

K Direct Torque Control of Induction Motor Using Space Vector Modulation (SVM- DTC)

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Abstract: In this study, direct torque control (DTC) of induction motor is evaluated based on space vector modulation (SVM). DTC is a method to control machine with utilizing torque and flux of motor controlled. The torque and current ripple are occurred in the conventional DTC. Reason of undesired torque and current ripple is low number of voltage vectors applied to the motor controlled by the conventional DTC technique. SVM-DTC is a technique to reduce the ripple. SVM techniques have several advantages that are offering better DC bus utilization, lower torque ripple, lower total harmonic distortion in the AC motor current, lower switching loss, and easier to implement in the digital systems. Simulation results from the classical and improved DTC are presented and compared. Result shows that the torque, flux linkage and stator current ripple are decreased with the improved DTC.

I. INTRODUCTION

Induction Motors (IMs) are widely used in high performance drives. Its history is very extensive and also control is important in applications. There are many IMs in a number of industrial, commercial and domestic applications of variable speed drives. Since IMs demands well control performances: precise and quick torque and flux response, large torque at low speed, wide speed range, the drive control system is the most sensitive point of IMs [1].

DTC is method to control machine with utilizing torque and flux of motor controlled. The basic DTC scheme consists of two comparators having different features, switching table, Voltage Source Inverter (VSI), flux and torque estimation block and IM.

Like a every control method has some advantages and disadvantages, DTC method has too. Some of the advantages are lower parameters dependency, making the system more robust and easier implements and the disadvantages are difficult to control flux and torque at low speed, current and torque distortion during the change of the sector in d-q plane, variable switching frequency, a high sampling frequency needed for digital implementation of hysteresis controllers, high torque ripple. The torque ripple generates noise and vibrations, causes errors in sensor less motor drives, and associated current ripples are in turn responsible for the EMI. The reason of the high current and torque ripple in DTC is the presence of hysteresis comparators together the limited number of available voltage vectors. To reduce the torque ripple, the stator flux vector change, which is demanded to compensate the torque and flux errors, determination should be done and also any voltage vector should be produced by the control mechanism. If a higher number of voltage vectors than those used in conventional DTC is used, the favorable motor control can be obtained. Because of complexity of power and control circuit, this approach is not satisfactory for low or medium power applications. One of the methods to increase the number of available vectors is an on-line modulation between active and null vectors.

In order to overcome the problem, the SVM-DTC and DSVM-DTC methodologies were proposed. The basis of the SVM-DTC methodology is the calculation of the required voltage space vector to compensate the flux and torque errors exactly by using a predictive technique and then its generation using the SVM at each sample period. There are different SVM techniques, which are Direct-Reverse SVM, Direct- Direct SVM, Direct-Direct with $V_{null}=[000]$, Direct-Direct with $V_{null}=[111]$ in industry applications. The choice of the SVM technique to be used will depend on the optimization criteria under consideration, whether it is the torque/current ripple, the harmonic losses or the switching losses.

II. INDUCTION MOTOR

An induction motor (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction. Other commonly used name is squirrel cage motor due to the fact that the rotor bars with short circuit rings resemble a squirrel cage (hamster wheel).

An electric motor converts electrical power to mechanical power in its rotor (rotating part). There are several ways to supply power to the rotor. In a DC motor this power is supplied to the armature directly from a DC source, while in an induction motor this power is induced in the rotating device. An induction motor is sometimes called a rotating transformer because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side. Induction motors are widely used, especially polyphase induction motors, which are frequently used in industrial drives.

Induction motors are now the preferred choice for industrial motors due to their rugged construction, absence of brushes (which are required in most DC motors) and — thanks to modern power electronics — the ability to control the speed of the motor.

Principle of operation and comparison to synchronous motors

A 3-phase power supply provides a rotating magnetic field in an induction motor.

The basic difference between an induction motor and a synchronous AC motor is that in the latter a current is supplied onto the rotor. This then creates a magnetic field which, through magnetic interaction, links to the rotating magnetic field in the

stator which in turn causes the rotor to turn. It is called synchronous because at steady state the speed of the rotor is the same as the speed of the rotating magnetic field in the stator.

By way of contrast, the induction motor does not have any direct supply onto the rotor; instead, a secondary current is induced in the rotor. To achieve this, stator windings are arranged around the rotor so that when energized with a polyphase supply they create a rotating magnetic field pattern which sweeps past the rotor. This changing magnetic field pattern can induce currents in the rotor conductors. These currents interact with the rotating magnetic field created by the stator and the rotor will turn.

However, for these currents to be induced, the speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and no currents will be induced. If by some chance this happens, the rotor typically slows slightly until a current is re-induced and then the rotor continues as before. This difference between the speed of the rotor and speed of the rotating magnetic field in the stator is called slip. It is unit less and is the ratio between the relative speeds of the magnetic field as seen by the rotor (the slip speed) to the speed of the rotating field. Due to this an induction motor is sometimes referred to as an asynchronous machine.

III. Construction

The stator consists of wound 'poles' that carry the supply current to induce a magnetic field that penetrates the rotor. In a very simple motor, there would be a single projecting piece of the stator (a salient pole) for each pole, with windings around it; in fact, to optimize the distribution of the magnetic field, the windings are distributed in many slots located around the stator, but the magnetic field still has the same number of north-south alternations. The number of 'poles' can vary between motor types but the poles are always in pairs (i.e. 2, 4, 6, etc.).

Induction motors can be built to run on either single-phase or three-phase power. Single-phase power is more widely available in residential buildings, but cannot produce a rotating field in the motor (the field merely oscillates back and forth), so single-phase induction motors must incorporate some kind of starting mechanism to produce a rotating field. They would, using the simplified analogy of salient poles, have one salient pole per pole number; a four-pole motor would have four salient poles. Three-phase motors have three salient poles per pole number, so a four-pole motor would have twelve salient poles. This allows the motor to produce a rotating field, allowing the motor to start with no extra equipment and run more efficiently than a similar single-phase motor.

There are two types of rotor:

- **Squirrel-cage rotor**

The most common rotor is a squirrel-cage rotor. It is made up of bars of either solid copper (most common) or aluminum that span the length of the rotor, and are connected through a ring at each end. The rotor bars in squirrel-cage induction motors are not straight, but have some skew to reduce noise and harmonics.

Slip ring rotor

A slip ring rotor replaces the bars of the squirrel-cage rotor with windings that are connected to slip rings. When these slip rings are shorted, the rotor behaves similarly to a squirrel-cage rotor; they can also be connected to resistors to produce a high-resistance rotor circuit, which can be beneficial in starting.

Speed control

The rotational speed of the rotor is controlled by the number of pole pairs (number of windings in the stator) and by the frequency of the supply voltage. Before the development of cheap power electronics, it was difficult to vary the frequency to the motor and therefore the uses for the induction motor were limited.

The general term for a power electronic device that controls the speed as well as other parameters is *inverter*. A typical unit will take the mains AC supply, rectify and smooth it into a "link" DC voltage, and, then convert it into the desired AC waveform.

Because the induction motor has no brushes and is easy to control, many older DC motors are being replaced with induction motors and accompanying inverters in industrial applications.

Starting of induction motors

Three Phase

Direct-on-line (DOL) starting

The simplest way to start a three-phase induction motor is to connect its terminals to the line. In an induction motor, the magnitude of the induced EMF in the rotor circuit is proportional to the stator field and the slip speed (the difference between synchronous and rotor speeds) of the motor, and the rotor current depends on this EMF. When the motor is started, the slip speed is equal to the synchronous speed, as the rotor speed is zero (slip equal to 1), so the induced EMF in the rotor is large. As a result, a very high current flows through the rotor. This is similar to a transformer with the secondary coil short circuited, which causes the primary coil to draw a high current from the mains. When an induction motor starts DOL, a very high current is drawn by the stator, on the order of 5 to 9 times the full load current. This high current can, in some motors, damage the windings; in addition, because it causes heavy line voltage drop, other appliances connected to the same line may be affected by the voltage fluctuation. To avoid such effects, several other strategies are employed for starting motors.

Star-delta starters

An induction motor's windings can be connected to a 3-phase AC line in two different ways: *wye* (*star* in Europe), where the windings are connected from phases of the supply to the neutral, and *delta* (sometimes *mesh* in Europe), where the windings are connected between phases of the supply. A delta connection results in a higher voltage to the windings than a wye connection (the voltage is multiplied by $\sqrt{3}$). A star-delta starter initially connects the motor in wye, which produces a lower starting current than delta, then switches to delta when the motor has reached a set speed. Their disadvantages over DOL starting are:

- Lower starting torque, which may be a serious issue with pumps or any devices with significant breakaway torque
- Increased complexity: more contactors and some sort of speed switch are needed
- Two shocks to the motor (one for the initial start and another when the motor switches from wye to delta)

Variable-frequency drives

VFDs can be of considerable use in starting as well as running motors. A VFD can easily start a motor at a lower frequency than the AC line, as well as a lower voltage, so that the motor starts with full rated torque and with no inrush of current. The rotor circuit's impedance increases with slip frequency, which is equal to supply frequency for a stationary rotor, so running at a lower frequency actually increases torque.

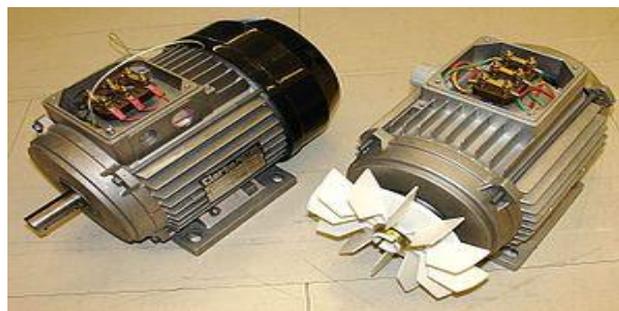
Single Phase

In a single phase induction motor, it is necessary to provide a starting circuit to start rotation of the rotor. If this is not done, rotation may be commenced by manually giving a slight turn to the rotor. The single phase induction motor may rotate in either direction and it is only the starting circuit which determines rotational direction.

For small motors of a few watts it is usual to "shade" the stator poles by means of a single turn of heavy copper wire around one corner of the pole. The current induced in the single turn is out of phase with the supply current and so causes an out-of-phase component in the magnetic field, which imparts to the field sufficient rotational character to start the motor. Starting torque is very low and efficiency is also reduced. Such shaded-pole motors are typically used in low-power applications with low or zero starting torque requirements, such as desk fans and record players.

Larger motors are provided with a second stator winding which is fed with an out-of-phase current to create a rotating magnetic field. The out-of-phase current may be derived by feeding the winding through a capacitor, or it may derive from the winding having different values of inductance and resistance from the main winding.

In some designs the second winding is disconnected once the motor is up to speed, usually either by means of a switch operated by centrifugal force acting on weights on the motor shaft, or by a positive temperature coefficient thermistor which after a few seconds of operation heats up and increases its resistance to a high value, reducing the current through the second winding to an insignificant level. Other designs keep the second winding continuously energized during running, which improves torque.



Three-phase induction motors



A squirrel-cage AC motor

Applications

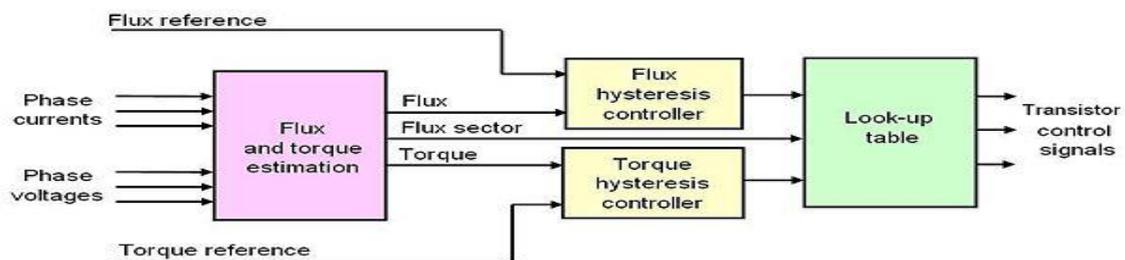
A wide variety of induction motors are available and are currently in use throughout a range of industrial applications. Induction motors typically include a rotor that rotates in response to a rotating magnetic flux generated by alternating current (AC) in a stator associated with the rotor. A rotational speed differential between the rotor and the rotating flux induces a current through a rotor cage. A rotor cage consists of a single aluminum casting having several conductive bars that run axially through the rotor and are joined at each end by two conductive end rings. Current induced in the bars creates a magnetic flux that opposes that of the stator, thus providing the rotor with rotational torque. The stator and rotor may be mechanically and electrically configured in a variety of manners depending upon a number of factors, including: the application, the power available to drive the motor, and so forth. The induction motors are divided again into an inner rotor type induction motor and an outer rotor type induction motor in accordance with relative positions of rotors and stators. The inner rotor type induction motor is generally applied to a washing machine or the like, and includes the rotor inside the stator. The ability to accurately determine the speed of a rotating rotor with respect to a stationary stator within an induction motor is vitally important to the every day operations of induction motors. A flat induction motor is a motor which has a disk-shaped stator and rotor placed coaxially around a rotating shaft with their surfaces opposing each other. Normally, the stator core and rotor core each have a spiral winding structure made of a magnetic steel strip. A plurality of open slots is formed in the winding structures from the outer edge toward the rotating shaft at equal intervals, leaving part of the magnetic steel strips. Single phase induction motors are normally provided with a cage type rotor and a coiled stator having two windings, one being for the running coil and the other for the starting coil. Single phase induction motors are widely used, due to their simplicity, strength and high performance. They are used in household appliances, such as refrigerators, air conditioners, hermetic compressors, washing machines, pumps, fans, as well as in some industrial applications. Linear induction motors are widely used in a number of industries and present certain advantages over rotary motors, particularly where propulsion along a predetermined path or guide way is required

IV. Direct Torque Control

Direct torque control (DTC) is one method used in variable frequency drives to control the torque (and thus finally the speed) of three-phase AC electric motors. This involves calculating an estimate of the motor's magnetic flux and torque based on the measured voltage and current of the motor.

Method

Stator flux linkage is estimated by integrating the stator voltages. Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector. The estimated flux magnitude and torque are then compared with their reference values. If either the estimated flux or torque deviates from the reference more than allowed tolerance, the transistors of the variable frequency drive are turned off and on in such a way that the flux and torque will return in their tolerance bands as fast as possible. Thus direct torque control is one form of the hysteresis or bang-bang control.



This control method implies the following properties of the control:

- Torque and flux can be changed very fast by changing the references
- The step response has no overshoot
- No coordinate transforms are needed, all calculations are done in stationary coordinate system
- No separate modulator is needed, the hysteresis control defines the switch control signals directly
- There are no PI current controllers. Thus no tuning of the control is required
- The switching frequency of the transistors is not constant. However, by controlling the width of the tolerance bands the average switching frequency can be kept roughly at its reference value. This also keeps the current and torque ripple small. Thus the torque and current ripple are of the same magnitude than with vector controlled drives with the same switching frequency.
- Due to the hysteresis control the switching process is random by nature. Thus there are no peaks in the current spectrum. This further means that the audible noise of the machine is low
- The intermediate DC circuit's voltage variation is automatically taken into account in the algorithm (in voltage integration). Thus no problems exist due to dc voltage ripple (aliasing) or dc voltage transients
- Synchronization to rotating machine is straightforward due to the fast control; Just make the torque reference zero and start the inverter. The flux will be identified by the first current pulse

- Digital control equipment has to be very fast in order to be able to prevent the flux and torque from deviating far from the tolerance bands. Typically the control algorithm has to be performed with 10 - 30 microseconds or shorter intervals. However, the amount of calculations required is small due to the simplicity of the algorithm
- The current and voltage measuring devices have to be high quality ones without noise and low-pass filtering, because noise and slow response ruins the hysteresis control
- In higher speeds the method is not sensitive to any motor parameters. However, at low speeds the error in stator resistance used in stator flux estimation becomes critical

The direct torque method performs very well even without speed sensors. However, the flux estimation is usually based on the integration of the motor phase voltages. Due to the inevitable errors in the voltage measurement and stator resistance estimate the integrals tend to become erroneous at low speed. Thus it is not possible to control the motor if the output frequency of the variable frequency drive is zero. However, by careful design of the control system it is possible to have the minimum frequency in the range 0.5 Hz to 1 Hz that is enough to make possible to start an induction motor with full torque from a standstill situation. A reversal of the rotation direction is possible too if the speed is passing through the zero range rapidly enough to prevent excessive flux estimate deviation. If continuous operation at low speeds including zero frequency operation is required, a speed or position sensor can be added to the DTC system. With the sensor high accuracy of the torque and speed control can be maintained in the whole speed range.

DIRECT TORQUE CONTROL FOR INDUCTION MOTOR

MAIN FEATURES OF DTC

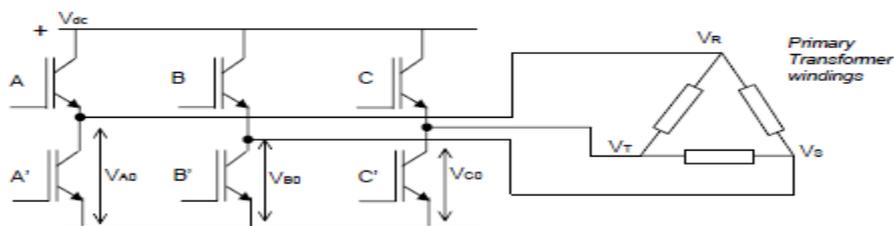
- Decoupled control of torque and flux
- Absence of mechanical transducers
- Current regulator, PWM pulse generation, PI control of flux and torque and co-ordinate transformation is not required
- Very simple control scheme and low computational time
- Reduced parameter sensitivity

V. SPACE VECTOR MODULATION

PWM, as discussed in paragraph 4, can be generated by analogue or digital control electronics. The advantages of digital controls over analogue are:

- Stability (no drift, offsets or aging effects)
- Precision (noise immunity)
- Flexibility (can be customized by changing software)

Even if done digitally, significant computing time is required, as the PWM signals have to be calculated in real time. By using Space Vector Modulation this calculation process is simplified. As it is simplified, less computing time is required, and therefore better performance can be obtained.



As we have 3 switches (A, B and C) there are 8 different switching combinations. For example A on, B off, C on. We can analyse for all switching combinations the phase-phase voltages on the primary winding of the transformer. If we look to the voltages that need to be generated between each leg (fig 8) we can split that into 8 different ‘spaces’, S1, S2 etc. For each space we can use the table to define which switching states the inverter must use to obtain those voltages. For example for period (‘space’) S1, we see that the VRS is positive, VST is negative and VTR is positive. Besides the fact that these voltages are positive or negative they also reach a point where they are zero. From the table it can be read that in period S1 the inverter needs to be switching between state Nr. 1, 2, 8 and 6.

Nr	A	B	C	VAO	VBO	VCO	VRS	VST	VTR	S1	S2	S3	S4	S5	S6
1	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X
2	0	0	1	0	0	Vdc	0	-Vdc	Vdc	X					X
3	0	1	0	0	Vdc	0	-Vdc	Vdc	0				X	X	
4	0	1	1	0	Vdc	Vdc	-Vdc	0	Vdc					X	X
5	1	0	0	Vdc	0	0	Vdc	0	-Vdc		X	X			
6	1	0	1	Vdc	0	Vdc	Vdc	-Vdc	0	X	X				
7	1	1	0	Vdc	Vdc	0	0	Vdc	-Vdc			X	X		
8	1	1	1	Vdc	Vdc	Vdc	0	0	0	X	X	X	X	X	X

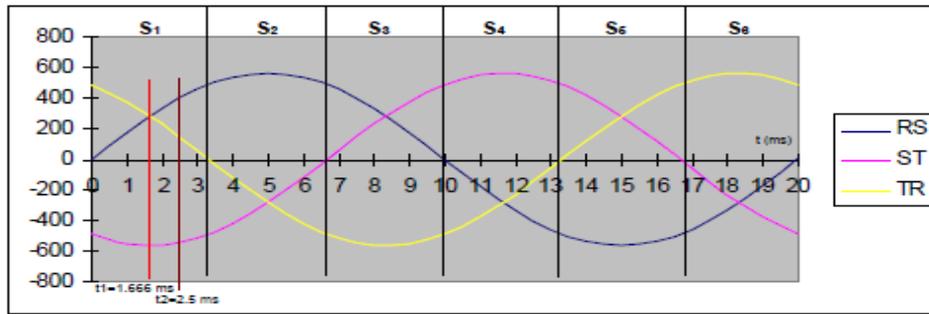
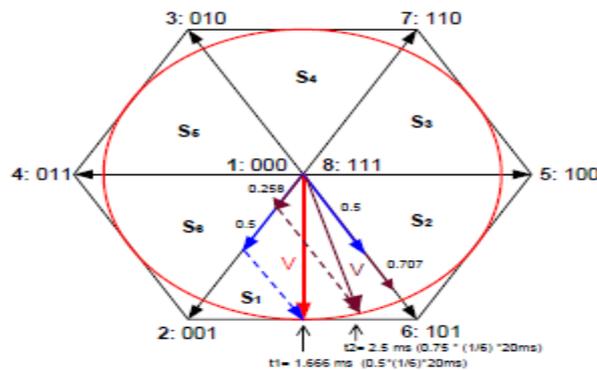


Fig above in combination with the table can also be represented in a hexagon, as shown in fig



In period S1 the inverter will switch between switching states 1,2, 8 and 6, in the period S2 between: 1, 6, 8 and 5. etc. One full period (in case of 50Hz 1 period is 20ms) can be represented by a vector V making one full circle in the hexagon. The period showed in figure 8 starts in the hexagon at state 2 and is then turning counter clockwise. As shown in fig 9 at t1=1.666 ms the vector V (red) is built up by staying 25% of the time in state 1, 25% of the time in state 2, 25% of the time in state 8 and 25% of the time in state 6. This switching pattern in one period of the switching frequency is shown in figure 10. For t2= 2.5 ms the required time per switching state is calculated as follows:

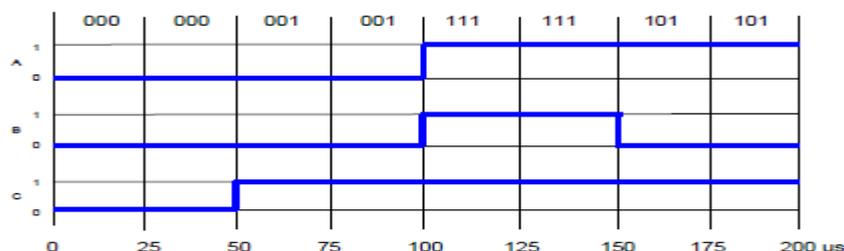
$$V_{RS} = \sin(2\pi \cdot f \cdot t) \quad \text{at } t=2.5\text{ms} \quad V_{RS} = 0.707 \quad (73.2\% \text{ of } 0.965 \text{ which is the total})$$

$$V_{TR} = \sin(2\pi \cdot f \cdot t - 4/3\pi) \quad \text{at } t=2.5\text{ms} \quad V_{TR} = 0.258 \quad (26.8\% \text{ of } 0.965 \text{ which is the total})$$

Please note that V_{RS} and V_{TR} are normalized to 1 where 1 corresponds with 665V, the maximum value ($400\sqrt{2}$)

So within one switching period the inverter needs to stay

- 25.0% of the time on state 1 (always)
- 26.8% * 50% = 13.4% of the time on state 2
- 25.0% of the time on state 8 (always)
- 73.2% * 50% = 36.6% of the time on state 6



shows the switching states as shown at t1 in fig 9 and visualizes the switching states of leg A,B and C during 1 period. (1 period is 200 microseconds, as the switching frequency is 5kHz).

In a UPS Space Vector Modulation can be implemented by means of DSPs (Digital Signal Processors). These are microprocessors which are suitable to process analogue signals. DSPs provide fast sampling rates which make them ideally suited to UPS control.

By using an isolation transformer on the output of the inverter, special modulation techniques can be applied. The modulation index can be increased with 15% by adding a 3rd harmonic (150Hz in case of 50Hz output) to the signal on each leg of the transformer. As the transformer is in dy configuration, this 3rd harmonic will not appear on the output voltage. This optimisation is not possible in transformerless inverters (UPS).

BENEFITS

Space Vector Modulation for a three phase UPS inverter makes it possible to adapt the switching behaviour to different situations such as: half load, full load, linear load, non-linear load, static load, pulsating load, etc. In combination with a zig-zag three phase transformer in the output this provides the following advantages:

- Very low values can be reached for the output voltage THD (<2% for linear loads., <3% for non linear loads)
- Robust dynamic response (<3% deviation at 100% load step, recovery time to <1%: <20ms)
- The efficiency of the inverter can be optimized, for each load condition.
- Because of the strong regulation in combination with a zig-zag transformer the inverter can accept a 100% unbalanced load and maintain the performance
- VM enables more efficient use of the DC voltage (15% more than conventional PWM techniques, so the inverter will accept a 15% lower DC voltage making full use of the available battery energy)
- By applying special modulation techniques the peak currents in the IGBTs can be reduced compared to similar inverters. This improves the MTBF of the inverter, since there is less thermal stress on the IGBT chip.
- By changing the switching behaviour of the inverter, the audible noise can also be influenced and therefore be minimized.

Space Vector Modulation provides excellent output performance, optimized efficiency, and high reliability compared to similar inverters with conventional Pulse Width Modulation.

VI. INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

IGBT has been developed by combining into it the best qualities of both BJT and PMOSFET. Thus an IGBT possesses high input impedance like a PMOSFET and has low on-state power loss as in a BJT. Further, IGBT is free from second breakdown problem present in BJT. All these merits have made IGBT very popular amongst power-electronics engineers. IGBT is also known as metal oxide insulated gate transistor (MOSIGT), conductively-modulated field effect transistor (COMFET) or gain-modulated FET(GEMFET). It was also initially called insulated gate transistor (IGT).

The **insulated-gate bipolar transistor** or **IGBT** is a three-terminal power semiconductor device, noted for high efficiency and fast switching. It switches electric power in many modern appliances: electric cars, variable speed refrigerators, air-conditioners, and even stereo systems with digital amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize complex waveforms with pulse width modulation and low-pass filters.

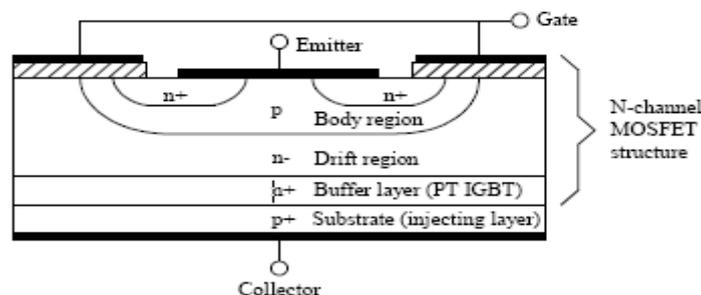
The IGBT combines the simple gate-drive characteristics of the MOSFETs with the high-current and low-saturation-voltage capability of bipolar transistors by combining an isolated-gate FET for the control input, and a bipolar power transistor as a switch, in a single device. The IGBT is used in medium- to high-power applications such as switched-mode power supply, traction motor control and induction heating. Large IGBT modules typically consist of many devices in parallel and can have very high current handling capabilities in the order of hundreds of amps with blocking voltages of 6,000 V.

The IGBT is a fairly recent invention. The first-generation devices of the 1980s and early 1990s were relatively slow in switching, and prone to failure through such modes as latch up and secondary breakdown. Second-generation devices were much improved, and the current third-generation ones are even better, with speed rivaling MOSFETs, and excellent ruggedness and tolerance of over loads.

Basic Structure

Fig illustrates the basic structure of an IGBT. It is constructed virtually in the same manner as a power MOSFET. There is, however, a major difference in the substrate. The n+ layer substrate at the drain in a PMOSFET is now substituted in the IGBT by a p+ layer substrate called collector C. Like a power MOSFET, an IGBT has also thousands of basic structure cell connected approximately on a single chip of silicon.

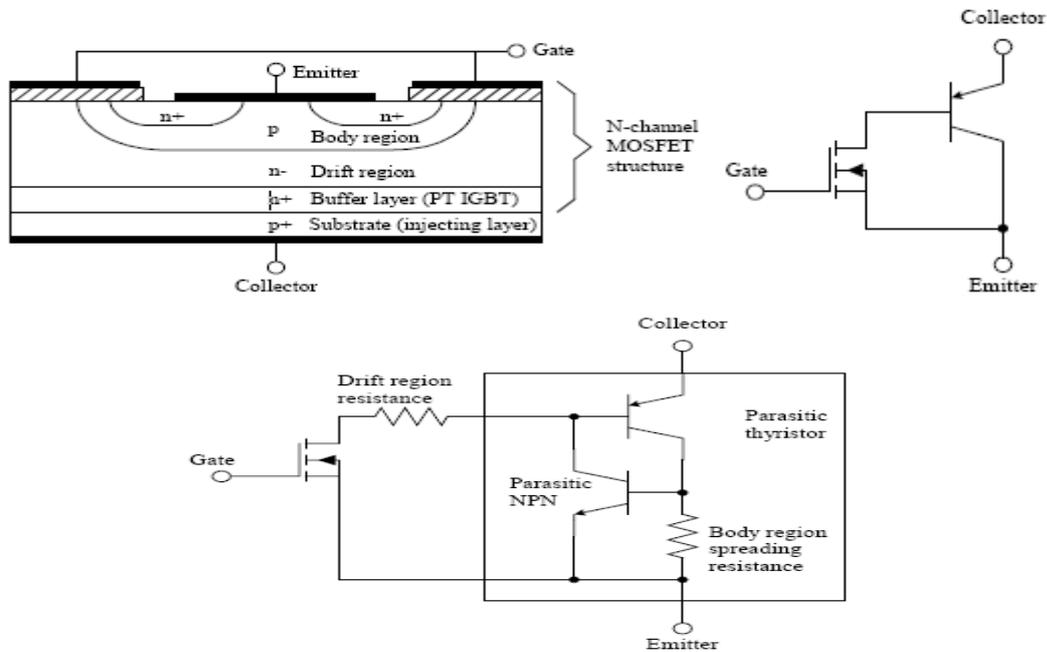
In IGBT, p+ substrate is called injection layer because it injects holes into n- layer. The n- layer is called drift region. As in other semiconductor devices, thickness of n- layer determines the voltage blocking capability of IGBT. The p layer is called body of IGBT. The n- layer in between p+ and p regions serves to accommodate the depletion layer of pn-junction, i.e. junction J2.



N-Channel IGBT Cross Section

Equivalent Circuit

An examination of reveals that if we move vertically up from collector to emitter. We come across p+, n-, p layer s. Thus, IGBT can be thought of as the combination of MOSFET and p+ n- p layer s. Thus, IGBT can be thought of as the combination of MOSFET and p+ n- p transistor Q1 .Here Rd is resistance offered by n- drift region. Approximate equivalent circuit of an IGBT.



Exact equivalent circuit

The existence of another path from collector to emitter, this path is collector, p+ n-, p (n-channel), n+ and emitter. There is, thus, another inherent transistor Q2 as n- pn+ in the structure of IGBT. The interconnection between two transistors Q1 and Q2.This gives the complete equivalent circuit of an IGBT. Here R_{by} is the existence offered by p region to flow of hole current I_h.

The two transistor equivalent circuit illustrates that an IGBT structure has a parasitic thyristor in it. Parasitic thyristor is shown in line.

Working

When collector is made positive with respect to emitter, IGBT gets forward biased. With no voltage between gate and emitter, two junctions between n- region and p region (i.e. junction J2) are reversed biased; so no current flows from collector to emitter

When gate is made positive with respect to emitter by voltage V_G, with gate-emitter voltage more than the threshold voltage V_{GET} of IGBT, an n-channel or inversion layer, is formed in the upper part of p region just beneath the gate, as in PMOSFET. This n- channel short circuits the n- region with n+ emitter regions. Electrons from the n+ emitter begin to flow to n- drift region through n-channel. As IGBT is forward biased with collector positive and emitter negative, p+ collector region injects holes into n- drift region .In short; n-drift region is flooded with electrons from p-body region and holes from p+ collector region. With this, the injection carrier density in n- drift region increases considerably and as a result, conductivity of n- region enhances significantly. Therefore, IGBT gets turned on and begins to conducts forward current I_C.

Current I_c, or I_e of two current components:

1. Holes current I_h due to injected holes flowing from collector,p+ n- p transistor Q1, p-body region resistance R_{by} and emitter .
2. Electronic current I_e due to injected electrons flowing from collector, or load, current I_{C=emitter} current I_e=I_h+I_e. Major component of collector current is electronic current I_e, i.e. main current path for collector, or load, current is through p+, n-, drift resistance R_d and n channel resistance R_{ch}. Therefore, the voltage drop in IGBT in its on-state is

$$V_{ce.on} = I_c \cdot R_{ch} + I_c \cdot R_d + V_{ji}$$

=voltage drop [in n- channel] + across drift in n- region + across forward biased p+ n- junction J1.

Here V_{ji} is usually 0.7 to 1v as in a p-n diode. The voltage drop I_c. R_{ch} is due to n-channel resistance, almost the same as in a PMOSFET. The voltage drop V_{df} = I_c.R_d in UGBT is much less than that in PMOSFET. It is due to substantial increase in the conductivity caused by injection of electrons and holes in n- drift region. The conductivity increase is the main reason for the low on-state voltage drop in IGBT than that it is in PMOSFET.

Latch-up in IGBT

From the above that IGBT structure has two inherent transistors Q1 and Q2, which constitute a parasitic thyristor. When IGBT is on, the hole current flows through transistor p+ n- p and p- body resistance R_{by}. If load current I_c is large,

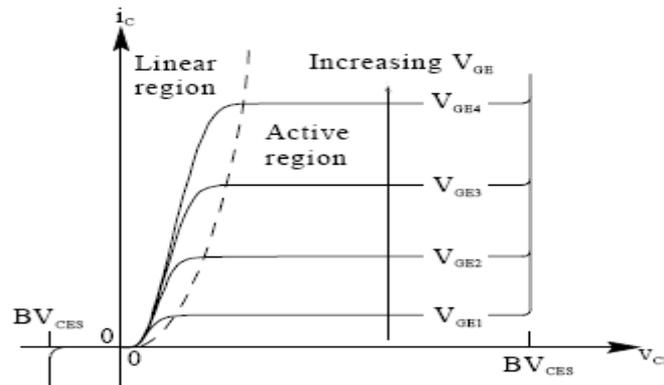
hole component of current I_h would also be large. This large current would increase the voltage drop $I_h \cdot R_{by}$ which may forward bias the base-p-emitter n^+ junction of transistor Q2. As a consequence, parasitic transistor Q2 gets turned on which further facilitates in the turn-on of parasitic transistor p^+n-p labeled Q1. The parasitic thyristor, consisting of Q1 and Q2, eventually latches on through regenerative action, when sum of their current gains $\alpha_1 + \alpha_2$ reaches unity as in a conventional thyristor. With parasitic thyristor on, IGBT latches up and after this, collector emitter current is no longer under the control of gate terminal. The only way now to turn-off the latched up IGBT is by forced commutation of current as is done in a conventional thyristor. If this latch up is not aborted quickly, excessive power dissipation may destroy the IGBT. The latch up discussed here occurs when the collector current I_{ce} exceeds a certain critical value. The device manufacturers always specify the maximum permissible value of load current I_{ce} that IGBT can handle without latch up.

At present, several modifications in the fabrication techniques are listed in the literatures which are used to avoid latch-up in IGBTs. As such, latch up free IGBTs are available.

IGBT Characteristics

The circuit shows the various parameters pertaining to IGBT characteristics. Static I-V or output characteristics of an IGBT (n-channel type) show the plot of collector current I_c versus collector-emitter voltage V_{ce} for various values of gate-emitter voltages V_{GE1} , V_{GE2} etc. These characteristics are shown below. In the forward direction, the shape of the output characteristics is similar to that of BJT. But here the controlling parameter is gate-emitter voltage V_{GE} because IGBT is a voltage controlled device. When the device is off, junction J2 blocks forward voltage and in case reverse voltage appears across collector and emitter, junction J1 blocks it. V_{rm} is the maximum reverse breakdown voltage.

The transfer characteristic of an IGBT is a plot of collector current I_c versus gate-emitter voltage V_{GE} . This characteristic is identical to that of power MOSFET. When V_{GE} is less than the threshold voltage V_{GET} , IGBT is in the off state.



Static V-I characteristics

Switching Characteristics

Switching characteristics of an IGBT during turn-on and turn-off are sketched. The turn-on time is defined as the time between by instance of forward blocking to forward on-state. Turn-on time is composed of delay time t_{dn} and rise time t_r , i.e. $t_{on} = t_{dn} + t_r$. The delay time is defined as the time for the collector-emitter voltage to fall from V_{ce} to $0.9 V_{ce}$. Here V_{ce} is the initial collector-emitter voltage. Time t_{dn} may also be defined as the time for the collector current to rise from its initial leakage current I_{ce} to $0.1 I_c$. Here I_c is the final value of the collector current.

The rise time t_r is the time during which collector-emitter falls from $0.9 V_{CE}$ to $0.1 V_{CE}$. It is also defined as the time for the collector current to rise from $0.1 I_c$ to its final value I_c . After time t_{on} , the collector current I_c and the collector-emitter voltage falls to small value called conduction drop = V_{CES} where subscript s denotes saturated value.

The turn-off time is somewhat complex. It consists of three intervals

1. Delay time t_{df}
2. Initial fall time t_{f1}
3. Final time t_{f2}

i.e. $t_{off} = t_{df} + t_{f1} + t_{f2}$

The delay time is the time during which gate voltage falls from V_{GE} to threshold voltage V_{GET} . As V_{GE} falls to V_{GET} during t_{df} , the collector current falls from I_c to $0.9 I_c$. At the end of the t_{df} , collector-emitter voltage begins to rise. The first fall time T_{f1} is defined as the time during which collector current falls from 90 to 20 % of its initial value I_c , or the time during which collector-emitter voltage rises from V_{ce} to $0.1 V_{ce}$.

The final fall time t_{f2} is the time during which collector current falls from 20 to 10% of I_c , or the time during which collector-emitter voltage rises from $0.1 V_{CE}$ to final value V_{CE} .

Applications of IGBTs

IGBTs are widely used in medium power applications such as AC and DC motor drives, UPS systems, power supplies and drives for solenoids, relays and contactors. Though IGBTs are somewhat more expensive than BJTs, yet they are becoming popular because of lower gate-drive requirement, lower switching losses and smaller snubber circuit

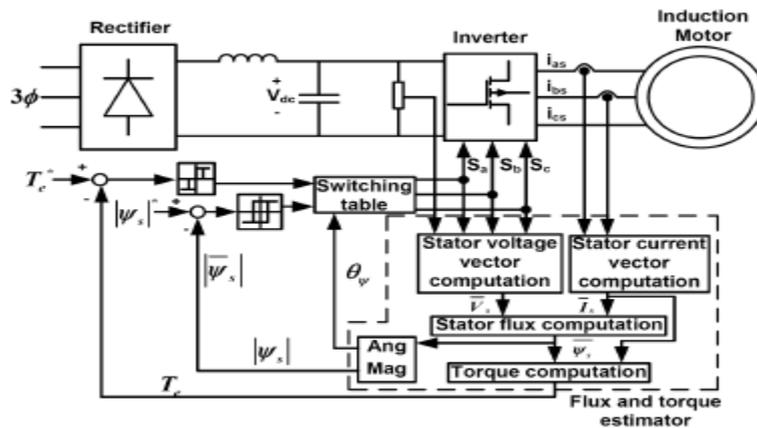
requirements. IGBT converter are more efficient with less size as well as cost, as compared to converters based on BJTs. Recently, IGBT inverter induction-motor drives using 15-20 KHZ. Switching frequency favour where audio-noise is objectionable. In most applications, IGBTs will eventually push out BJTs. At present, the state of the art IGBTs of 1200vots, 500 Amps ratings , 0.25-20 μ s turn off time with operating frequency are available.

VII. CONTROL METHOD

A) Conventional DTC

DTC method has been first proposed for induction machines. DTC technique introduced by Takahashi and Noguchi for low and medium power application and DTC technique introduced by Depenbrock for high power application are popular in industry. DTC strategy is quite different from that of the field orientation control (FOC) or vector control, which does not need complicated coordination transformations and decoupling calculation . The basic model of the conventional DTC induction motor scheme is shown in Figure 1. Two stator currents (i_{SA} and i_{SB}) and DC-bus voltage V_{DC} are sampled. d-q components of stator voltage and current space vectors in the stationary reference frame and also magnitude of the stator flux and electric torque are calculated as shown below

Basic DTC induction scheme



$$V_{zd} = \frac{2}{3} V_{dc} (S_A - \frac{S_B + S_C}{2})$$

$$V_{zq} = \frac{1}{\sqrt{3}} V_{dc} (S_A - S_C)$$

$$i_{zd} = i_{SA}$$

$$i_{zq} = \frac{i_{SA} + 2i_{SB}}{\sqrt{3}}$$

$$|\Psi_s| = \sqrt{\Psi_{zd}^2 + \Psi_{zq}^2}$$

$$T_e = \frac{3}{2} P (\Psi_{zd} i_{zq} - \Psi_{zq} i_{zd})$$

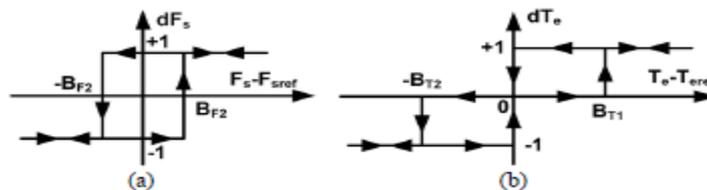
$$\Psi_{zd} = \int (V_{zd} - R_s i_{zd}) dt$$

$$\Psi_{zq} = \int (V_{zq} - R_s i_{zq}) dt$$

The magnitude of stator flux and electric torque calculated are compared with their reference values in the hysteresis comparators shown in Figure 2 and then the outputs of the comparators are fed to a switching table to select an appropriate inverter voltage vector. The switching table shown as Table I determine the voltage vector to apply based on the position of the stator flux and the required changes in stator flux magnitude and torque [8]. The selected voltage vector will be applied to the induction motor at the end of the sample time. In VSI, there are six equally spaced voltage vectors having the same amplitude and two zero voltage vectors. VSI voltage vectors are shown in Figure 3.

In DTC, torque and flux are controlled independently by selecting the optimum voltage space vector for entire switching period and the errors are maintained with in the hysteresis band [9]. In conventional DTC, only one vector is applied for the entire sampling period. So for small errors, the motor torque may exceed the upper\lower torque limit. Instead by using more than one vector with in the sampling period torque ripple can be reduced. The slip frequency can be controlled precisely by inserting zero vectors [10]. For the small the hysteresis band, frequency of operation of PWM inverter could be very high. The switching frequency always varies according to the width of hysteresis band.

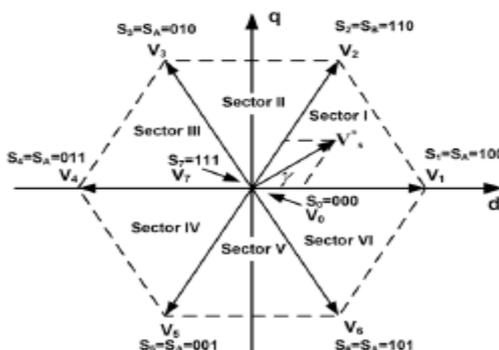
Hsteresis comparator a) stator flux b) torque



Switching table

Flux error position	Torque error position	Sector I	Sector II	Sector III	Sector IV	Sector V	Sector VI
1	1	V2(110)	V3(010)	V4(011)	V5(001)	V6(101)	V1(100)
	0	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)
	-1	V6(101)	V1(100)	V2(110)	V3(010)	V4(011)	V5(001)
0	1	V3(010)	V4(011)	V5(001)	V6(101)	V1(100)	V2(110)
	0	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)
	-1	V5(001)	V6(101)	V1(100)	V2(110)	V3(010)	V4(011)

VSI voltage vectors



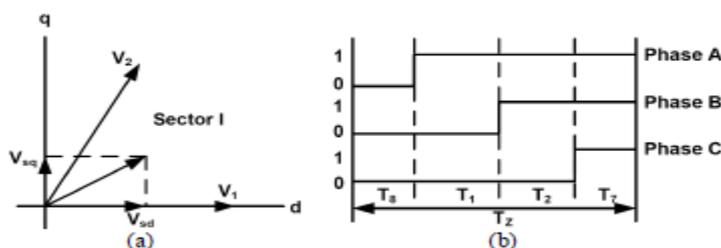
B) Space Vector Modulation

Common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. Several techniques have been developed to improve the torque performance. One of them is to reduce the ripples is based on SVM technique.

SVM was first presented by a group of German researched in the second half of the 1980s. Since then, a lot of work has been done on the theory and implementation of SVM techniques. SVM techniques have several advantages that are offering better DC bus utilization, lower torque ripple, lower

Total Harmonic Distortion (THD) in the AC motor current, lower switching losses, and easier to implement in the digital systems. At each cycle period, a preview technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. The torque ripple for this SVM DTC is significantly improved and switching frequency is maintained constant [11]. SVM, based on the switching between two adjacent boundary active vectors and a zero vector during one switching period, T_z , and for a given reference voltage vector in the first sector (0-60°) is shown in Figure

SVM in the first sector (a) reference voltage vector (b) switching pattern for three phase modulation



The switching times can be calculated using the following equations

$$V_s \approx V_{sd} + jV_{sq}$$

where the vectors V_{sd} and V_{sq} are obtained from the appropriate voltage vectors for any given sector.

$$T_z \vec{V}_s = T_A \vec{V}_1 + T_B \vec{V}_2$$

$$T_A \sqrt{\frac{2}{3}} V_{dc} \begin{bmatrix} \cos 0^\circ \\ \sin 0^\circ \end{bmatrix} + T_B \sqrt{\frac{2}{3}} V_{dc} \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

$$= T_z \sqrt{\frac{2}{3}} V_{dc} a \begin{bmatrix} \cos \gamma \\ \sin \gamma \end{bmatrix}$$

$$T_A = T_z a \frac{\sin(\pi/3 - \gamma)}{\sin(\pi/3)}$$

$$T_B = T_z a \frac{\sin(\gamma)}{\sin(\pi/3)}$$

$$T_0 = T_7 = T_z - T_B - T_A$$

$$0 \leq \gamma \leq \pi/3, a = \frac{|\vec{V}_s|}{\sqrt{\frac{2}{3}} V_{dc}}$$

The reference vector $V^* s$, a constant magnitude and frequency in the steady-state, is sampled at equal time intervals of T_z . Within this sample time, the inverter is switched and made to remain at different switching states for different durations of time such that the average space vector generated within sample period is equal to the sampled value of the reference vector, both in terms of magnitude and angle. The switching states that can be used within T_z are the two zero states and the active states which are SA and SB, with vectors V_1 and V_2 respectively forming the start and the end boundaries of the sector as shown in Figure 4. The two switching states (SA and SB) are named active switching states. SA indicates the inverter switching states (001), (100), or (010) and SB indicates the inverter switching states (101), (110) or (011). Active vector times, T_A and T_B , are defined as the times due to the active switching states, SA and SB respectively. Null vector times T_0 and T_7 are defined as the times due to the null switching states S_0 , (000), and S_7 , (111) respectively. In DTC, with the space vector PWM technique, the DTC transient performance and robustness are preserved and the steady state torque ripple is reduced. Moreover, the inverter switching frequency is constant and totally controllable.

VIII. SIMULATION RESULTS

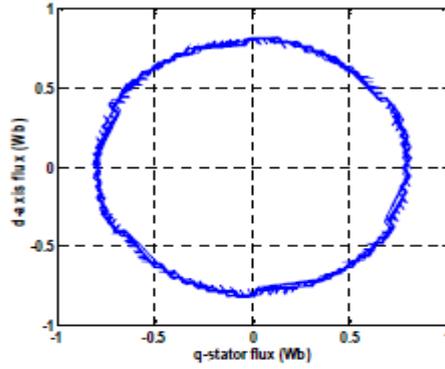
Two Matlab models were developed to examine the different control algorithm. One is used for the conventional DTC and the other for the modified DTC. The parameters of the induction motor are shown in Table II.

TABLE II. Parameters of the induction motor used

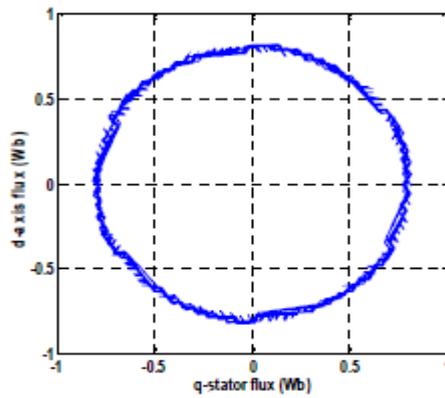
Stator resistance R_s	3 Ω
Rotor resistance R_r	5.6 Ω
Rotor Inductance L_r	0.0154 H
Mutual inductance M	0.0102 H
Stator Inductance L_s	0.0154 H
Phase voltage V	250 V
Base speed w_b	314 rad/s
Inertia J	0.002 kgm^2
Frequency f	50 Hz

The steady state behavior of induction motor with the conventional DTC and SVM-DTC are illustrated in Figure. Figure 5 and 6 show a comparison of stator flux space vector obtained using two control methods. As it is possible to see in Figure 7-12 an appreciable reduction of current, flux and torque ripple has been obtained using the SVM-DTC technique.

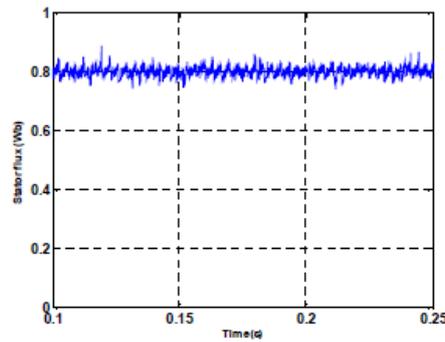
d-q staror flux with a conventional DTC scheme



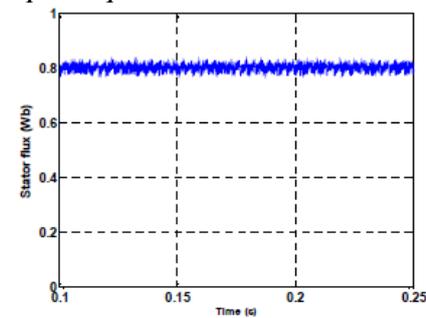
d-q stator flux with SVM-DTC scheme

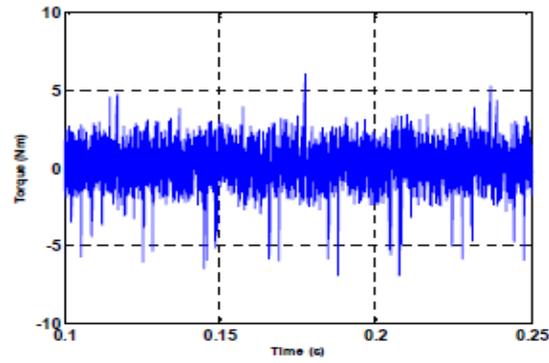


Stator flux magnitude with conventional DTC scheme

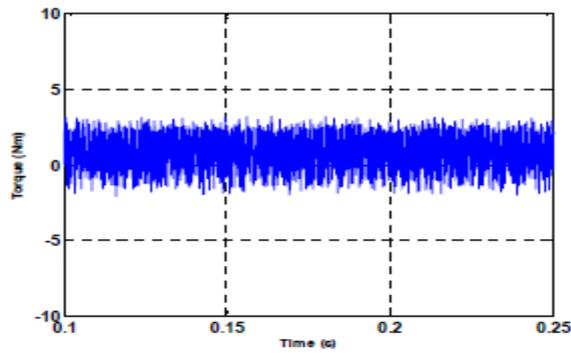


Out put torque with conventional DTC scheme

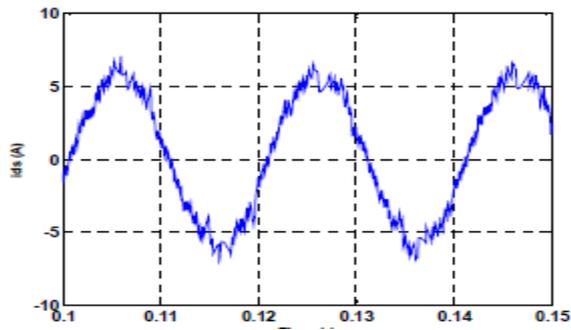




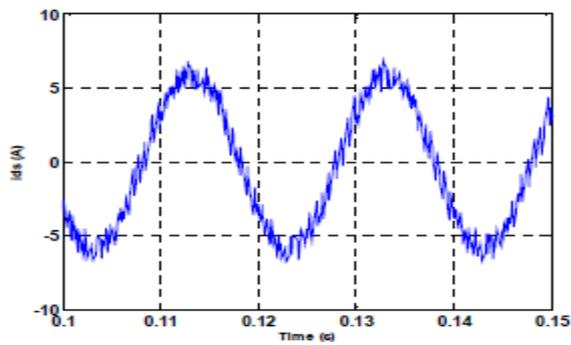
Out put torque with SVM-DTC scheme



Stator d-current with conventional DTC scheme

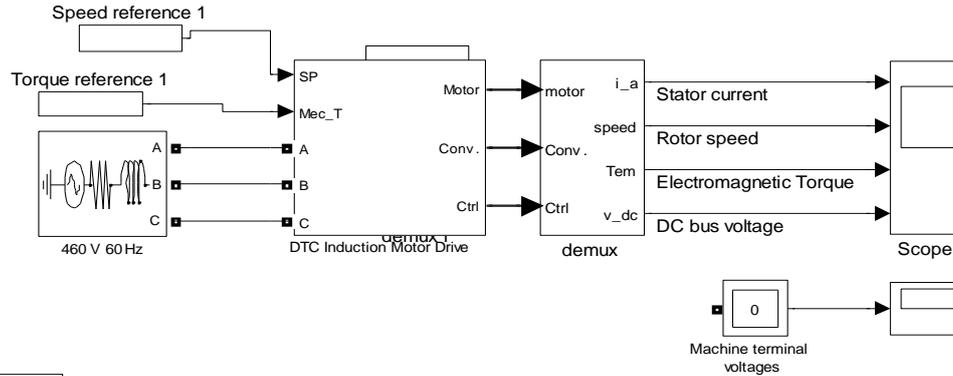


Stator d-current with SVM-DTC scheme



SIMULINK CIRCUIT:

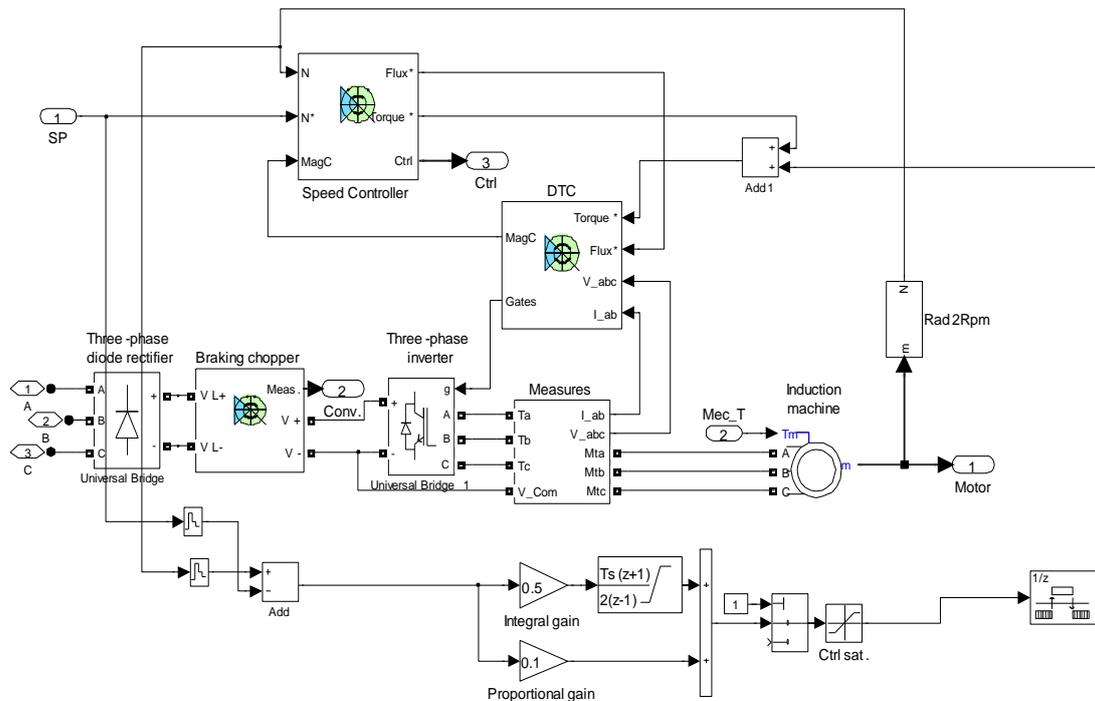
DTC WITH OUT SVM



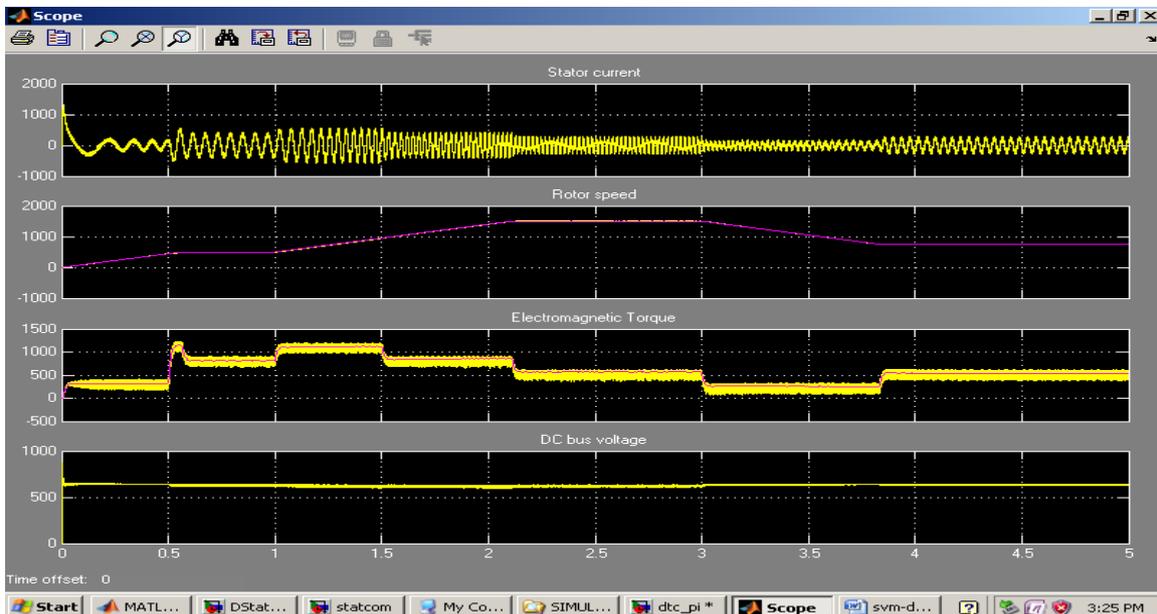
Discrete,
 $T_s = 1e-006$ s.

DTC Induction Motor Drive during speed regulation

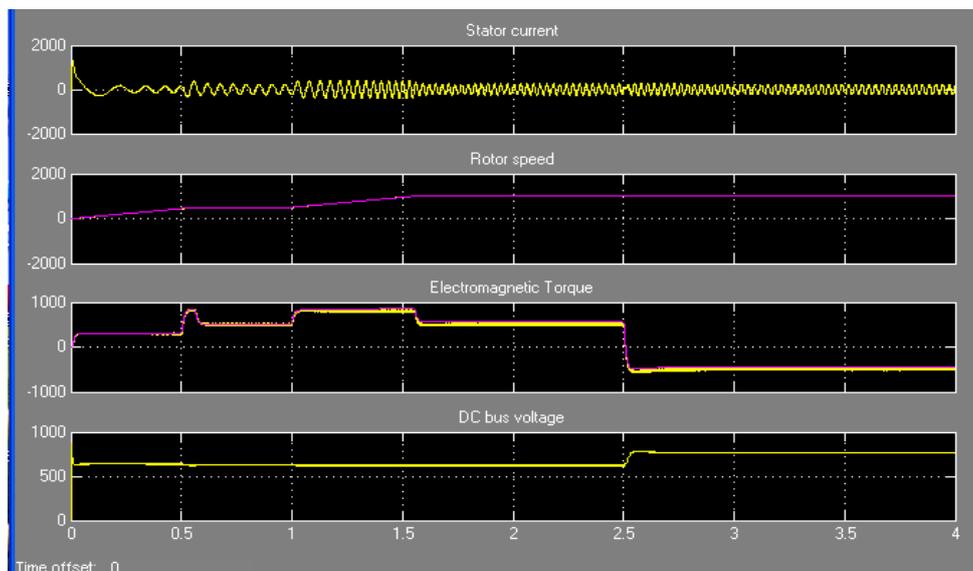
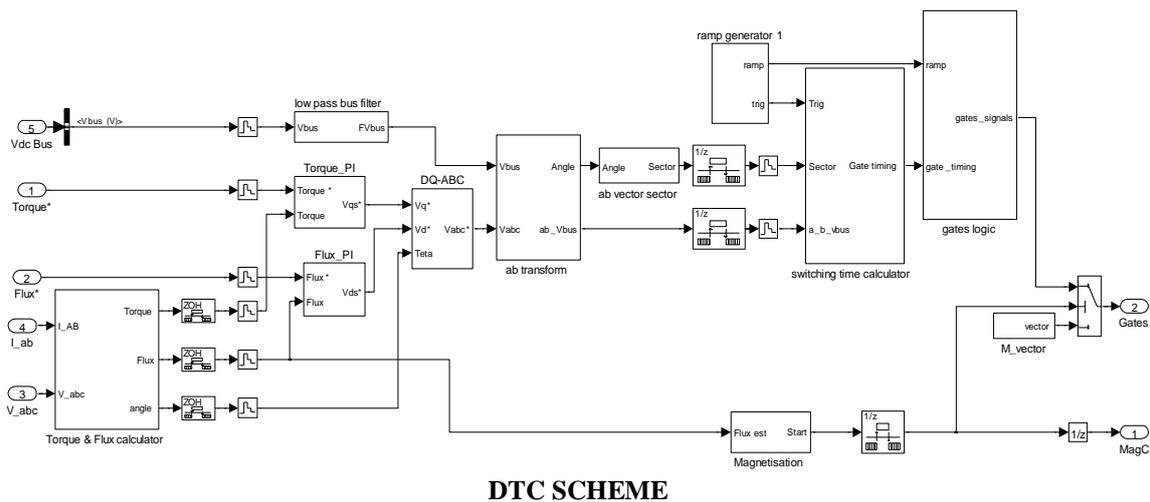
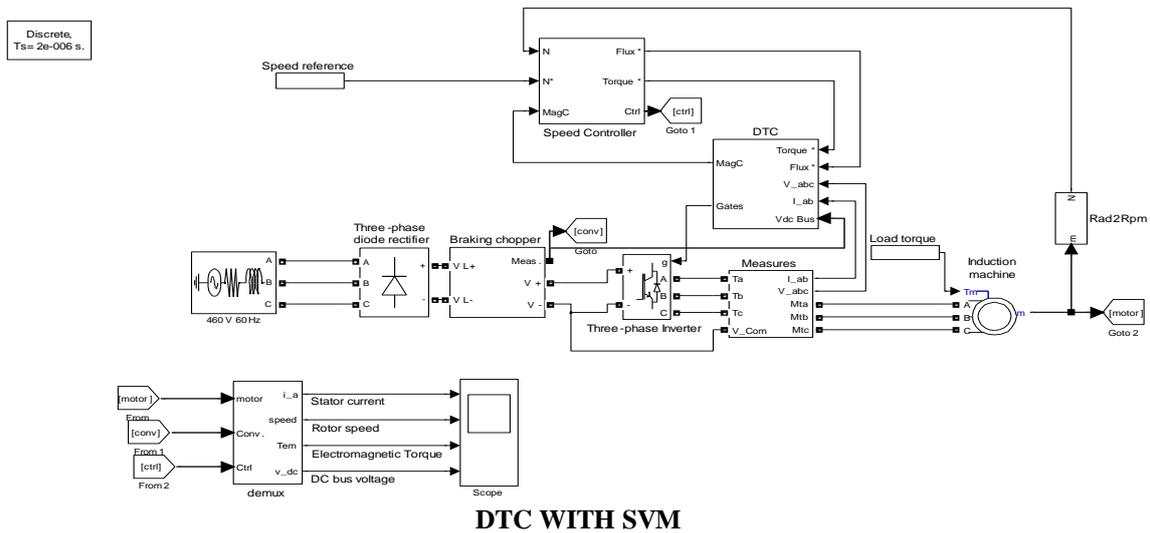
More Info



DTC IM DRIVE



OUTPUT RESPONSE WITH OUT SVM



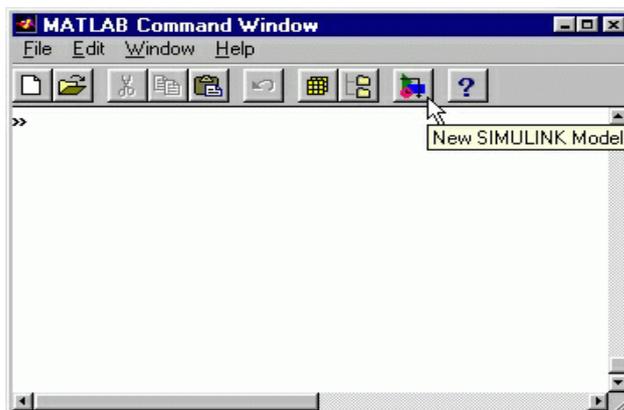
SIMULINK:

Simulink is a platform for multinomial simulation and Model-Based Design for dynamic systems. It provides an interactive graphical environment and a customizable set of block libraries, and can be extended for specialized applications.

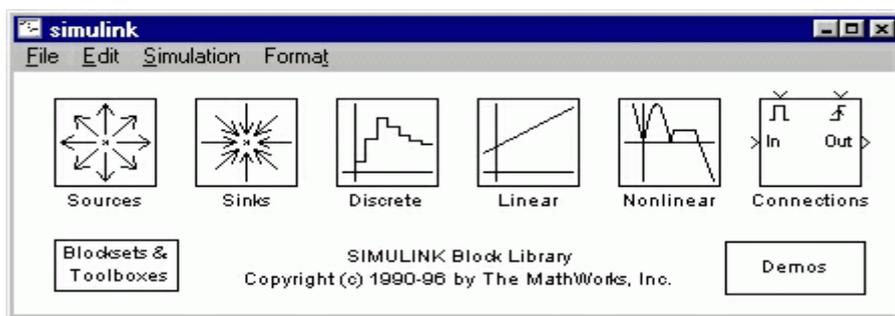
Simulink is a graphical extension to MATLAB for modeling and simulation of systems. In Simulink, systems are drawn on screen as block diagrams. Many elements of block diagrams are available, such as transfer functions, summing junctions, etc., as well as virtual input and output devices such as function generators and oscilloscopes. Simulink is

integrated with MATLAB and data can be easily transferred between the programs. In these tutorials, we will apply Simulink to the examples from the MATLAB tutorials to model the systems, build controllers, and simulate the systems. Simulink is supported on UNIX, Macintosh, and Windows environments; and is included in the student version of MATLAB for personal computers.

Simulink is started from the MATLAB command prompt by entering the following command: `simulink`
 Alternatively, you can hit the New Simulink Model button at the top of the MATLAB command window as shown below:



When it starts, Simulink brings up two windows. The first is the main Simulink window, which appears as:



The second window is a blank, untitled, model window. This is the window into which a new model can be drawn.

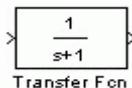
Basic Elements

There are two major classes of items in Simulink: **blocks** and **lines**. Blocks are used to generate, modify, combine, output, and display signals. Lines are used to transfer signals from one block to another.

Blocks: There are several general classes of blocks:

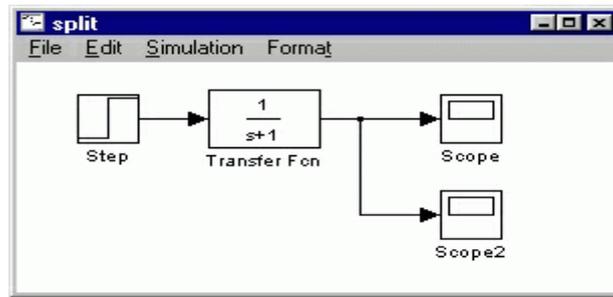
- Sources: Used to generate various signals
- Sinks: Used to output or display signals
- Discrete: Linear, discrete-time system elements (transfer functions, state-space models, etc.)
- Linear: Linear, continuous-time system elements and connections (summing junctions, gains, etc.)
- Nonlinear: Nonlinear operators (arbitrary functions, saturation, delay, etc.)
- Connections: Multiplex, Demultiplex, System Macros, etc.

Blocks have zero to several input terminals and zero to several output terminals. Unused input terminals are indicated by a small open triangle. Unused output terminals are indicated by a small triangular point. The block shown below has an unused input terminal on the left and an unused output terminal on the right.



Lines

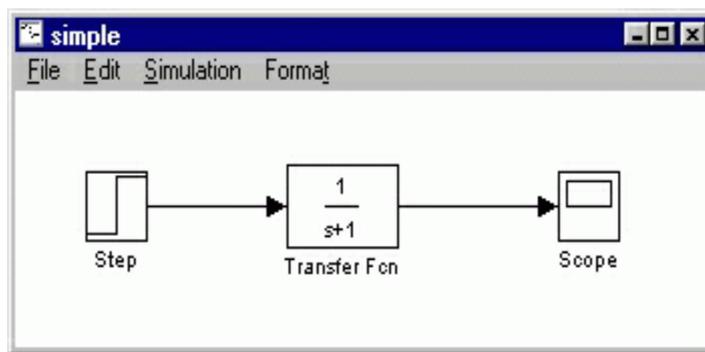
Lines transmit signals in the direction indicated by the arrow. Lines must always transmit signals from the output terminal of one block to the input terminal of another block. On exception to this is a line can tap off of another line, splitting the signal to each of two destination blocks, as shown below (click the figure to download the model file called split.mdl).



Lines can never inject a signal *into* another line; lines must be combined through the use of a block such as a summing junction.

A signal can be either a scalar signal or a vector signal. For Single-Input, Single-Output systems, scalar signals are generally used. For Multi-Input, Multi-Output systems, vector signals are often used, consisting of two or more scalar signals. The lines used to transmit scalar and vector signals are identical. The type of signal carried by a line is determined by the blocks on either end of the line.

Simple Example

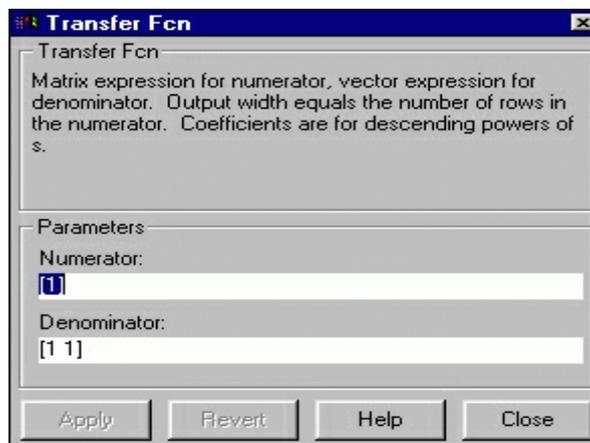


The *simple* model (from the model file section) consists of three blocks: Step, Transfer Fcn, and Scope. The Step is a **source block** from which a step input signal originates. This signal is transferred through the **line** in the direction indicated by the arrow to the Transfer Function **linear block**. The Transfer Function modifies its input signal and outputs a new signal on a line to the Scope. The Scope is a **sink block** used to display a signal much like an oscilloscope.

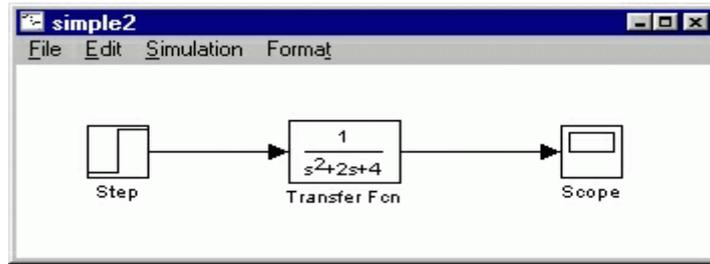
There are many more types of blocks available in Simulink, some of which will be discussed later. Right now, we will examine just the three we have used in the *simple* model.

Modifying Blocks

A block can be modified by double-clicking on it. For example, if you double-click on the "Transfer Fcn" block in the *simple* model, you will see the following dialog box.

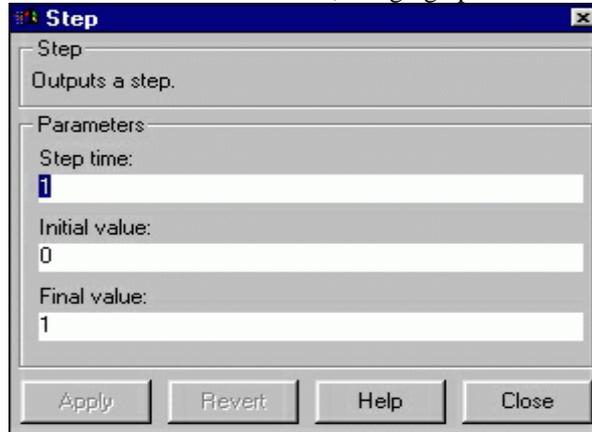


This dialog box contains fields for the numerator and the denominator of the block's transfer function. By entering a vector containing the coefficients of the desired numerator or denominator polynomial, the desired transfer function can be entered. For example, to change the denominator to s^2+2s+1 , enter the following into the denominator field: [1 2 1] and hit the close button, the model window will change to the following,

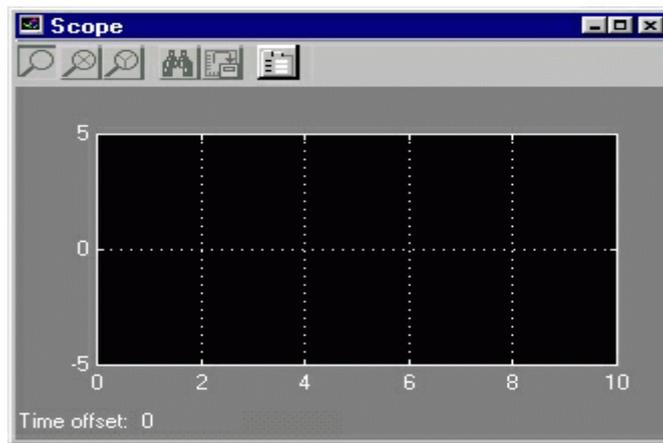


which reflects the change in the denominator of the transfer function.

The "step" block can also be double-clicked, bringing up the following dialog box.



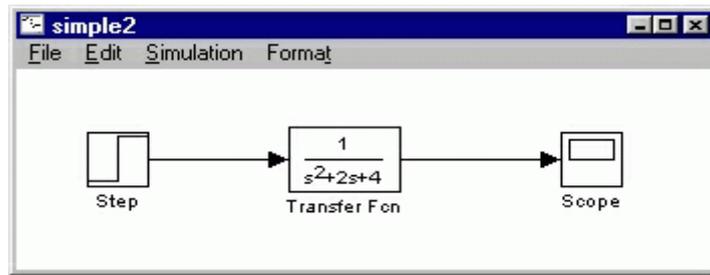
The default parameters in this dialog box generate a step function occurring at time=1 sec, from an initial level of zero to a level of 1. (in other words, a unit step at t=1). Each of these parameters can be changed. Close this dialog before continuing. The most complicated of these three blocks is the "Scope" block. Double clicking on this brings up a blank oscilloscope screen.



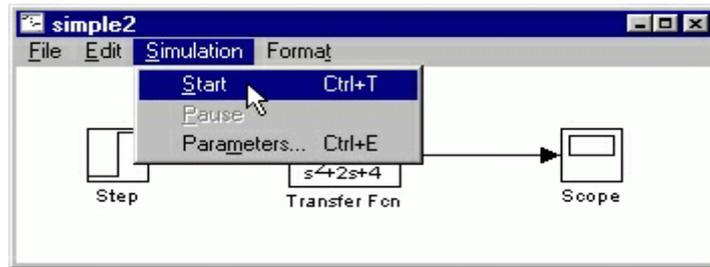
When a simulation is performed, the signal which feeds into the scope will be displayed in this window. Detailed operation of the scope will not be covered in this tutorial. The only function we will use is the auto scale button, which appears as a pair of binoculars in the upper portion of the window.

Running Simulations

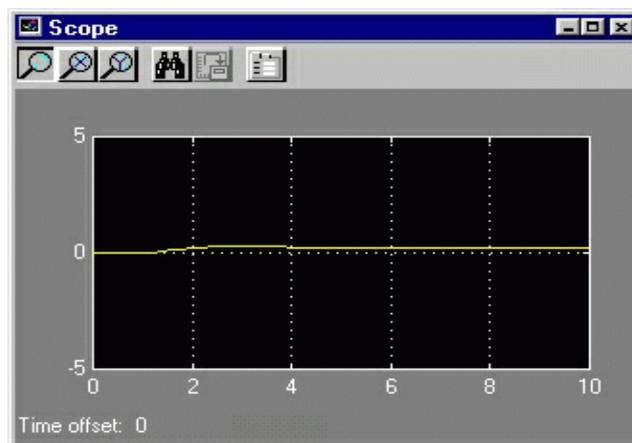
To run a simulation, we will work with the following model file:



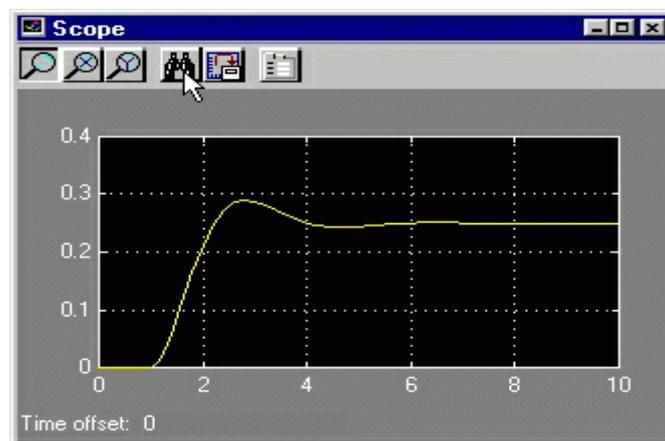
Before running a simulation of this system, first open the scope window by double-clicking on the scope block. Then, to start the simulation, either select **Start** from the **Simulation** menu (as shown below) or hit Ctrl-T in the model window.



The simulation should run very quickly and the scope window will appear as shown below.

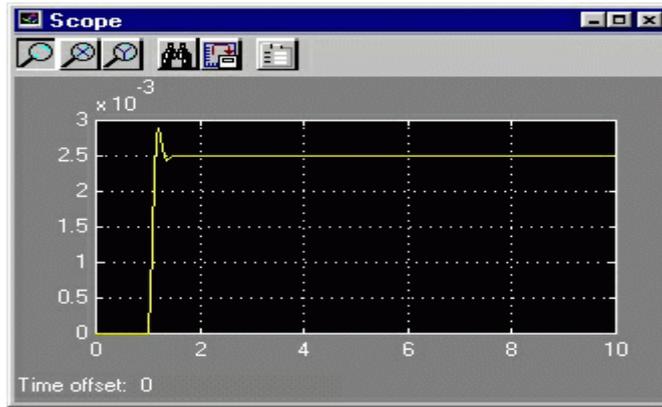


Note that the simulation output (shown in yellow) is at a very low level relative to the axes of the scope. To fix this, hit the auto scale button (binoculars), which will rescale the axes as shown below.

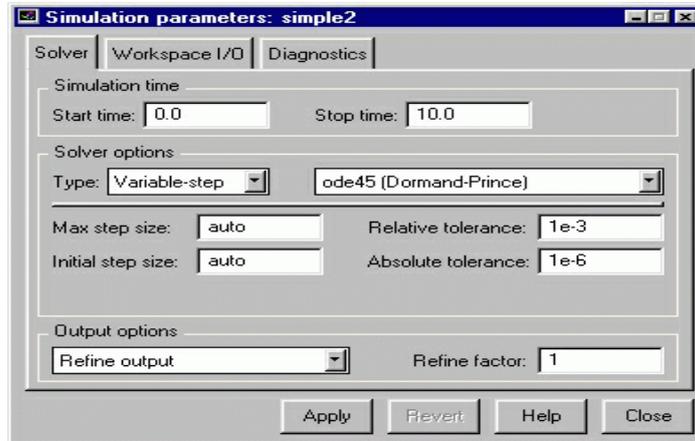


Note that the step response does not begin until $t=1$. This can be changed by double-clicking on the "step" block. Now, we will change the parameters of the system and simulate the system again. Double-click on the "Transfer Fcn" block in the model window and change the denominator to
 $[1 \ 20 \ 400]$

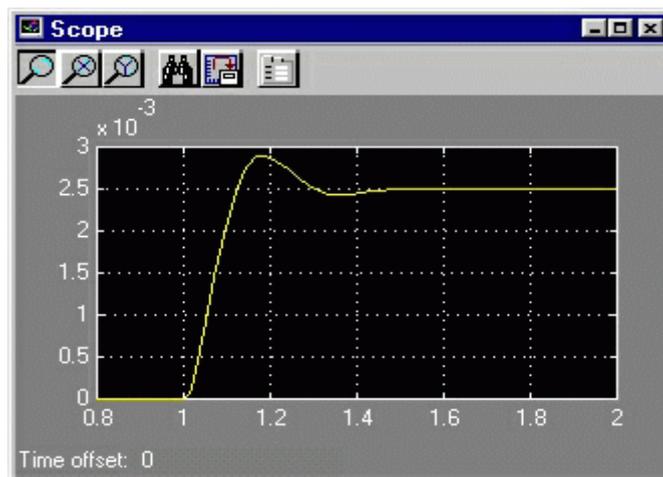
Re-run the simulation (hit Ctrl-T) and you should see what appears as a flat line in the scope window. Hit the auto scale button, and you should see the following in the scope window.



Notice that the auto scale button only changes the vertical axis. Since the new transfer function has a very fast response, it compressed into a very narrow part of the scope window. This is not really a problem with the scope, but with the simulation itself. Simulink simulated the system for a full ten seconds even though the system had reached steady state shortly after one second. To correct this, you need to change the parameters of the simulation itself. In the model window, select **Parameters** from the **Simulation** menu. You will see the following dialog box.



There are many simulation parameter options; we will only be concerned with the start and stop times, which tell Simulink over what time period to perform the simulation. Change **Start time** from 0.0 to 0.8 (since the step doesn't occur until $t=1.0$). Change **Stop time** from 10.0 to 2.0, which should be only shortly after the system settles. Close the dialog box and rerun the simulation. After hitting the auto scale button, the scope window should provide a much better display of the step response as shown below.



IX. CONCLUSION

In classical DTC, as the torque ripple is maintained within hysteresis band, switching frequency changes with speed. Moreover, the torque ripple is important problem at low speed. So using constant switching frequency a desired torque ripple can be achieved at low speeds where it really matters. The torque ripple for this SVM-DTC is significantly improved and switching frequency is maintained constant. Numerical simulations have been carried out showing the advantages of the SVM-DTC method with respect to the conventional DTC.

REFERENCES

- [1] S. Jianguo and C. Quanshi, "Research of electric vehicle IM controller based on space vector modulation direct torque control," *Proceedings of the Eighth International Conference on Electrical Machines and Systems, ICEMS 2005*, vol. 2, pp. 1617-1620, 2005.
- [2] D. Ocean, L. Romeral, J.A. Ortega, J. Cusido, and A. Garcia, "Discrete space vector modulation applied on a PMSM motor," *12th International Power Electronics and Motion Control Conference, EPE-PEMC 2006* p. 320-325, 2006.
- [3] H.R. Keyhani, M.R. Zolghadri, and A. Homaifar, "An extended and improved discrete space vector modulation direct torque control for induction motors," *35th Annual IEEE Power Electronics Specialists Conference*, Germany, pp. 3414-3420, 2004.
- [4] R.H. Ahmad, G.G. Karady, T.D. Blake, and P. Pinewski, "Comparison of space vector modulation techniques based on performance indexes and hardware implementation," *23rd International Conference on Industrial Electronics, Control and Instrumentation, IECON 97*, vol. 2, p. 682-687, 1997.
- [5] I. Takashi and T. Noguchi, "A new quick-response and high-efficiency control of an induction motor," *IEEE Trans. Industry Applications*, vol. A-22, no.5, pp. 820-827, 1986.
- [6] M. Depenbrock, "Direct self control (DSC) of inverter-fed induction machines," *IEEE Trans. Power Electronics*, vol. 3, no. 4, pp. 420-429, 1988.
- [7] M. Jin, J. Qiu, C. Shi, and R. Lin, "A fuzzy DTC method with a SVM defuzzification to permanent magnet synchronous machine," *The 30th Annual Conference of the IEEE Industrial Electronics Society, Korea* p. 3196-3199, 2004
- [8] M. Vasudevan and R. Arumugam, "New direct torque control scheme of induction motor for electric vehicles," *5th Asian Control Conference*, pp. 377-383, 2004.
- [9] A. Kumar, B.G. Fernandes, and K. Chatterjee, "Simplified SVPWM DTC of 3-phase induction motor using the concept of imaginary switching times," *The 30th Annual Conference of the IEEE Industrial Electronics Society, Korea*, pp. 341-346, 2004.
- [10] U. Senthil and B.G. Fernandes, "Hybrid space vector pulse width modulation based direct torque controlled induction motor drive," *IEEE 4th Annual Power Electronics Specialist Conference, PESC'02*, vol. 3, p. 1112-1117, 2003.
- [11] . Chen, K.L. Fang, and Z.F. Hu, "A scheme of fuzzy direct torque control for induction machine," *Proceedings of the Fourth International Conference on Machine Learning and Cybernetics, Guangzhou*, pp. 03-807, 2005.
- [12] H.I. Okumus, "Improved direct torque control of induction machine drives," *PhD Thesis, University of Bristol, UK*, July 2001.
- [13] L. Tang, M.F. Rahman, "A new direct torque control strategy for flux and torque ripple reduction for induction motors drive by using space vector modulation," *IEEE 32nd Annual Power Electronics Specialists Conference, PESC 2001*, vol. 3, pp. 1440-1445, 2001.
- [14] D. Swierczynski, M.P. Kazmierkowski, and F. Blaabjerg, "DSP based direct torque control of permanent magnet synchronous motor (PMSM) using space vector modulation (DTC-SVM)," *Proceedings of the 2002 IEEE International Symposium on Industrial Electronics, ISIE 2002*, vol. , pp. 723-727, 2002.