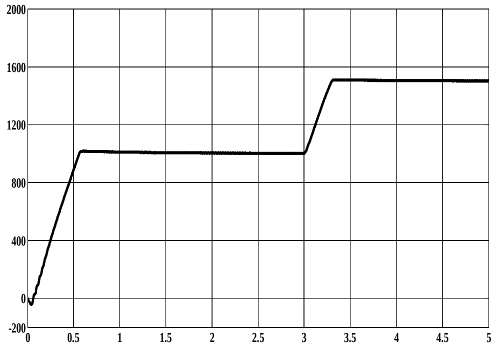

Figure 6 Motor speed

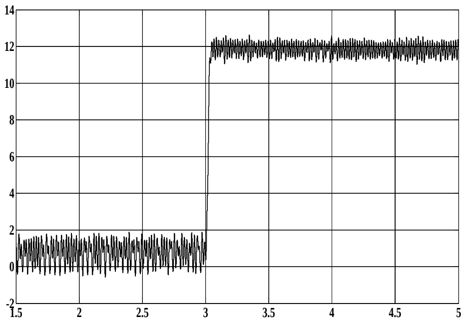

Figure 7 Motor Torque response

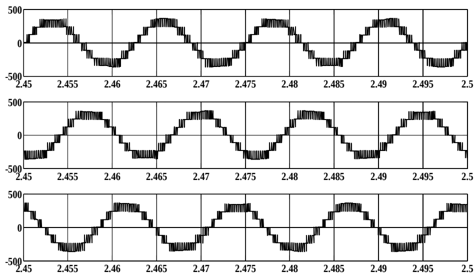

Figure 8 line-to-line inverter output voltages

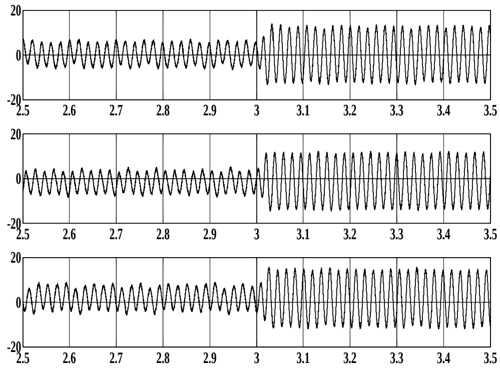

Figure 9. Stator currents

VII. CONCLUSION

Torque and flux control for induction motor drives are presented. The DTC drive which has been employed has achieved the reference speed and torque properly. Also ripples in torque and stator currents are very small due to the high quality of the hybrid MLI used as a power circuit. The IM is power using PV module as an renewable energy source. The provided simulation results show that the DTC drive works successfully.

Another achievement of the power circuit is the reduced switching losses of the hybrid MLI and thus increasing overall system performances.

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