THE PRELIMINARY RESEARCH FOR IMPLEMENTATION OF IMPROVED DTC SCHEME OF HIGH PERFORMANCE PMSM DRIVES

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Abstrak

Kendali torsi langsung (DTC) adalah salah satu pendekatan kendali yang banyak digunakan pada sistem kendali PMSM. Metode ini mendukung tanggapan torsi yang sangat cepat dan presisi. Bagaimanapun, metode DTC tidak sepenuhnya sempurna dan mempunyai beberapa kekurangan. Sangat banyak peneliti yang telah mengusulkan modifikasi skema DTC dasar untuk kemudi PMSM. Semua kontribusi ini mengijinkan peningkatan unjuk kerja, tetapi pada waktu yang sama menjadikan skema DTC menjadi lebih kompleks. Lebih lanjut, sistem kendali kemudi PMSM umumnya berbasis pada mikrokontroller dan DSP. Beberapa peneliti juga telah menggunakan DSP dan FPGA bersama-sama untuk membangun DTC untuk kemudi AC. Hal ini memungkinkan peningkatan unjuk kerja, tetapi akan meningkatkan biaya. Karena alasan-alasan di atas, paper ini mengusulkan skema DTC baru untuk diterapkan hanya berbasis FPGA. Penelitian awal ini telah menunjukkan bahwa skema DTC yang diusulkan dapat mereduksi riak fluks dan torsi secara signifikan. Oleh karena itu, paper ini juga merekomendasikan realisasi skema DTC yang diusulkan berbasis FPGA saja, agar mendukung eksekusi komputasi sangat cepat. Implementasi ini akan melahirkan potensi untuk mengganti tidak hanya motor induksi tetapi juga motor servo DC pada sejumlah kemudi unjuk kerja tinggi pada proses industri, komersial, domestik dan aplikasi-aplikasi kemudi milter modern.

***Kata kunci**: DTC, FPGA, PMSM*

Abstract

The direct torque control (DTC) is one of control approache that is used commonly in PMSM control system. This method supports a very quick and precise torque response. However, the DTC method is not perfect and has some disadvantages. Many researchers have been proposed to modify the basic DTC scheme for PMSM drive. All this contributions allow performance to be improved, but at the same time they lead to more complex schemes. Furthermore, the PMSM drive control systems are usually based on microcontroller and DSP. Some researchers also have been used DSP and FPGA together to develop DTC for AC drives. These allow improving the performance, but they will increase cost. For the reason above, this paper proposed a new DTC scheme to apply only based on FPGA. The preliminary research showed that the proposed DTC sheme can reduce torque and flux ripples significantly. Therefore, this paper also recomend to realize proposed DTC scheme based on FPGA in order to support to execute very fast computation.The implementation is hoped that it will very potential to replace not only the induction motor but also the DC servo motor in a number of industrial process, commercial, domestic and modern military applications of high-performance drive.

***Keywords**: DTC, FPGA, PMSM*

1. INTRODUCTION

Development of practical permanent magnet synchronous motor (PMSM) technology permits lower speed and higher torque output as compared to a conventional AC induction motor. It provide the attributes of efficiency, reliability, quiet operation, etc, plus have the

additional advantages of higher power density, superior power factor (low current), low rotor temperature, and synchronous operation. Advancement in magnet technologies allows operation at higher temperatures without permanent magnetization loss. This technology permits reduction in the number of mechanical drive components required in many machine applications. These advantages have resulted in an increased application of the PMSM in vehicles drive (or hybrid vehicles), robotic, ships, windmills, compressors, pumps and fans. Furthermore high-performance, highly dynamic drives with PMSMs have many applications in such industrial processes and transport systems where a fast and accurate torque response is required. As reliability and cost of modern PMSM drives are of importance, advanced control techniques have been developed.

The control approaches used most commonly in PMSM control system are V/f scalar control, vector control or Field Oriented Control (FOC) and Direct Torque Control (DTC) [1-5]. The DTC technology was proposed by Takahashi [6] and Depenbrock [7] in middle of 1980s. It has many potential compared scalar control and FOC. It has attracted more attentions and dramatically developed with its novel control means, compact system structure and excellent static state performance. In the basic DTC system, the voltage vector is selected among the ones deliverable by the inverter feeding the motor with the help of hysteresis controllers. The method gives the drives a very fast torque response, but it is not perfect and has some disadvantages. It stills left some problems [1-5, 8-45], such as: variable switching frequency, high torque and flux ripples, require of high sampling time, current and torque distortion and drift in flux estimator. Many researchers [1-2, 8-40, 42] during last decade have been proposed to modify the basic switching table, hysteresis comparator and flux estimator of the basic DTC scheme for PMSM drives. All this contributions allow performance to be improved, but at the same time they lead to more complex schemes.

Furthermore, the PMSM drive control systems are usually based on microcontroller [46-50] and digital signal processing (DSP) [11, 13, 32-46, 48]. These software-based platforms are often not adequate to implement simple control functions which require very high speed response. The Field Programmable Gate Array (FPGA) is programmable hardware-based platform, so it supports to execute very fast tasks [51-58]. Some researchers also have been used DSP and FPGA together to develop DTC for AC drives [43-45]. These allow improving the performance, but they will increase cost. For this reason, in this paper proposed a new effective DTC scheme will be developed and proposed to apply only based on FPGA. By using the proposed DTC scheme and implement it on a system based on FPGA, it is hoped that a novel DTC scheme (simple, robust, quick and accurate torque and flux response, constant frequency switching, without a speed sensor and low cost) for practical very high performance PMSM drives can be realized in hardware-platform based on FPGA. It will support high performance operation of PMSM control in many industrial processes, transport systems and modern military applications, such as: industrial robotics, vehicles drive (or hybrid vehicles), ships, windmills, compressors, pumps, fans and launching of rocket. Furthermore, it also will improve energy efficiency.

2. PERMANENT MAGNET MOTOR SYNCHRONOUS (PMSM)

Nowadays, a PMSM has been more and more popular with its simple structure, small volume and high power density, reliable operation, high torque capability, and especially high efficient. PMSM mostly applies to the occasions of fast torque and high performance. PMSM are widely used in high-performance drives. The drive train of hybrid electric vehicles (HEV) is one application of PMSM in the traction drive application. The main shaft servo system of computer numerical control (CNC) machine tool and servo system of industrial robot are also adopting PMSM gradually. Other applications of PMSM are in railway traction, propulsion vehicle, adjustable-speed pump drives, super-high speed centrifugal compressors, washing machine, paper machine, high current automotive applications, wheelchair, and spinning machines applications.

Recently, an increased interest in application of PMSM in speed controlled drives has been observed. This is stimulated mainly by [1,2]:

- Development of modern high switching frequency semiconductor power devices (as for example IGBT module of 5-th generation)

- Specialized DSP for AC drive application with integrated PWM system, A/D converter as well as processing of encoder signal
- Hardware-based specialized device platform (as for example FPGA and CPLD)

With using suitable control, the PMSM has the potential of replacing not only the induction motor but also the DC servo motor in a number of industrial, modern military, commercial and domestic applications of variable speed drives.

3. THE CONTROL APPROACHES OF PMSM DRIVES

The control approaches used most commonly in PMSM control system are constant V/f scalar control and vector control (FOC and DTC) [1-5]. As it can be seen from Fig. 1, vector control provides much better performance in comparison with scalar control, and it can also to avoid oversaturation of the magnetic circuit, increasing the magnetizing current and losses.

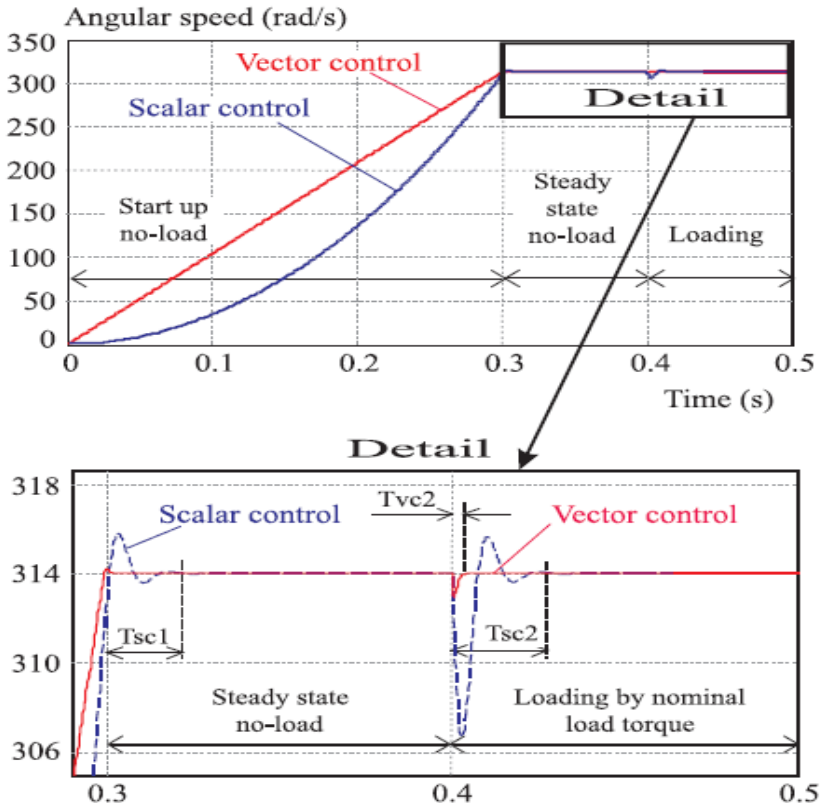


Fig. 1. Angular speed of PMSM controlled by Vector control and Scalar control strategies.

The FOC gives the PMSM high performance, but it is not simple. In this method, the motor equations are transformed in a coordinate system that rotates in synchronism with permanent magnet flux. A block diagram of a basic FOC scheme is presented in Fig. 2.

The problem of decoupling the stator current in a dynamic fashion is avoided by DTC methods. This vector technology was proposed Takahashi [6] and Depenbrock [7] for induction motor drives in the middle of 1980's; it also was proposed and developed in 1990's for PMSM drive [1, 4, 35, 36]. Fig. 3 shows the diagram of a DTC PMSM drive. DTC provides a very quick and precise torque response without the complex field orientation block and the inner current regulation loop. Hence, the approach is very well suited for operation at saturated voltage.

Due to the DTC of PMSM drive is shown in Fig. 3, usually a DC bus voltage sensor and two output current sensors are needed for the flux and torque estimator. Position sensor is not necessary for the torque and flux control. The switching state of inverter is updated in each

sampling time. Within each sampling interval, the inverter keeps the state until the output states of the hysteresis controller change. Therefore, the switching frequency is usually not fixed; it changes with the rotor speed, load and bandwidth of the flux and torque hysteresis comparator. In order to estimate the stator flux and torque, an integrator is used. The voltage vector can be obtained by multiplying the DC bus voltage with selected voltage space vector. The current vector can be obtained by measuring any 2 of the 3 phase current. The stator resistance is used as a constant for flux estimation. It can vary by as much as 100% due to temperature and will deteriorate the system performance significantly, especially a low speed [1, 16].

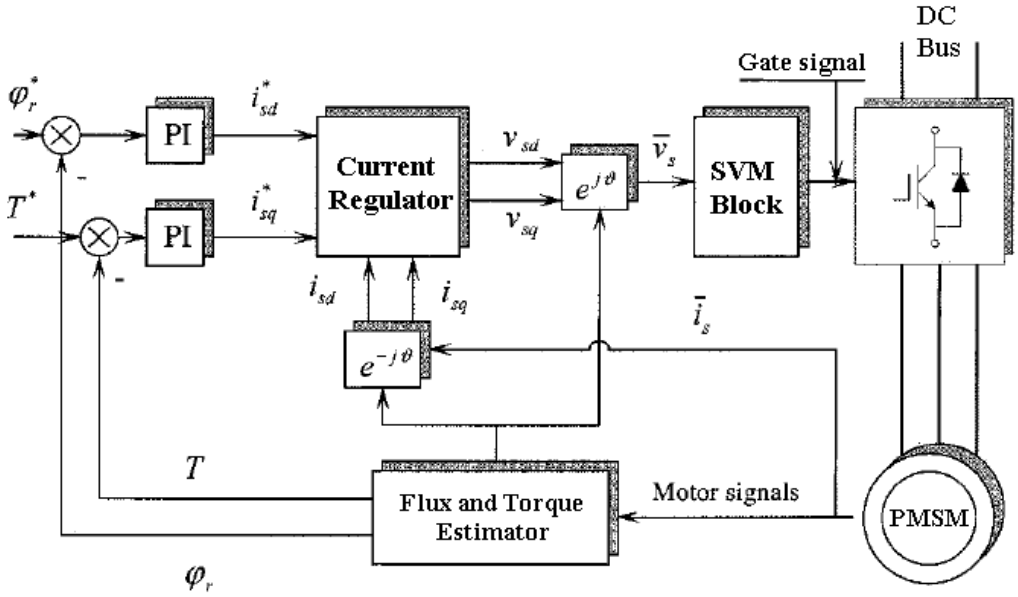


Fig. 2. Basic FOC scheme of PMSM drive system.

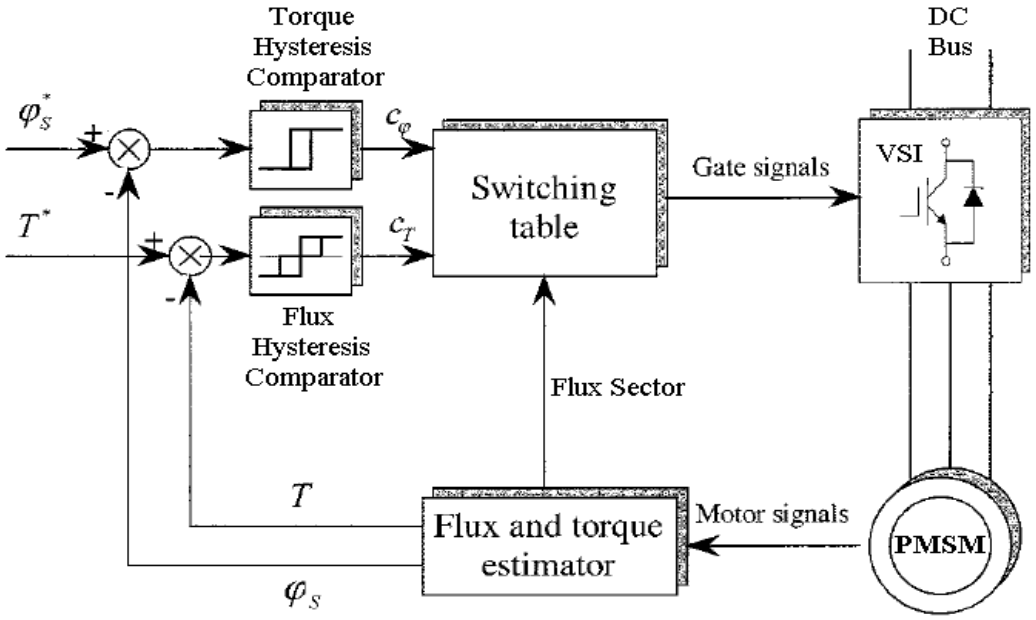


Fig. 3. Basic DTC scheme of PMSM drive system.

Table 1. Comparison between FOC and DTC

Comparison	FOC	DTC
Field orientation (reference frame transformation)	Required	Not required
Control scheme	Complex	Simple
Stator current control	Yes	No
Motor parameters required	R_s, R_r L_{ls}, L_{lr}, and L_m	R_s
Sensitivity to motor parameter variations	Sensitive	Not very sensitive
PWM Scheme	Carrier based, SVM or Hysteresis band	Hysteresis band
Switching behaviour	Defined (for carrier based and SVM)	Variable

The DTC scheme has attracted more attention and dramatically developed with novel control means, compact system structure and excellent static state performances. It is very simple. The configuration is much simpler than the FOC system due to the absence of frame transformer, pulse width modulator and position encoder, which introduce delays and requires mechanical transducer. Comparison between FOC and DTC is shown in Table 1. It offers fast torque and flux control due to its inherently decoupled control structure of torque and flux which is directly based slope on the instantaneous errors in torque and flux. The voltage vector of the DTC is selected among the ones deliverable by the inverter feeding the motor with the help of hysteresis controllers. It comprises of switching table and hysteresis comparator, which are relatively easy to be implemented [1, 36].

4. IMPROVED DIRECT TORQUE CONTROL SCHEMES FOR PMSM DRIVES

Although the DTC scheme is an attractive proposition in its own right, this basic DTC for PMSM drive has some drawback. It stills lefts some problems [1-5, 8-45], such as: variable switching frequency, torque and flux ripples, require of high sampling time, current and torque distortion and drift in flux estimator. In order to get an excellent performance, many modifications of the basic switching table, hysteresis comparator and flux estimator of the basic DTC (similar techniques those used in induction machine) have been proposed during last decade, as like:

a. Using new switching table
   - Subdividing voltage vector [11, 25, 28, 33]
   - Variety of structure switching table [15]
   - PWM (Pulse Width Modulation) [10, 13]
   - SVM (Space Vector Modulation) [1, 3, 5, 12, 14, 17, 29, 37-39, 42]
b. Modification of structure of inverter:
   - Three level inverter [23]
   - Matrix converter [30]
c. Modification of hysteresis controller
   - Direct Reactive Energy and Torque (DRET) control method [9]
   - Reference flux vector calculator (RFVC) [16]
   - Variable structure control (VSC) [24]
d. New of torque and flux estimator
   - Maximum torque per ampere or maximum torque per flux (MTPF) [19]
   - Different flux linkage reference [26]

Due to some modification of the DTC techniques for PMSM above, most researches are done in simulation with Matlab/Simulink. Although, some researchers also have been tried to realize DTC system for PMSM based on DSP [11, 17, 29, 32, 35-39, 42]. From their research, show that all this contributions allow performance to be improved, but at the same time they lead to more complex schemes.

5. THE PRELIMINARY RESEARCH FOR IMPLEMENTATION OF IMPROVED DTC SCHEME

The PMSM drive control systems are usually based on microcontroller [46-50] and DSP [11, 13, 32-46, 48]. These software-based platforms are often not adequate to implement simple control functions which require very high speed response. The high performance sensorless AC drives require a fast digital realization of many mathematical operations concerning control and estimators' algorithms, which are time consuming. Therefore developing of custom-built digital interfaces as well as digital data processing blocks and sometimes even integration of ADC converters into one integrated circuit is necessary. Due to the fact that developing an ASIC chip is expensive and laborious, the FPGA based solution should rather be used on the design stage of the algorithm. Other, the FPGA is programmable hardware-based platform, so it supports to execute very fast tasks [51-58].

In recent years, some researchers have been used the FPGA for motor control applications, as like:

- Implementation of basic DTC for induction motor drive [51-52, 56-57]
- Implementation SVM for PMSM drive [53-54]
- Implementation FOC for PMSM drive [55, 58]
- Implementation SVM-DTC for induction motor drive [59]

Regarding [51-59], implementations of the systems based on FPGA have some advantages: quickly implemented, reprogrammable, simplifying test and validation of new control strategies, an appropriate solution in order to boost performances of controllers, low cost development, use of convenient software tools and more significant integration density, and FPGA technology is now considered by an increasing number of designers in various fields of application. This is because an FPGA-based implementation of controllers can efficiently answer current and future challenges of this field. Among them, we can quote:

- *The decrease of the cost*, for at least three reasons: the use of an architecture based only on the specific needs of the algorithm to implement, the application of highly advanced and specific methodologies improving implementation time also called "*time to market*", and the expected development in VLSI design that will allow integrating a full controller system with its analog interface in a single chip, also called System on a Chip;
- *The confidentiality*, a specific architecture, integrating the know-how of a company, is not easily duplicable;
- *The embedded systems* with many constraints as in aircraft applications;
- *The improvements of control performances*. For example, execution time can be dramatically reduced by designing dedicated parallel architectures. Besides, an FPGA-based controller can be adapted in run-time to the needs of the plant by dynamically reconfiguring it.

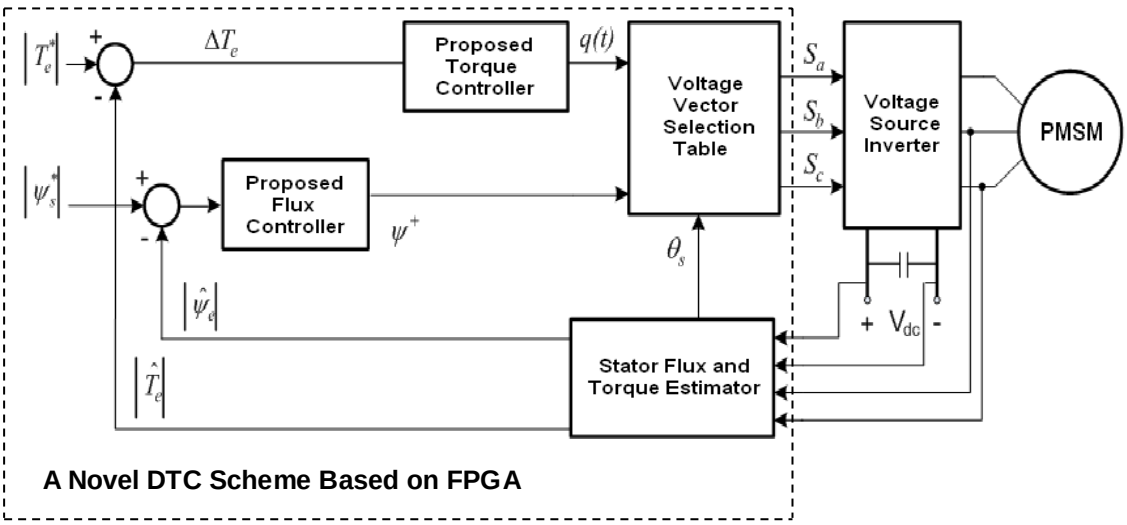
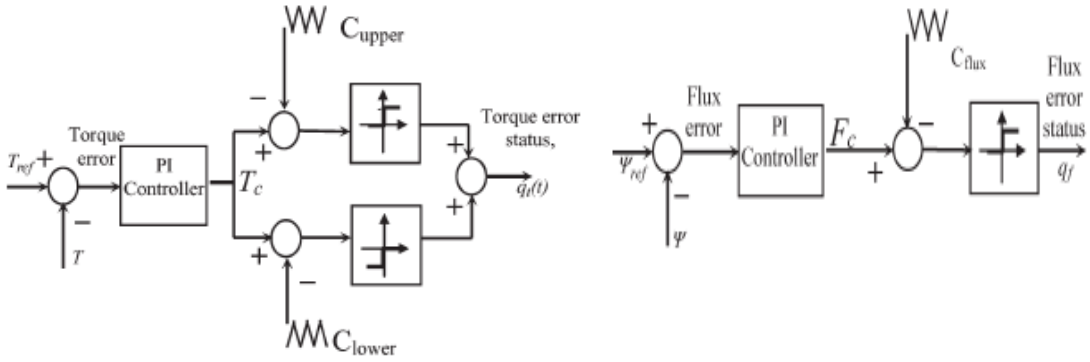


Fig 4. Block diagram of proposed a novel DTC scheme of PMSM drive using FPGA



a. Proposed torque controller with any modification from [49]

b. Proposed flux controller with any modification from [49]

Figure 5. Proposed torque and flux controller of a novel DTC scheme for PMSM drive

Regarding the reasons above, this paper proposed to develop a novel DTC scheme for PMSM drive using slightly modified DTC scheme in [43-45, 60] (because basically DTC scheme of induction motor drive has a few different with DTC scheme of PMSM drive) and propose to apply only based on FPGA. Block diagram of proposed novel DTC scheme of PMSM drive using FPGA shown in Figure 4 and its proposed torque and flux controller is shown in Figure 5. In this research, stator flux and torque estimator be calculated from voltage model of PMSM.

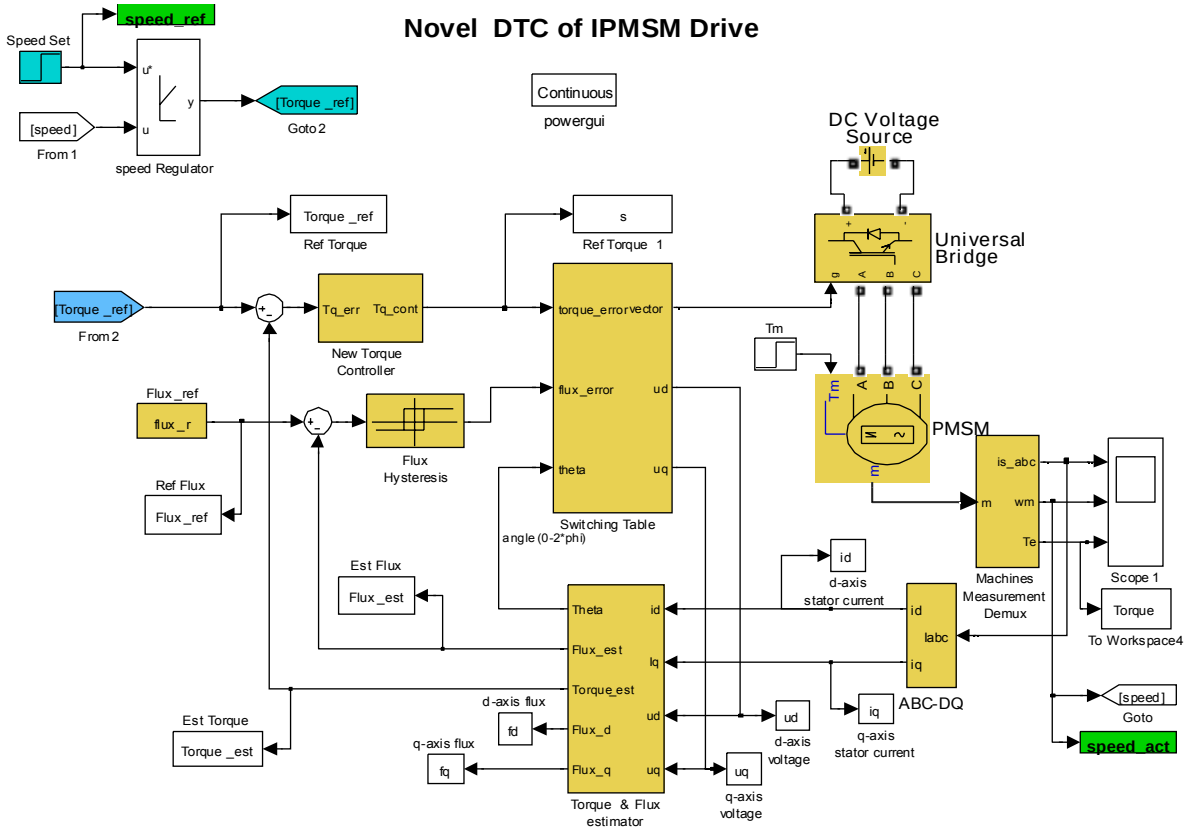


Fig. 6. A block diagram of a proposed DTC system for PMSM drives

As preliminary research, simulation of proposed DTC scheme above that it be compared with hysteresis DTC has been developed. The PMSM DTC simulation system is based on the Matlab/Simulink 6.6 (R2007a). A block diagram of a proposed DTC system for PMSM is shown in Fig.6, which includes the ABC to DQ transformation, torque and flux estimator subsystem, etc.

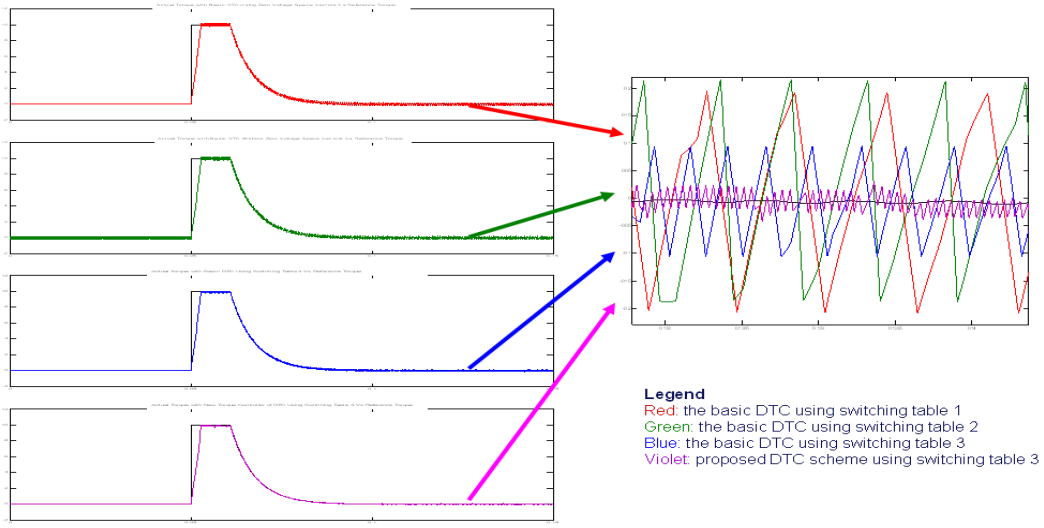


Fig. 7. Comparison of the electromagnetic torque response under the basic DTC using eight-state table, using six-state table, using bipolar torque eight-state table, and under proposed DTC scheme

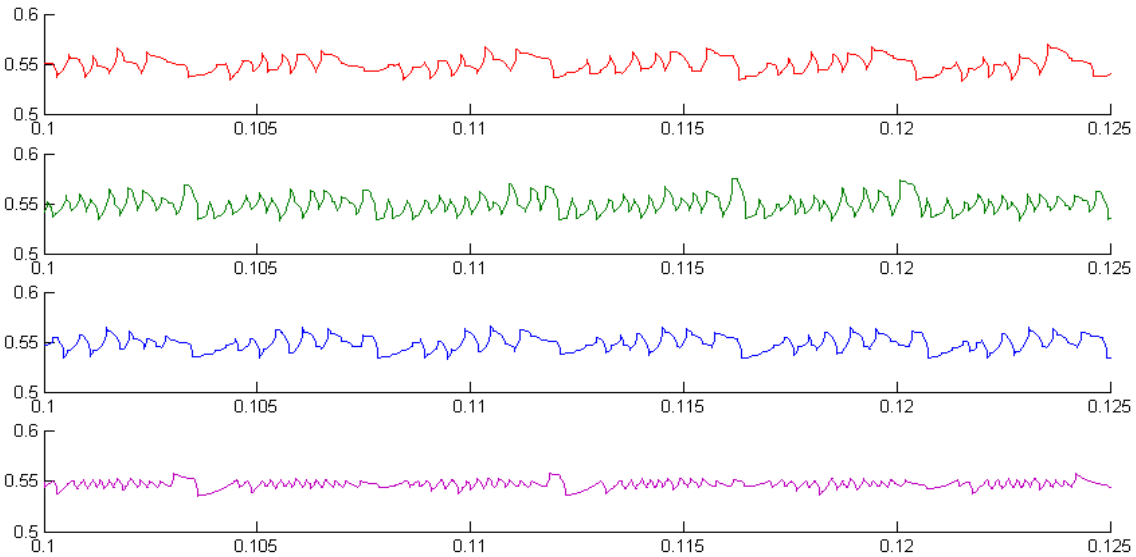


Fig.8. Comparison of the flux response under the basic DTC using eight-state table, using six-state table, using bipolar torque eight-state table, and under proposed DTC scheme

The comparison of the electromagnetic torque and flux response simulation under the basic DTC using eight-state table, using six-state table, using bipolar torque eight-state table, and under proposed DTC scheme is shown consequently in Fig.7 and Fig. 8. It is seen, that the proposed DTC system for PMSM can reduce torque and flux ripples. Therefore, this paper

recomend to realize proposed DTC scheme for PMSM drive based on FPGA, in order to support to execute very fast computation.

6. CONCLUSION

The DTC method provides a very quick and precise torque response without the complex field orientation block and the inner current regulation loop. However, this method is not perfect and has some disadvantages, such as: variable switching frequency, torque and flux ripples and require of high sampling time. This paper proposed a new DTC scheme to apply only based on FPGA. The preliminary research showed that the proposed DTC sheme can reduce torque and flux ripples significantly. Therefore, this paper also recomend to realize proposed DTC scheme for PMSM drive based on FPGA in order to support to execute very fast computation.The implementation is hoped that it will very potential to replace not only the induction motor but also the DC servo motor in a number of industrial process, commercial, domestic and modern military applications of high-performance drive.

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