Digital Implementation of Direct Torque Control of Induction Machines

Muhd Zharif Rifqi Zuber Ahmadi, Auzani Jidin, Mohd Razali Mohamad Sapiee*, Md Nazri Othman, Ravin Nair P.Nagarajan, M.H Jopri*
Faculty of Engineering Technology* and Faculty of Electrical Engineering
Universiti Teknikal Malaysia Melaka (UTeM)
Hang Tuah Jaya, 76100 Durian Tunggal, Malacca, Malaysia

***Abstract*- This paper presents a digital implementation of Direct Torque Control (DTC) for three-phase induction machine using eZdspF28335. It can be shown that the execution of DTC algorithm can be optimized by applying IQ-Math blocks which are available in MATLAB software. Applying this approach, the complex digital calculation for all mathematic operations such as multiplication, division, subtraction and etc., can be simplified and hence calculate at faster rate. It is also emphasized that the selection of Q-point that represents the fraction length of data should be appropriate in order to achieve high-degree of computational accuracy. The DTC algorithm based IQ-Math blocks was simulated and implement in real practice using eZdsp F28335 to verify its feasibility and effectiveness.**

Keywords:

I. INTRODUCTION

Direct Torque Control (DTC) of induction motor drives have become increasingly popular in the drives industry due to simple control structure and it also offers high dynamic performance of instantaneous electromagnetic torque. Since it was introduced in the middle of 1980's [1][2] many researchers have shown great interest to make several modifications and improvements.

Initially, variations of DTC were proposed to overcome the two main disadvantages of a conventional DTC scheme, namely larger torque ripple and variable inverter's switching frequency. The problems normally occur in digital implementation due to the use of hysteresis controllers. For examples, the problems have been solved by using variable hysteresis band [3], controlled duty ratio cycle technique [4][5], constant frequency torque controller [6] and space vector modulation approach [7][8].

In recent years, the improvements of DTC performances for achieving fast torque dynamic [9] and high-torque capability [10] had gained much attention. Furthermore, some researchers explored the application of multilevel inverters in DTC, to obtain the most optimal switching vectors with more number of switching vectors provided [11][12]. These improvements are mainly important for high-power medium voltage applications, especially for electric vehicle and traction drives.

However, until now, no study on digital computational of DTC has been reported, particularly in obtaining optimal calculation (i.e. minimum error with maximum sampling frequency). The research takes an effort to report the optimal way in digital computation by using IQ-math (with fixed-point) approach. It can be proven that the modeling of DTC using IQ-Math blocks can obtain minimum error and high sampling frequency for simulation as well as experimentation. The rest of sections are described as follows; Section II explains the principle of DTC, Section III presents the simulation and experimented models of DTC, Section IV discusses the optimization of DTC algorithm using IQ-Math blocks, then followed by Section V that shows the simulation and experimental results and, finally Section VI deduces the conclusion of the paper.

II. Principle of Direct Torque Control

The behavior of induction machine in DTC drives can be described in terms of space vectors by the following equations written in stator stationary reference frame.

$$\mathbf{v_s} = r_s\mathbf{i_s} + \frac{d\mathbf{\Psi_s}}{dt} \quad (1)$$

$$0 = r_r\mathbf{i_r} - j\omega_r\mathbf{\Psi_r} + \frac{d\mathbf{\Psi_r}}{dt} \quad (2)$$

$$\mathbf{\Psi_s} = L_s\mathbf{i_s} + L_m\mathbf{i_r} \quad (3)$$

$$\mathbf{\Psi_r} = L_r\mathbf{i_r} + L_m\mathbf{i_s} \quad (4)$$

$$T_e = \frac{3}{2}P\Psi_s i_s \sin\delta \quad (5)$$

where P is the number of pole pairs, ω_r is the rotor electric angular speed in rad./s, L_s, L_r and L_m are the motor inductances and δ is the angle between the stator flux linkage and stator current space vectors.

Fig.1 shows a de-coupled control structure of DTC hysteresis-based induction machine as proposed in [1]. The de-coupled control enables a quick instantaneous and dynamic control for both stator flux and electromagnetic torque. This also makes possible for the flux (Ψ_s) and torque (T_e) to be controlled independently using two-level and three-level hysteresis comparators, respectively. The hysteresis comparators are responsible to produce appropriate errors status (S_T and S_Ψ) which are then used along with the sector flux information (S_n) to index a look-up table for selecting suitable switching states (S_a, S_b, S_c).

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The stator flux can be estimated using stator voltage equation (1). Equations (6) and (7) represent the expression of the respective d-axis and q-axis of stator flux components in a stationary reference frame.

$$\Psi_{\mathbf{s,d}} = \int \left(v_{s,d} - r_s i_{s,d}\right) dt \tag{6}$$

$$\Psi_{\mathbf{s,q}} = \int \left(v_{s,q} - r_s i_{s,q}\right) dt \tag{7}$$

where $v_{s,d}$ ($i_{s,d}$) and $v_{s,q}$ ($i_{s,q}$) are the d- and q-axis of stator voltage (current) components respectively.

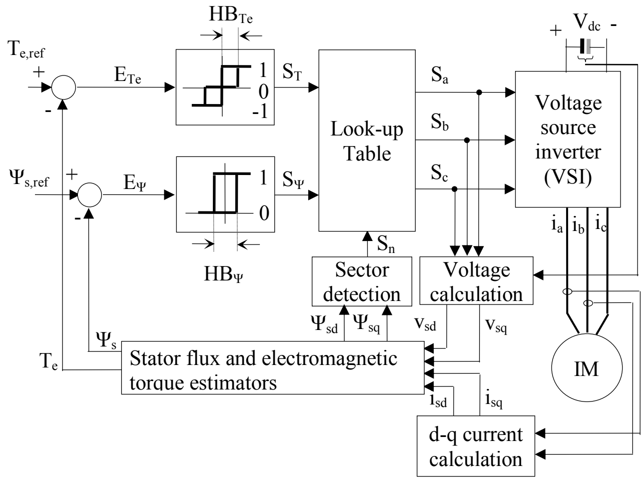

Fig. 1. Structure of DTC of Induction Machine

The magnitude of stator flux that is basically required to represent a DC quantity can be simply obtained as;

$$\Psi_s = \sqrt{\left(\Psi_{s,d}^2 + \Psi_{s,q}^2\right)} \tag{8}$$

The d-axis and q-axis stator voltage components used in equation (6) and (7) can be calculated using switching status (i.e. S_a, S_b, S_c) information as shown below and the eliminating the application of voltage sensors:

$$v_{\mathbf{s,d}} = \frac{1}{3} V_{DC}\left(2S_a - S_b - S_c\right) \tag{9}$$

$$v_{\mathbf{s,q}} = \frac{1}{\sqrt{3}} V_{DC}\left(S_b - S_c\right) \tag{10}$$

where V_{DC} is the DC input voltage of 3-phase voltage source inverter (VSI). If two of the three-phase stator currents (i.e. i_a and i_b) are known/sensed and by then after applying the Clarke Transformation, the d-axis and q-axis components of stator current vector are obtained as below:

$$i_{\mathbf{s,d}} = i_{\mathbf{a}} \tag{11}$$

$$i_{\mathbf{s,q}} = \frac{(i_a + 2i_b)}{\sqrt{3}} \tag{12}$$

The equation of output torque as given in equation (5) can be rewritten into another expression as given in (13), which can be used to estimate the output torque.

$$T_{\mathbf{e}} = \frac{3}{2} P\left(\Psi_{s,d} i_{s,q} - \Psi_{s,q} i_{s,d}\right) \tag{13}$$

where P is the number of pole pairs'.

III. Simulation and Experimentation Models of DTC

This section will discuss the simulation and experimentation models of DTC of induction machine. The DTC algorithm is modeled using IQ-math blocks available in MATLAB. By applying the IQ-math blocks the optimal execution of DTC algorithm can be obtained. The simulation model of DTC using the blocks can be loaded to program the DSP for implementing the DTC hardware system. Figure 2 shows the complete structure of DTC of induction machine which is constructed using MATLAB/Simulink and IQ-math blocks. It can be noticed that manual switches are used for selecting the environment mode either the model is required to perform under simulation mode (i.e. manual switches select lower position) or experimental mode (i.e. manual switches select upper position). For convenience, the discussion on modeling of DTC with IQ-math blocks is limited to the model of stator flux estimation which is the crucial part in obtaining high DTC drive performance.

In practice, the pure integration in equations (6) and (7) in estimating the flux, however causes initial and drift problem due to the DC offset and noise measurement. Thus, a low pass filter replaces by the pure integrator to minimize the problem. By converting the time-domain into Laplace-domain and inserting the term of cut-off frequency in equations (6) and (7), under sinusoidal steady state condition, the d-axis and q-axis component of stator flux are written as

$$\Psi_{\mathbf{s,d}} = \frac{v_{s,d} - i_{s,d} r_s}{j\omega_e + \omega_c} \tag{14}$$

$$\Psi_{\mathbf{s,q}} = \frac{v_{s,q} - i_{s,q} r_s}{j\omega_e + \omega_c} \tag{15}$$

where ω_c is the cut-off frequency of the low pass filter in rad./s which is very small compared to synchronous angular frequency ω_e. In implementing the estimation in digital computation (i.e. DSP), it is necessary to express these equations into discrete forms as follows;

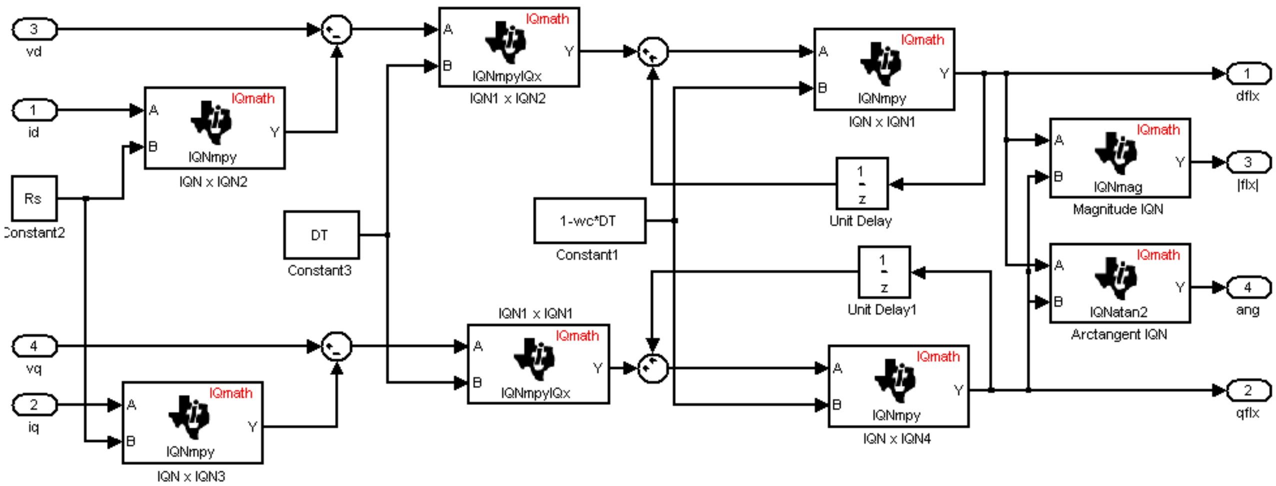

Fig.2. Stator flux estimation using IQ-math blocks

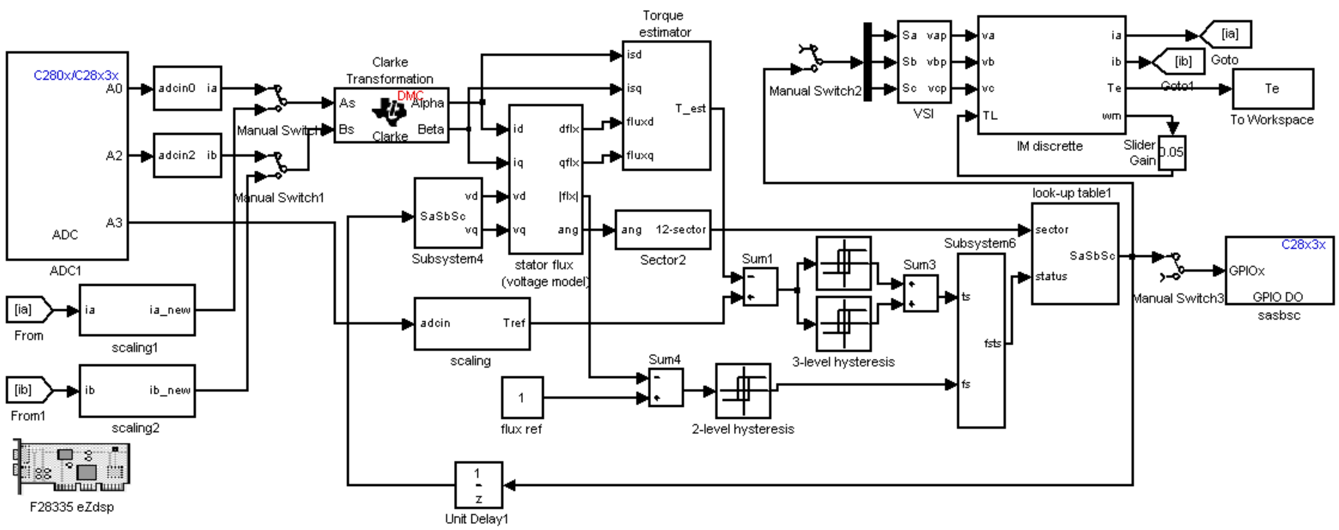

Fig.3. Complete model of DTC of induction machine

$$\Psi_{s,d}(k) = \left[\Psi_{s,d}(k-1) + v_{s,d}(k) - i_{s,d}(k) r_s\right](1 - \omega_c DT) \quad (16)$$

$$\Psi_{s,q}(k) = \left[\Psi_{s,q}(k-1) + v_{s,q}(k) - i_{s,q}(k) r_s\right](1 - \omega_c DT) \quad (17)$$

where DT is the sampling period of simulation and DSP. Based on equations (16) and (17), the estimation of stator flux is constructed using IQ-math blocks as shown in Fig. 2.

IV. OPTIMIZATION OF DTC ALGORITHM USING IQ-MATH BLOCKS

The computational performance of DTC algorithm using IQ-Math blocks is more optimal than that of using conventional Simulink blocks. It can be shown that by applying the complex algorithm, the sampling period, (i.e. time taken to perform one set of instruction for one cycle) may become twice or more if the algorithm is programmed using Simulink blocks. The complex algorithm which causes burden in computations can be simplified or optimized if the algorithm is programmed using IQ-Math blocks. By doing so, the algorithm code can be executed at the minimum sampling period of time.

The digital computations for all operands (e.g. multiplication, division, addition or subtraction) with IQ-math blocks require appropriate selection of quotient-point (Q-point) value according to the length of fraction part. This is to ensure the accuracy of computation, especially in estimating the stator flux which involves various lengths of data.

Consider the 4-bit multiplication example as given in Table I. The example shows that two input numbers are split into two parts, i.e. integer part (I) and fraction part (Q or quotient), where both inputs are defined as I1Q3 format. These type of fixed-point numbers are often called 'IQ' numbers, or for simplicity just Q-numbers. Basically, the multiplication using conventional digital computation approach gives the length of the result by adding both I and Q portions, such that I1Q3*I1Q3 = I2Q6.

For simplification, the intermediate product will be stored with the four bits around the binary point, means that, the multiplication process keeps the data format (I1Q3) in the same format as the input values. In such manner, the speed of calculation can be performed at a higher rate. However, the calculation might not be precise if the selection of Q-point is inappropriate as chosen in the example. The result obtained is ended up with -4/16 stored back to Data Memory, whereas bits 2^{-4} to 2^{-6} are truncated. The correct result should be -3/16.

The IQ-Math approach applies the simplified (or latter) method which provides faster calculation. However, it can cause error in calculation if the Q-point value is not chosen at appropriate value.

TABLE I. AN EXAMPLE OF FOUR-BIT MULTIPLICATION

	Binary	Decimal
	0•1 0 0	1/2
	x 1•1 0 1	- 3/8
	0 0 0 0 0 1 0 0	
	0 0 0 0 0 0 0	
	0 0 0 1 0 0	
	1 1 1 0 0	
	1 1 1 1 0 1 0 0	- 3/16
Accumulator	1 1•1 1 0 1 0 0	
Data memory	1•1 1 0	- 1/4

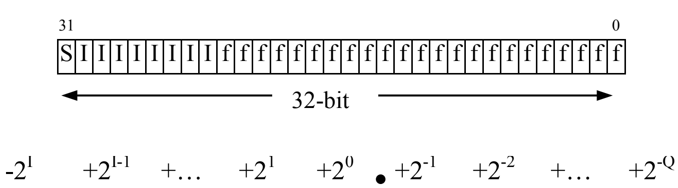

Fig. 4 Fractional representation for data format I9Q23. "I" is integer-fraction and "Q" is Quotient-fraction.

By employing DSP TMS320F28335, it can perform on 32-bit fixed-point and Q point can be located anywhere in the binary representation. This gives the designer/programmer the opportunity to trade off dynamic range against resolution and hence to achieve high degree of accuracy in computing the algorithm. For an example, the fractional representation for data format I9Q23 or Q=23 in 32-bit fixed-point with resolution is 2^{-23}, is shown in Fig. 4. The Most Significant Bit (MSB) denoted as 'S' is a sign bit; S=0 for positive sign and S=1 for negative sign. In order to achieve high order of accuracy, the selection of Q-point should be higher for calculating data which contains small decimal value.

V. SIMULATION AND EXPERIMENTAL RESULTS

The simulation model of the DTC using the IQ-Math blocks was performed using MATLAB/Simulink simulation package. The actual parameters of induction machine as tabulated in Table II were used in the simulation.

TABLE II.
INDUCTION MACHINE PARAMETERS

Stator resistance	9.25 Ω
Rotor resistance	4.51 Ω
Stator self inductance	306.6 mH
Rotor self inductance	306.6 mH
Mutual inductance	290 mH
Moment of inertia	0.01 kg.m^2
Number of poles	4
Rated Speed	1410 rpm
Rated flux	0.5 Wb
Rated torque	5 Nm

In order to highlight the importance of selecting an appropriate Q-point value for high accuracy in estimating the flux, two sets of DTC model were carried out in the simulation, which are defined as follows.

DTC1 *Q-point value is 29 in estimating the flux*

DTC2 *Q-point value is 15 in estimating the flux*

Fig.5. shows the simulation results of d-axis and q-axis flux components obtained in *DTC1* and *DTC2*. Both DTC models control the stator flux at the rated flux (i.e. Ψ_{ref} = 0.5 Wb) to compare the different selection of Q-point values. Fig.6 shows the stator flux locus corresponding to the results obtained in Fig.5. It can be observed from the Fig.5, the control of flux in *DTC1* is under control, on the other hand the control of flux in *DTC2* results in larger amplitude with a DC offset introduced. The effects also can be observed from the Fig.6.

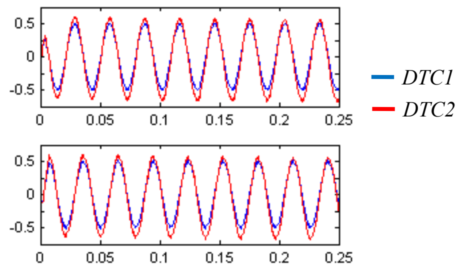

Fig.5. d-axis and q-axis flux components in *DTC1* and *DTC2*.

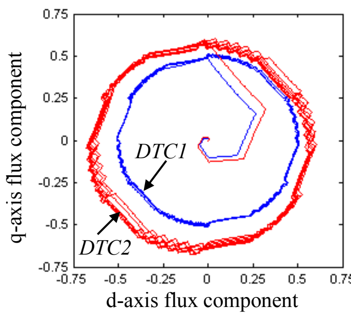

Fig.6. Stator flux locus resulted in *DTC1* and *DTC2*.

The results shown in Fig.5 and 6, indicate that the selection of Q-point value at 29 results in accurate flux control. This is due to the fact that some parameters and calculation involves small decimal values such as sampling period (DT=50µs) and multiplication based on equations (16) and (17).

The IQ-Math based DTC model, i.e *DTC1* is also used to program the eZdspF28335 in realizing the DTC drive system as shown in Fig.7. Some experimental results were obtained as given in Figs.8 to 11 for verifying the effectiveness and feasibility of the IQ-Math model approach in actual DTC drive system.

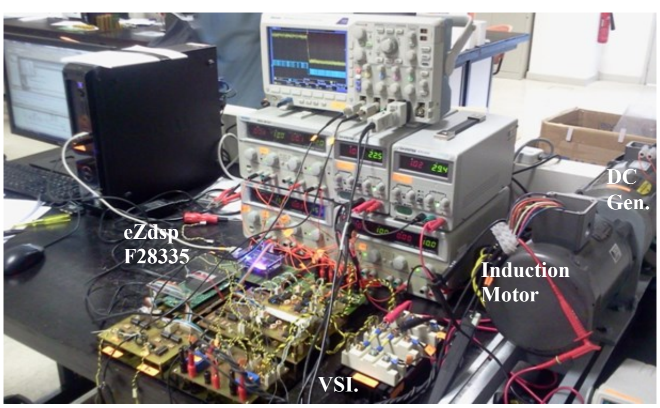

Fig.7. Picture of DTC of Induction Machine

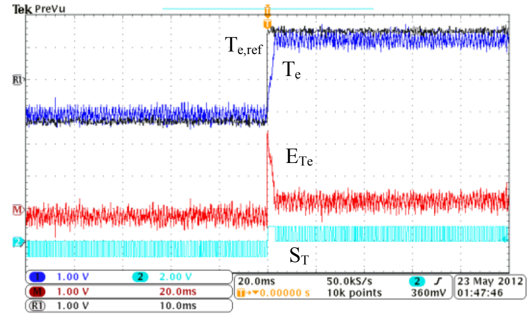

Fig.8. Experimental results for a step change of torque control. Torque (T_e) [2Nm/div], Torque error (E_{TE}) [2Nm/div], and torque error status (S_T) [2-unit/div.]

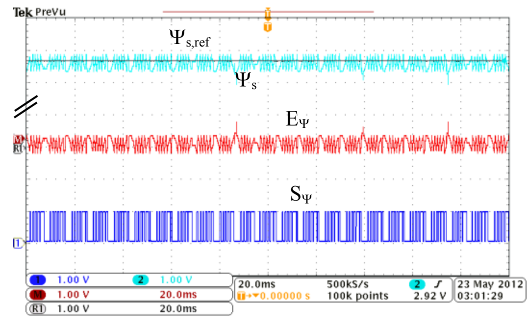

Fig.9. Experimental results of flux control. Flux (Ψ_s) [0.02Wb/div], flux error (E_Ψ) [0.02Wb/div], and flux error status (S_Ψ) [1-unit/div.]

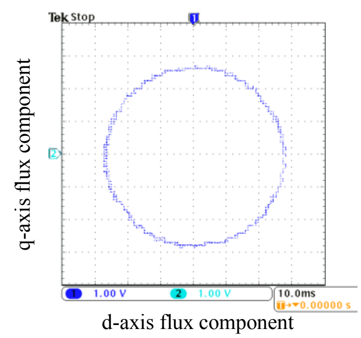

Fig.10. Stator flux locus at rated stator flux

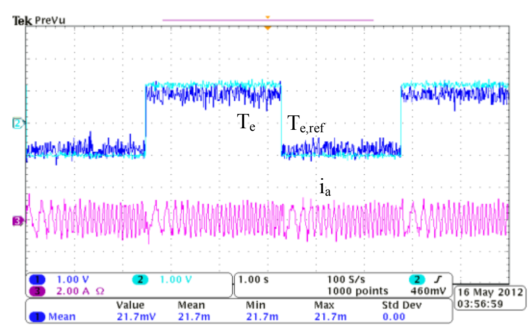

Fig.11. Experimental results of current waveform (i_a) for square wave reference torque. Torque (2Nm/div), current (2A/div)

V. Conclusion

This paper has presented the modeling of Direct Torque Control of induction machine using IQ-math blocks (in MATLAB environment) for simulation and experimentation. It has shown that the computation in DTC is optimized using the blocks instead of using conventional Simulink blocks. However, the appropriate selection of Q-point value is required to achieve proper stator flux estimation and hence improves the DTC operation. From the simulation and experimental results, it showed that the same code/model used in simulation can be used in practical implementation with enhanced sampling frequency and minimized errors.

Acknowledgment

The authors would like to thank the Ministry of Higher Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant PJP/2012/FTK(6C)/S01009 for this research.

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