

Enhanced Performance of DTC-DSC of Induction Machine utilizing 3-Level Cascade H-Bridge Multilevel Inverter

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Abstract—The paper presents a new 3L DTC-DSC scheme for induction motor driver by selecting proper voltage vector for medium and high application. In conventional 3L DTC two different voltage vectors are assigned to vary flux for low speed, medium speed and high speed applications. This paper purposes a scheme for low speed operation of induction machines by using the same technique as conventional 3L DTC. However for a high speed operation, only a single voltage vector is applied thus resulting dodecagon flux locus. The new scheme also improves the torque capabilities and the dynamic of torque performances.

I. INTRODUCTION

An induction motor is the most widely used due to its low cost, high realibility and and performances. Different technique ranging from the inexpensive constant voltage/frequency ratio strategy to the sophisticated field oriented control (FOC) can be used to control torque in an induction motor. The FOC method requires the knowledge of the position of rotor flux vector to properly control the component of the stator current. Basically there are two methods to obtain the position of the rotor flux which are indirect field oriented control (IFOC) and direct field oriented control (DFOC). In pratical, the implementation of the FOC method are very complex due to the requirement of the flux sensor such as search coil and Hall effect based device[1,2].

In order to overcome the complexity of the FOC scheme, a direct torque control (DTC) and direct self control (DSC) was introduced by Takahashi, Nagochi from Japan and Deenbrock from Germany respectively. The basic concepts of DTC is to control the electromagnetic torque and flux linkage directly and independently using the eight voltage vectors[3]. The DTC scheme offers many advantages over other high performance torque controllers such as only a stator resistance parameter is required to estimate the statir flux and high-torque control performance can be established by applying appropriate selection of voltage vectors via a look-up table which is without complex modulator, current regulator and frame transformation.

DSC scheme is slightly different from the DTC where the lookuptable is not implemented in DCS scheme. Besides, only a single voltage vector is selected in order to control flux of induction motor thus resulting hexagonal flux locus.

Although there are many advantages of the DTC and DSC schemes over vector controller, it still has few drawbacks such as large torque ripple and variable switching frequencies. This is due to the switching state of the inverter is updated once every sampling time and the inverter keeps the same state until the output of each hysteresis controller change thus large ripples in torque and flux linkage occurs [4,5]. Besides that the switching frequency varies with load, rotor speed and the bandwidth of the two hysteresis controller. Futhermore the conventional DTC and DSC schemes have some disadvatages when operating at high frequency mainly due to switching losses and limitation of the device rating. Thus, it can be only used for low and medium power application due to the limitation of the available voltage vector [6,].

The lack of the available voltage vector is further improved by researchers by implementing multilevel inverter in the DTC scheme. By applying multilevel more voltage vector available to optimise the selection of voltage vector. By selecting an appropriate voltage vector, the torque and flux ripple could be minimized. Multilevel inverter used in high power application could create high power and reduce harmonics[7,8]. Basically there are three topologies available regarding the multilevel inverter[9,10]. Neutral point clamped topology was first introduced by Nabae [11,12]. The output voltage waveform has better performances in comparison with the conventional inverter. Later on this topology was further improved by Bhagwat and Stefanovic by using multiple level and generically known as diode clamped multilevel inverter which requires the voltage blocking capability of the clamping diode varies with the level [12]. Meynard introduced flyingback capacitor [13]. Instead of clamping diode , the voltage across the open switch is constrained by clamping diode. Finally cascaded half bridge multilevel is introduced (CHMI). The major advantage of this inverter is the isolated DC power supply requirement on each phase thus make it as

an attractive selection for low voltage and high-power applications.

This paper proposes a simple way to achieve dynamic torque and improve the torque capability by using hybrid of DTC (low speed operation) DSC (high speed operation) as compared to the conventional DTC scheme. In this paper the basic principle of direct self control (DSC) will be briefly explained in Section II. However the conventional DTC scheme will not be explained since this scheme is well explained and widely discussed in many technical papers.

II. BASIC DIRECT SELF CONTROL OPERATION

Direct self control was first introduced by M. Depenbrock from Germany [4]. The major differences between the conventional DTC and DSC are the requirement of sector identification and a lookuptable for selecting voltage vector. In DSC scheme, the six voltage vectors (V_1, V_2, \dots, V_6) are used to generate hexagonal flux locus which are determined according to the output generated from three units of hysteresis comparators ($\Psi_{s,A}^+, \Psi_{s,b}^+, \Psi_{s,c}^+$). They are two required parameters in order to generate the outputs which are commands of the stator flux ($\Psi_{s,ref}$) and the phase components ($\Psi_{s,A}, \Psi_{s,B}, \Psi_{s,C}$). For the torque hysteresis part, when the output torque satisfies its demand ($T_{stat} = 0$), the torque hysteresis comparator produces the signal that determines zero voltage vector (V_0, V_7). For constant torque region, the generation of the switching states (S_a, S_b, S_c) which determines the voltage vector can be described by the following equations:

$$S_a = \Psi_{s,A}^+, S_b = \Psi_{s,B}^+, S_c = \Psi_{s,C}^+ \quad \text{for } T_{stat} = 1 \quad (1)$$

$$S_a = 0, S_b = 0, S_c = 0 \quad \text{for } T_{stat} = 0 \quad (2)$$

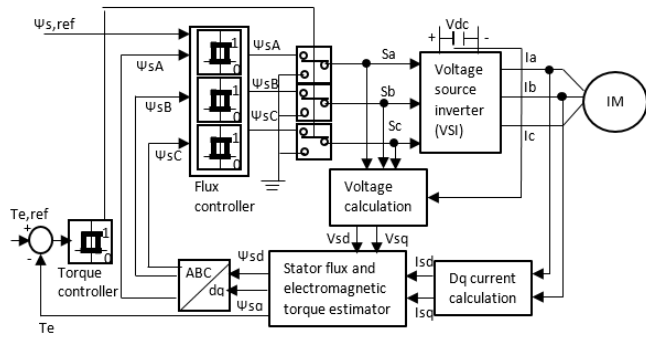


Fig.1 : Structure of Direct Self Control induction machines

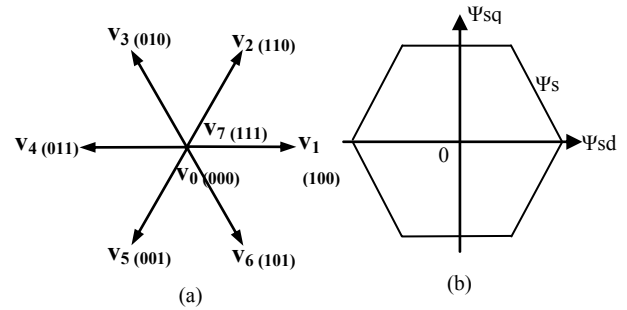


Fig.2. Flux vector to hexagonal in DSC scheme. (a) Voltage vector (b) Flux locus

III. 3-LEVEL CASCADED H-BRIDGE MULTILEVEL INVERTER

This section describes briefly about the power circuit configuration, available voltage vector and circuit operation of 3L CHMI.

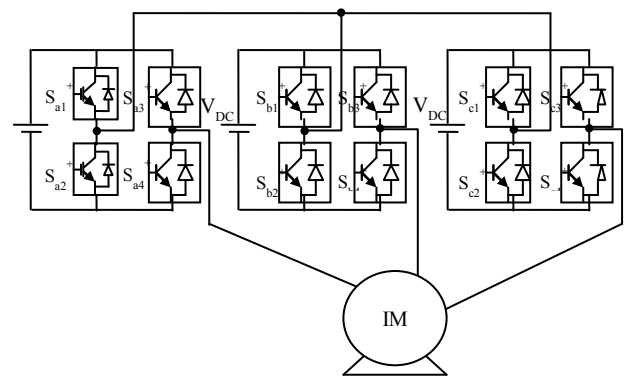


Fig.3 : Structure of Direct Self Control induction machines

For a three phase system, the output of the three identical structure of single phase CHMI can be connected in either wye or delta configuration. Fig 3 illustrates the schematic diagram of wye connected 3-level CHMI with separated dc sources. For a three phase 3-level CHMI one half bridge dc source with four switches are needed per phase. Thus, total of three half bridge dc sources involving 12 power switches are required for this circuit configuration. This means that six pairs of gating signals have to be generated to be fed to the switches. The switching are designed in such a way that only one pair of switches is operating at the carrier frequency while the other pair operates at the references frequency, thus having two high and low frequency switches

IV. THE PROPOSED METHOD

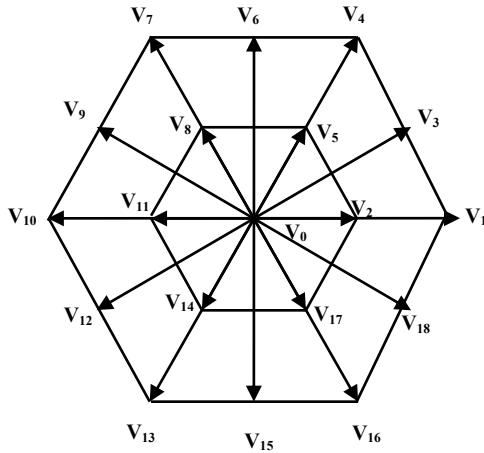


Fig.4 Available voltage vector in 3-level CHMI.

Since the power cells are connected in series, the total phase voltage generated by the inverter can be expressed as

$$v_{iN} = \sum_{j=1}^m v_{ij} = \sum_{j=1}^m v_{ij} (S_{j1} - S_{j2}), \quad i \in a, b, c \quad (3)$$

where V_{iN} is the total output voltage of phase i (with respect to the neutral of the inverter N), V_{ij} is the output of voltage of cell j of phase I, m is the number dc supply per phase and (S_{j1}, S_{j2}) the switching state associated with to cell j. The output voltage of V_{ij} by one of the four binary combination of the switching state with '1' and '0'.

The inverter generates 3^m different voltage level. For 3-level CHMI the number of dc supply per phase is only one therefore it can generate $3^1 = 3$ different voltage level. In a three phase system, the number of different voltage vector is given by $3L(L - 1) + 1$, where L is the number of levels. For example in 3L CHMI, the number of different voltage vector is $3(3)(3 - 1) + 1 = 19$

Table 1 shows the switching state of 3-level CHMI in producing three different level of voltages. The same switching state is applied for each phase a, b or c.

TABLE I
3-LEVEL CHMI SWITCHING STATE FOR PHASE A
Cell per phase (Example for phase A)

Sa1	Sa3	Sa2	Sa	Total
0	1	1	0	+Vdc
0 & 1	0 & 1	0 & 1	0 & 1	0
1	0	0	1	-Vdc

This section describes briefly about the method that are applied to enhance the performance of the induction motor. The primary aim is to generate dodecagon flux locus during medium and high speed operation. In order to achieve it few modification need to be done in conventional DTC scheme.

Basic DTC scheme offers an instant torque and flux control by selecting appropriate voltage vector in controlling both flux and torque. During a large torque error condition, no zero voltage vector is selected in order to reduce the torque. At the same time, the flux hysteresis will regulate the flux to follow a circular path by using two active voltage vectors. Due to the rapid changes in the flux vector position, a quick dynamic torque response is achieved. However this method does not give the fastest dynamic torque response simply because two active voltage vectors are used during the dynamics condition. The fastest dynamic torque can be achieved by selecting only a single voltage vector instead of two voltage vector within a sector.

In order to fully understand the behavior of the voltage vectors on the torque production in DTC hysteresis based drives, the torque equation can be expressed :

$$\tau_e = \frac{3}{2} p \frac{k}{\sigma L_s} |\Psi_s| |\Psi_r| \sin(\delta) \quad (4)$$

where :

- δ = load angle, is the angle between stator and rotor fluxes,
- p = number of poles,
- $k = L_m / L_s$,
- $\sigma = 1 - L_m^2 / (L_s L_r)$, with L_s, L_r and L_m as the stator, rotor and mutual inductance respectively.

By neglecting the voltage drop in stators resistance R_s , the stator flux vector is the time integral of the stator voltage vector. Therefore for small period of T_s :

$$\Delta \Psi_s = v_s T_s \quad (5)$$

If stator and rotor flux amplitudes are kept constant (4), it is clear that the torque could be controlled directly by changing the load angle. Note that, the variation of stator flux vector is affected by the application of voltage vector while the rotor flux vector rotates continuously at uniform angular velocity lagging the stator flux vector, as defined in Fig. 5. By considering (4) and (5) it shows that the stators voltage vector can be used to manipulate the load angle and consequently to control the torque.

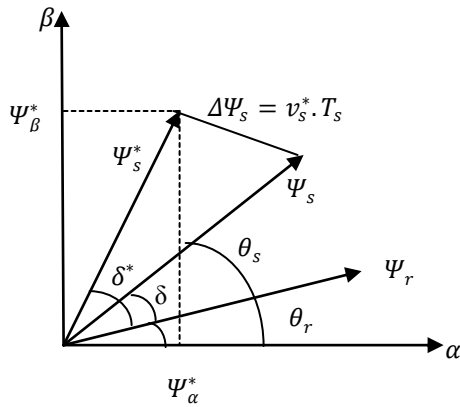


Fig.5 DTC operating principle: Stator voltage influence over the stator flux voltage

The selection of group of voltage vectors can be inherently determined by the torque error status produced from the 5-level torque hysteresis comparator as well as 2-level hysteresis comparator as shown in Fig. 6. In the proposed strategy, a few modification is done in the lookuptable and sector definition. The conventional DTC method is used during low speed motor operation in which two voltage vector are used to form a circular flux as shown in Fig. 7. However, only one voltage vector is selected and held for high speed operations in order to achieve fastest dynamic torque as shown in Fig.8

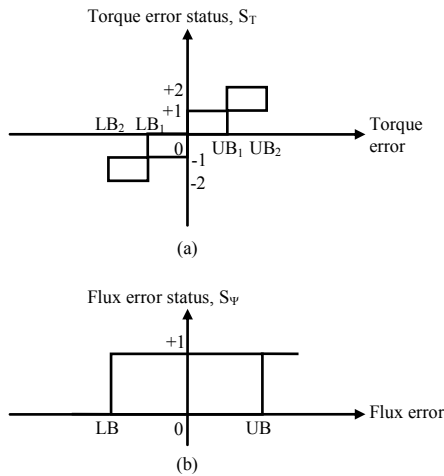


Fig.6 Hysteresis comparators for (a) 5- Level hysteresis band for torque controller (b) 2-Level hysteresis band for flux controller.

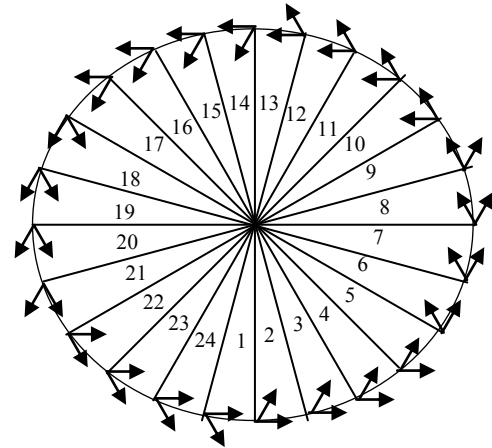


Fig.7 Two voltage vectors for low speed operation.

As can be seen from Fig. 7, 24-sector is defined and two voltage vectors are employed for each sector. 24 sectors are defined in order to hold the voltage vector from $V_1, V_3, V_4, V_6, V_7, V_9, V_{10}, V_{12}, V_{13}, V_{15}, V_{16}$ and V_{18} in producing dodecagon flux locus as shown in Fig. 8.

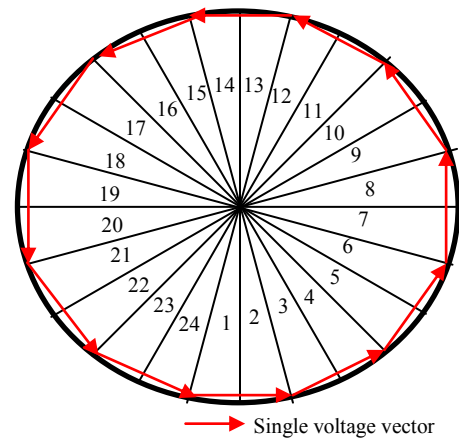


Fig.8 Single voltage is applied for every two sector to produce dodecagon flux locus.

TABLE 2
LOOKUPTABLE 3L CHMI FOR PURPOSED SCHEME

Sector 1					
Fs \ Ts	2	1	0	-1	-2
1	V_1	V_{17}	V_0	V_{11}	V_{10}
0	V_1	V_2	V_7	V_8	V_{10}

Sector 2					
Fs \ Ts	2	1	0	-1	-2
1	V_1	V_2	V_7	V_{14}	V_{10}
0	V_1	V_5	V_0	V_{11}	V_{10}

Sector 3					
Fs \ Ts	2	1	0	-1	-2
1	V_3	V_2	V_0	V_{14}	V_{12}
0	V_3	V_5	V_7	V_{11}	V_{12}

Sector 4					
Fs \ Ts	2	1	0	-1	-2
1	V_3	V_2	V_7	V_{14}	V_{12}
0	V_3	V_5	V_0	V_{11}	V_{12}

Sector 5					
Fs \ Ts	2	1	0	-1	-2
1	V_4	V_2	V_0	V_{14}	V_{13}
0	V_4	V_5	V_7	V_{11}	V_{13}

Sector 6					
Fs \ Ts	2	1	0	-1	-2
1	V_4	V_5	V_7	V_{17}	V_{13}
0	V_4	V_8	V_0	V_{14}	V_{13}

Sector 7					
Fs \ Ts	2	1	0	-1	-2
1	V_6	V_5	V_0	V_{17}	V_{15}
0	V_6	V_8	V_7	V_{14}	V_{15}

Sector 8					
Fs \ Ts	2	1	0	-1	-2
1	V_6	V_5	V_7	V_{17}	V_{15}
0	V_6	V_8	V_0	V_{14}	V_{15}

Sector 9					
Fs \ Ts	2	1	0	-1	-2
1	V_7	V_5	V_0	V_{17}	V_{16}
0	V_7	V_8	V_7	V_{14}	V_{16}

Sector 10					
Fs \ Ts	2	1	0	-1	-2
1	V_7	V_8	V_7	V_2	V_{16}
0	V_7	V_{11}	V_0	V_{17}	V_{16}

Sector 11					
Fs \ Ts	2	1	0	-1	-2
1	V_9	V_8	V_0	V_2	V_{18}
0	V_9	V_{11}	V_7	V_{17}	V_{18}

Sector 12					
Fs \ Ts	2	1	0	-1	-2
1	V_9	V_8	V_7	V_2	V_{18}
0	V_9	V_{11}	V_0	V_{17}	V_{18}

Sector 13					
Fs \ Ts	2	1	0	-1	-2
1	V_{10}	V_8	V_0	V_2	V_1
0	V_{10}	V_{11}	V_7	V_{17}	V_1

Sector 14					
Fs \ Ts	2	1	0	-1	-2
1	V_{10}	V_{11}	V_7	V_5	V_1
0	V_{10}	V_{14}	V_0	V_2	V_1

Sector 15					
Fs \ Ts	2	1	0	-1	-2
1	V_{12}	V_{11}	V_0	V_5	V_3
0	V_{12}	V_{14}	V_7	V_2	V_3

Sector 16					
Fs \ Ts	2	1	0	-1	-2
1	V_{12}	V_{11}	V_7	V_5	V_3
0	V_{12}	V_{14}	V_0	V_2	V_3

Sector 17					
Fs \ Ts	2	1	0	-1	-2
1	V_{13}	V_{11}	V_0	V_5	V_4
0	V_{13}	V_{14}	V_7	V_2	V_4

Sector 18					
Fs \ Ts	2	1	0	-1	-2
1	V_{13}	V_{14}	V_7	V_8	V_4
0	V_{13}	V_{17}	V_0	V_5	V_4

Sector 19					
Fs \ Ts	2	1	0	-1	-2
1	V_{15}	V_{14}	V_0	V_8	V_6
0	V_{15}	V_{17}	V_7	V_5	V_6

Sector 20					
Fs \ Ts	2	1	0	-1	-2
1	V_{15}	V_{14}	V_7	V_8	V_6
0	V_{15}	V_{17}	V_0	V_5	V_6

Sector 21					
Fs \ Ts	2	1	0	-1	-2
1	V_{16}	V_{17}	V_0	V_8	V_7
0	V_{16}	V_2	V_7	V_5	V_7

Sector 22					
Fs \ Ts	2	1	0	-1	-2
1	V_{16}	V_{17}	V_7	V_{11}	V_7
0	V_{16}	V_2	V_0	V_8	V_7

Sector 23					
Fs \ Ts	2	1	0	-1	-2
1	V_{18}	V_{17}	V_0	V_{11}	V_9
0	V_{18}	V_2	V_7	V_8	V_9

Sector 24					
Fs \ Ts	2	1	0	-1	-2
1	V_{18}	V_{17}	V_7	V_{11}	V_9
0	V_{18}	V_2	V_0	V_8	V_9

*Ts = Torque Status

*Fs = Flux Status

V. SIMULATION RESULTS

In order to clarify the proposed of 3-level DTC- DSC CHMI, the algorithm has been carried out by using the Simulink\MATLAB environment in order to achieve the main propose of fastest dynamic torque, torque ripple minimization and extent the torque capability. In this section, two simulation results will be compared with similar condition applied for 3-Level DTC-DSC CHMI and 2-Level conventional inverter.

Fig. 9 and Fig. 11 show that the output responses at three conditions applied for 3-Level DTC-DSC CHMI and 2-Level conventional inverter namely, 1: reference torque changes from 0 Nm to 5 Nm for low speed, 2: 5 Nm to 10 Nm for medium speed and 3: 5 Nm to 10 Nm for high speed. both results show that the torque ripple is greatly reduced. The first row, represents the torque response after applying the step change of torque demand in the system. The second row illustrates the waveform of the flux error (WB and the third and fourth row show the voltage for d-axis component and q-axis component.

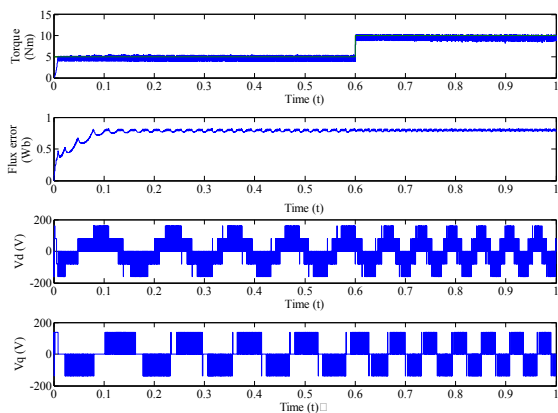


Fig.9. Torque response,flux error,vd and vq for the conventional DTC

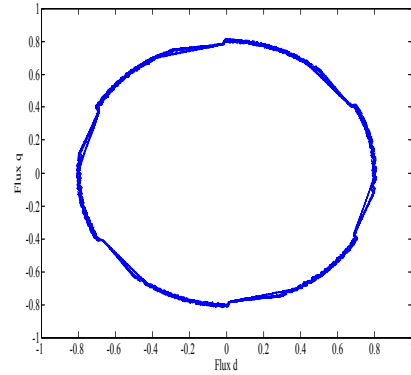


Fig.10. Flux locus for conventional DTC

Fig. 10 and Fig. 12 show the flux locus for for 2 level conventional DTC scheme and 3L DTC-DSC scheme. From Fig 10,two active voltage vectors are selected to form a circular flux locus and Fig. 12 shows only one active voltage is selected and held to form dodecagon flux locus. Fig 13 shows the fastest dynamic torque response. From Fig 13, it deduces that by holding a single voltage vector the fastest dynamic torque could be achieved.

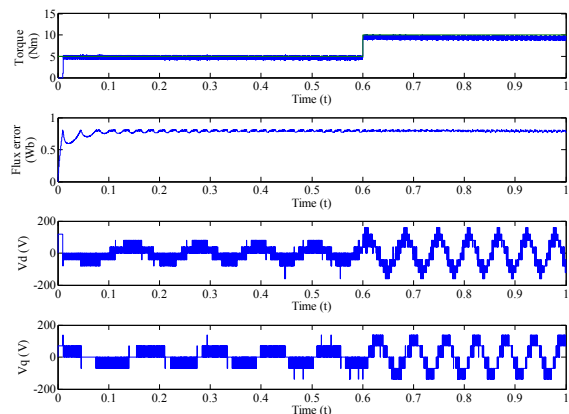


Fig.11. Torque response,flux error,vd and vq for the 3L DTC-DSC CHMI

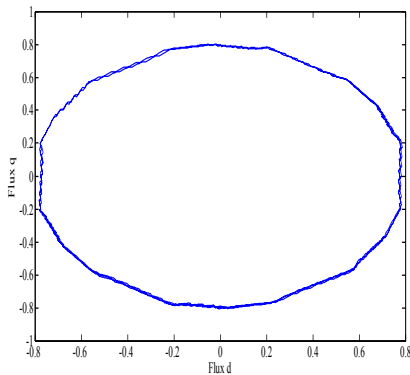


Fig.12. Flux locus dodecagon for 3L DTC-DSC CHMI

VI. CONCLUSION

DTC scheme offers many advantages over other high performance torque controllers. It has showed that, the use of multilevel inverter has potential to replace the conventional 2-Level inverter for performance enhancement the of motor drives. From the simulation results, it has been proven that the 3-Level DTS-DSC CHMI is more excellent in performance especially during dynamic torque response. From the simulation results, the torque ripple is also reduced by using the multilevel inverter in comparison to the conventional inverter. Moreover, 3-Level inverter of DTC-DSC is suitable for high power applications since it offers fastest dynamic torque response.

VI. ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Education (MOE) and Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant FRGS/2013/FKE/TK02/02/1/F00159 for this research.

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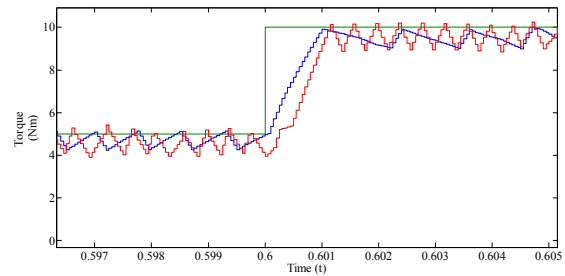


Fig.13. dynamic torque response (blue) 3L DTC-DSC CHMI (red) 2 level conventional DTC

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