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PERFORMANCE OF DIRECT TORQUE CONTROL IMPLEMENTED IN SPEED DRIVE

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ABSTRACT

During the last decades, the rapid development of power semiconductor devices has allowed the increased use of adjustable speed ac drives in a variety of applications, especially in the process-control industry. In many applications, the capability of controlling the speed effectively can improve the efficiency of the ac motors and thus lead to large savings in energy. Among the several approaches used to control ac motors is the direct torque control (DTC), occupies an important place. DTC of ac motors is known to have very favorable control performance and implementation properties. The control scheme is based on the control of torque and flux utilizing the stator flux field orientation. Field orientation is achieved using advanced motor theory to calculate the torque directly and without using modulation. DTC enables the control of speed and torque over a very broad range. The torque response is particularly fast and it is possible to maintain constant speed, even when the mechanical load imposes sudden and unexpected mechanical shock. Thus the advancement of this ac drive technology enables the machine to achieve excellent dynamic performance. This paper is an attempt to investigate and evaluate the characteristics and operating principle of DTC scheme. Experimental tests have been carried out using ABB speed drive unit (ACS800 model), squirrel-cage induction motor and three-phase pendulum machine with integrated torque pick-up to validate the effectiveness and feasibilities of this controlling technique.

Keywords*:* speed drive, induction motor, direct torque control, field-oriented control

1. Introduction

Over the past few decades, the revolution of variable speed drives have lead to better quality and higher productivity in various industrial applications. Before the introduction of microcontrollers and power semiconductor devices, variable speed actuators were dominated by dc motors, as they are simplest to control and equip with the ability of providing inherent decoupling of torque and flux. Today, due to the higher cost of maintenance for dc motors and other problems arise in the usage of dc drives [5, 11], the researchers have slowly encouraged the replacement by the ac drive in variable speed drive systems [15, 16]. By using the high frequency power inverters, ac motor's speed and torque can be controlled effectively and efficiently [9, 12].

Researches have come out a wide variety of control schemes for the induction motor drives like voltage/frequency control, field-oriented control (FOC), direct torque control (DTC), etc. The main differences between them are the motor's performance and viability and cost in its real implementation [3, 4, 7, 10].

The voltage/frequency control scheme is the simplest and it uses parameters such as magnitude of voltage and frequency as controlling variables to achieve the command speed without using speed feedback. Such arrangement, without a speed feedback is the open-loop drive [8]. Apart from that, the basic principle of field-oriented control or vector control is to control both the magnitude and phase of the stator current vector such that the machine flux is regulated during static and dynamic conditions. Nearly instantaneous torque can be obtained as the flux and torque of the machine are controlled independently, in a similar fashion to the separate excited dc motor [4, 5].

However, in recent years, much of the research in the induction motor drive area is focused on sensorless methods of speed control. One such control scheme used is the direct torque control, which has significantly improved the drive performance when compared to the vector control. Basically the control of torque and speed are based on the electromagnetic state of ac motor. This technique involves the dead beat control of torque and flux within two hysteresis bands [3, 6, 10]. The flux and torque are constrained to lie respectively in between a set of lower and upper limits. The main advantages of DTC are minimal torque response time, absence of complex coordinate transformation, voltage or current modulator and simpler implementation [14]. Undoubtedly, the concept of direct torque control (DTC) is most suitable to be adopted in induction drive for controlling the speed and torque of the squirrel-cage 3-phase induction motor [6].

2. Speed Drive

The induction motor drives can be classified into two broad categories, which are adjustable-speed drives and servo drives based on their applications. Adjustable speed drive (VSD) is used to control the flow of energy from the mains to the process [14]. In general, the energy is supplied to the process through the motor shaft. Torque and speed are the two physical quantities that describe the state of the shaft. Electric motors and coupling combinations used for altering the speed will behave as either a "Speed Control" or "Torque Control". When the variable speed drive operates in speed control mode, the load is driven at speed reference but the torque is determined by load. Likewise, when operating in torque control mode, the load is driven by a torque reference, but the speed changes to the point where the load torque equals the torque delivered by the motor.

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For practical investigation, ACS800 speed drive has been used in this experiment. It is the latest ac drive technology manufactured by ABB [1, 2]. The heart of the ACS800 is direct torque control (DTC), a revolutionary motor control method that allows direct control of all the core motor variables, especially stator flux and torque. As a result, it can accurately control both of the motor speed and torque without feedback from the motor shaft, down to zero speed. The advanced motor software model allows the motor state calculations to be updated by the 40MHz digital signal processor (DSP) together with ACSI hardware at 40,000 times per second [12]. Every single switching in the drive is decided separately and hence, the drive always produces the optimal switching combination that avoids switching losses and can instantly reacts to dynamic changes.

In DTC, there is no need for a separate modulator, as used in PWM drives to control the frequency and voltage and the absence of middle man significantly speeds up the response of the drives to the changes in required torque [14]. The open loop dynamic speed control accuracy matches that of ac drive using closed loop flux vector control. The ACS800 drive is well proven for excellent performance and reliability since the open loop torque step rise time is less than 5 milliseconds compared to over 100 milliseconds in ac drives [12]. Figure 1 shows the performance of DTC method compared to traditional PWM method.

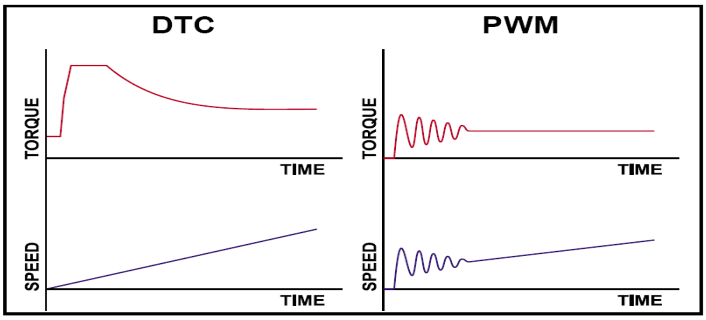

Figure 1: Performance of DTC Method Compared to Traditional PWM Method

It is possible to select scalar control [2] as the motor control method instead of direct torque control (DTC). In the scalar control mode, frequency and voltage are the main control variables and are applied to the stator windings. The induction motor is controlled by inverter in the form of PWM pulse train dictating both the voltage and frequency. When the volts/hertz ratio is held constant, the flux in the motor remains essentially same over a broad speed range. Normally, scalar control mode is used in ACS800 drive for special applications, such as when the nominal current of the motor is less than 1/6 of the nominal output current of the drive, if a drive is used without a motor connected, etc. This control technique is performed detailed by ‘Scalar control by speed drive for three-phase induction motor’ [2].

The single drive configuration contains a rectifier, dc link and an inverter in one single ac drive unit. The six-pulse rectifier converts three-phase ac voltage to dc voltage and the capacitor bank is used for energy storage that stabilizes the intermediate circuit dc voltage or stiffens the dc link voltage. Besides, the six-pulse insulated gate bipolar transistors (IGBT) inverter converts the dc voltage to ac voltage and vice versa. The motor operation is controlled by switching the IGBTs. The DTC control principal turns IGBT switches on and off directly based on the difference between the actual ac motor torque and the user’s reference torque. On the whole, IGBT are used as the switching devices in the voltage source inverter bridge as they have the ability of being turned off and on. Moreover, they offer high switching speed with enough power rating. Each IGBT has an inverse parallel-connected diode, which provides alternate path for the motor current after the IGBT is switched off.

Based on direct torque control technology, the ACS800 drive offers highly advanced features as standard. The ACS800 features built-in preprogrammed application macros for configuration of parameters such as inputs, outputs and signal processing [13]. There are five standard macros and two user macros. Table 1 contains a summary of the macros and their suitable applications.

The intelligent ac drive also equipped with a complete set of standard software features that offers premium functionality and flexibility like flux optimization, automatic start, flux braking, relative output voltage boost at zero speed (IR compensation), process PID control, etc. In this paper, the most common features used for direct torque control (DTC) are motor identification, acceleration and deceleration ramps, speed controller tuning and constant speeds.

Table 1: The Standard Application Macros in ACS800

Macro	Suitable Applications
Factory	▪ For ordinary speed control applications, such as conveyors, speed-controlled pumps and fans, test benches with predefined constant speeds
Hand/Auto	▪ Speed control application. ▪ For local and remote operation.
PID Control	▪ For process control applications. For instance, different closed loop control system such as pressure control, level control and flow control. ▪ Possible to switch between process and speed control.
Torque Control	▪ For processes where torque control is required. ▪ Switching between torque and speed control is possible.
Sequential Control	▪ For repetitive cycles, where one to seven constant speeds can be used. ▪ Speed reference is also provided.
User Macro 1 & 2	▪ The user can save the customized standard macro and the result of motor identification into the permanent memory and recall the data at a later time.

The motor identification is an essential feature needed for DTC technology in ACS800 drive. Basically, the performance of DTC is very much relying on an accurate motor model determined during the motor start-up. A motor identification magnetization is automatically performed at the first time the start command is given. During this first start-up, the motor is magnetized at zero speed for several seconds in order to create precise motor model in the drive. Besides that, two user-selectable acceleration and deceleration ramps can be obtained from the set of standard software features available in the ac drive. When the desired operating speed of the ac motor is changed, the drive will not try to make the motor instantaneously jump from the old desired speed to the new desired speed. Instead, the rate of motor acceleration and deceleration depends on the adjusted acceleration or deceleration times and the ramp shape. There are two ramp shapes, which are linear and S-curve, figure 2, accessible in the speed drive. The linear curve is suitable for drive requiring steady or slow acceleration or deceleration, whereas the S-curve is ideal for conveyors carrying fragile loads or other applications where a smooth transition is required when changing the speed [13].

During the motor identification, the speed controller is automatically tuned. However, it is possible to manually adjust the controller gain, integration time and derivation time so that the drive will have better dynamic performance and the efficiency of the motor can be maximized. Hence, PID controller is used in

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ACS800 drive to eliminate the error and stabilize the process output at the desired value [1]. The controller tends to compare the reference signal with the actual signal. The difference is then processed to calculate a new value for a manipulated variable, and then brings the process measured value back to its desired set-point. This is performed by PID Control [11]. Figure 3 and Figure 4 show the speed responses at a speed reference step and a simplified block diagram of the speed controller respectively.

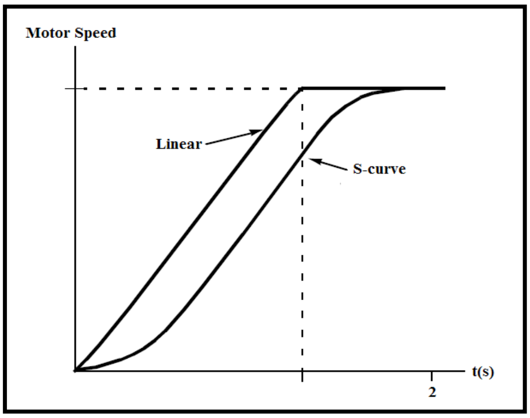

Figure 2: Available Ramp Shape in ACS800 drive – Linear and S-curve

Apart from that, the ACS800 drive enables the user to predefine 15 constant speeds. When constant speed is activated, it overrides the external reference and this function normally operates on a 6 milliseconds time interval. Constants speeds can be selected through sequential control macro application as this macro offers seven present constant speeds which can be activated by digital inputs. In practice, sequential control allows the ac motor to operate in numerous preset speeds according to the time settings. This control method is performed PID Control [1].
Moreover, a wide feature range of pre-programmed protection functions provides protection for the drive, motor and the process. In ACS800 drive, in order to ensure a convenient commissioning procedure, the start-up assistant will guide the user through the start-up procedure, helping the user to feed the requested data (parameter values) to the drive. Basically, the start-up assistant provides 14 different languages. It asks for motor nominal values as well as I/O configuration and application specific parameters like torque ramp up and ramp down times. The assistant also checks that the entered values are valid and within the allowed range.

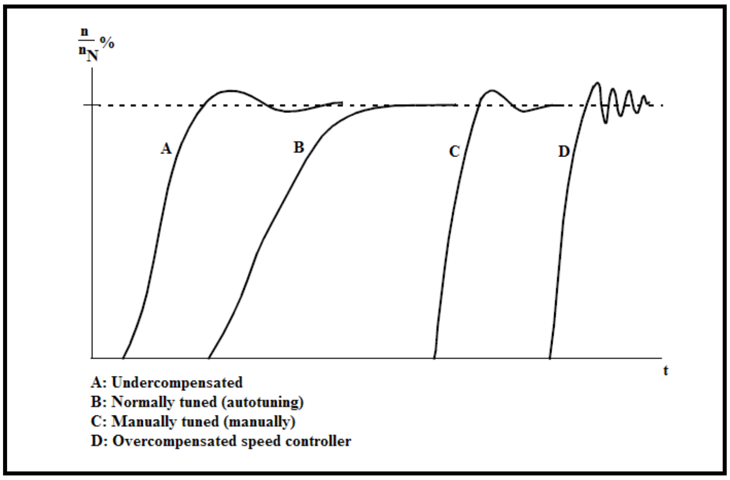

Figure 3: Speed Responses at a Speed Reference Step

Adaptive programming features are included in the drive application program. It is like having a small Programming Logic Controller (PLC) inside the drive [6]. Adaptive programming consists of a set of blocks, which can be programmed to perform any 20 predefined functions. Inputs can be defined to the blocks, wiring between the blocks and connections to the drive I/O or to the drive control. In this way, new input and output signals are created and used to modify the drive's speed or torque control

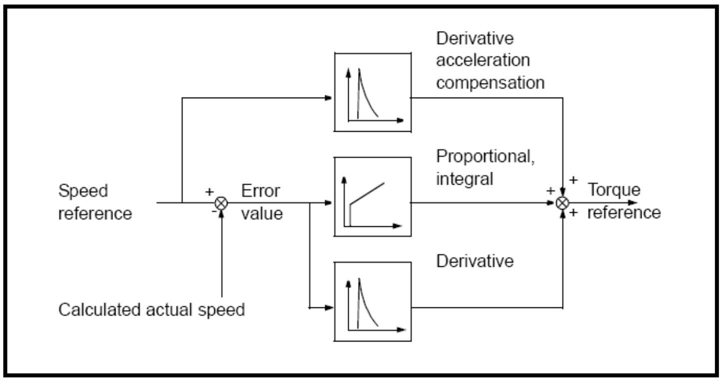

Figure 4: Block Diagram of the Speed Controller

3. Direct Torque Control Scheme

Direct torque control (DTC) of ac motors was developed as an alternative to field-oriented control [10]. In a direct torque controlled induction motor supplied by a voltage source inverter (VSI), it is possible to directly control the electromagnetic torque and stator flux within the prefixed hysteresis band limits by the selection of optimum inverter voltage vector. This means that the torque and flux are constrained to lie respectively within a set of upper and lower limits. Using DTC, it is possible to obtain good dynamic control of the torque without using the tachometer or position encoder to feedback the speed or position of the motor shaft [10]. For this reason, DTC can be classified as "sensorless type" control scheme. This greatly simplified control structure has significantly improved the drive performance in terms of the torque and speed response.
For speed control test, several speed reference settings, such as 1350 rpm, 1000 rpm, 700 rpm and 400 rpm have been used for investigation. The experimental data has been collected and the resulting torque-speed characteristic curves for different speed references have been shown in Figure 5. When the mechanical torque of the three-phase pendulum machine increases from 0 Nm to 1.7 Nm, the speed of the squirrel-cage induction motor is kept constant at the speed reference point, but the electromagnetic torque increases gradually along with the mechanical torque. This has indeed achieved the desired outcome of the speed control. In practical, when the ACS800 drive operates in speed control mode, the driven load is expected to run at a prefixed speed independent of a load torque. Therefore, the torque speed relationship can be interpreted as a family of straight lines in this case.
Based on Figure 6 to Figure 8, the three graphs exhibit the same characteristic in which the motor current; voltage and power are increasing proportionally with the increment of electromagnetic torque. The torque of the motor is computed by dividing the developed power with the rotor speed:
The electromagnetic torque is increasing with the increment of current and voltage of induction motor as the DTC technology in ACS800 drive will keep the flux density at its rated value throughout the electromagnetic torque range. In addition, the slip should uphold at the operating region.
The resulting torque-speed characteristic curves for different torque references have been shown in Figure 9. The electromagnetic torque will be maintained at its torque reference point depending on the load demand and the torque reference supplied. For instance: when 90% torque reference is provided to the ACS800 drive, the electromagnetic torque will stay at the region of 88% to 90% after the mechanical torque of the three-phase pendulum machine is increased to 0.8Nm and above.

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Before that, the electromagnetic torque keeps increasing along with the increment of mechanical torque. Take for example, if the torque reference provided to ACS800 drive is prefixed at 90%, the electromagnetic torque will keep increasing gradually when the mechanical torque is raised from 0 Nm to 0.8 Nm before it comes to the stable point. At the early stage, the electromagnetic torque will not maintain at the torque reference point due to the reason that when the motor is lightly loaded, the induction drive will not operate at the rated flux. Consequently, the drive will reduce the flux ϕ_s by lowering the upper limit and lower limit of the flux without changing the tolerance band. As a result, the iron losses of the motor can be minimized

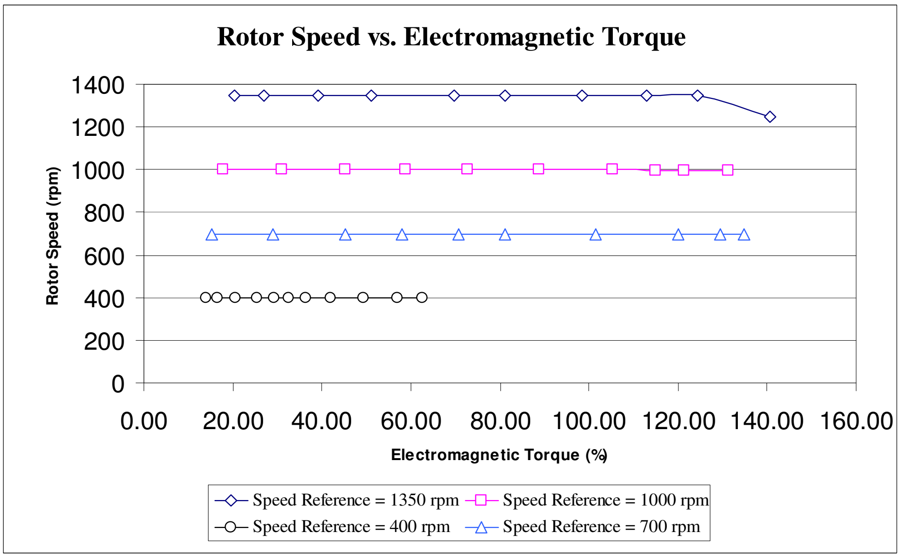

Figure 5: Rotor Speed vs. Electromagnetic Torque (Speed Control)

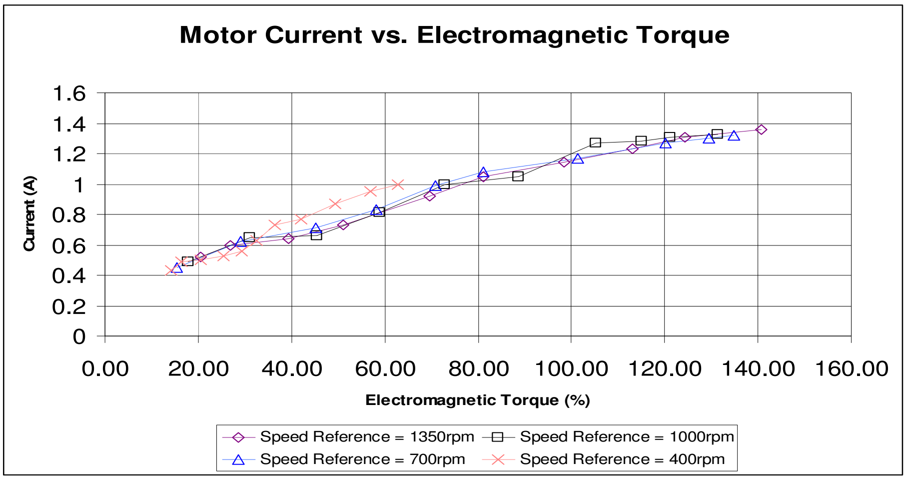

Figure 6: Motor Current vs. Electromagnetic Torque (Speed Control)

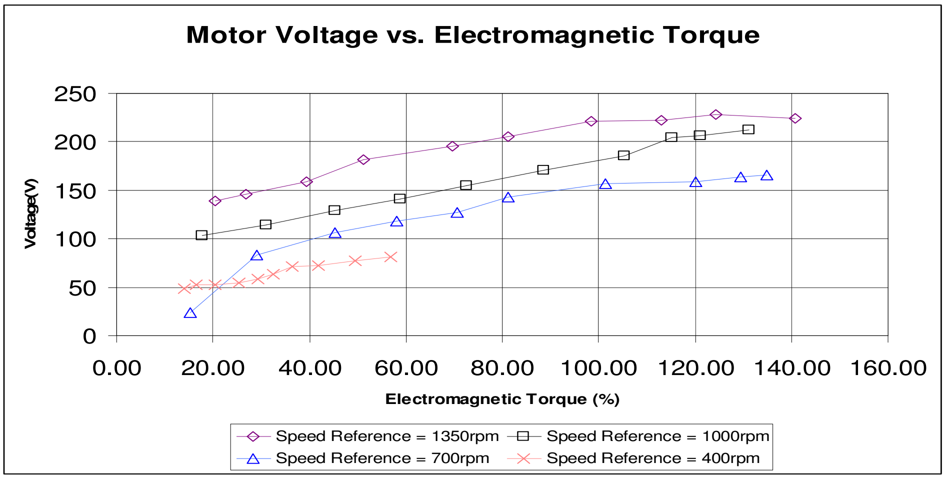

Figure 7: Motor Voltage vs. Electromagnetic Torque (Speed Control)

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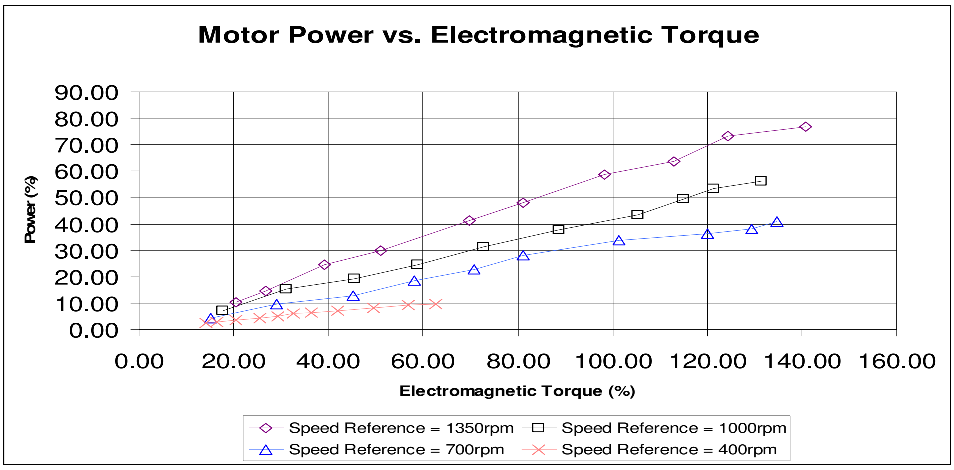

Figure 8: Motor Power vs. Electromagnetic Torque (Speed Control)

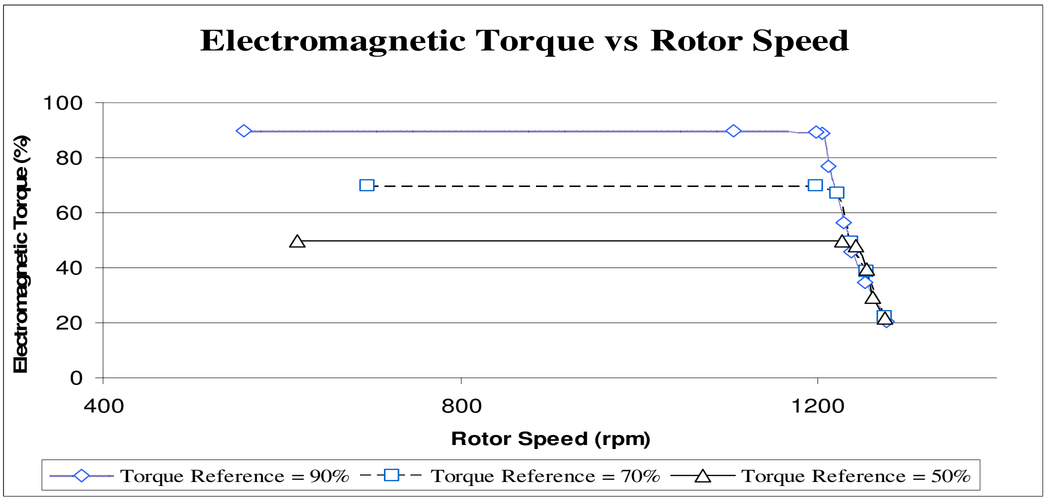

Figure 9: Rotor Speed vs. Electromagnetic Torque (Torque Control)

4. Conclusion

A valuable theoretical knowledge and practical experience have been acquired. From a series of experiments conducted and analysis, it has been found that the response of the ACS800 drive to change in required torque and speed are fast and precise. Direct torque control (DTC) scheme is simpler to implement, as torque and flux are the only motor variables that are directly controlled without the need of speed feedback. These controlling variables together with the effects of flux and torque hysteresis band amplitudes have greatly influence the drive performance. For that reason, variable speed drive is used to maximize the efficiency of the ac motor or production while attaining effective energy saving.

After completing the practical investigation, the results obtained from experimental tests show that the speed and torque of 3-phase induction motor can be controlled using the DTC technology in ACS800 speed drive. When the ACS800 drive operates in speed control mode, the load is driven at the speed reference independent of load torque. Similarly, the motor will operate according to the torque reference when the drive is in torque control mode. Briefly, either torque or speed of motor can be controlled at any one time using the ACS800 drive.

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