Introduction to Feed Forward Torque Control

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This white paper introduces a new sensorless motor controller that can be used to control motor torque, speed and position of most permanent magnet motors. This includes AC servo motors, brushless DC motors and hybrid stepper motors. Features of this new controller, called feed forward torque control, include:

- Full dynamic speed control with full damping right down to zero speed and extending into the over-speed or flux-weakening region
- Very insensitive to motor parameter variations, can handle large mismatches in inertia
- Motor current automatically adjusts to match the load resulting in cool motor operation, except at zero and low speeds where a holding current is applied
- Temporary overloads are handled by reverting to constant torque mode
- Robust, stall-proof operation - motor will automatically recover from a forced stop
- Very fast speed and position control: ideal for multi-axis control
- Extremely smooth and quite
- Precise speed control with 30,000:1 speed range
- Simple set up - no manual tuning

Before describing how the new controller operates, we will first revue how torque is controlled in a standard servo drive with position feedback, often called field oriented control. The diagram below (Figure 1) illustrates how this type of torque control works.

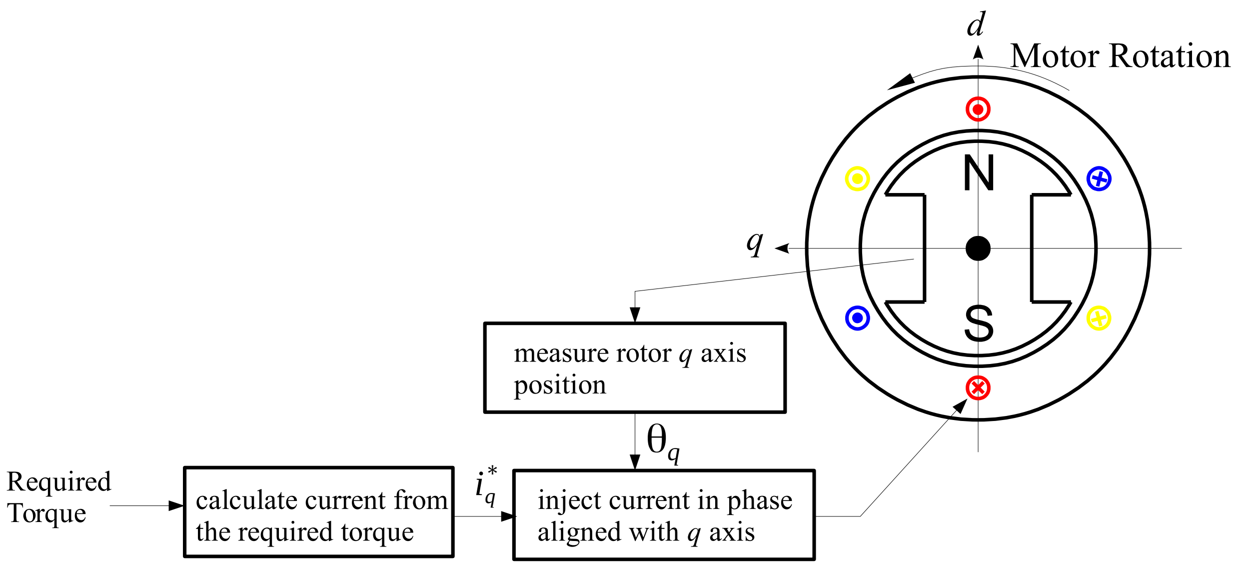

Figure 1. Torque control method for a standard servo drive.

The control of the motor torque is achieved by first calculating the required component of winding current in the q axis direction (i_q^* = required torque divided by the motor flux). The rotor q axis direction is then measured, usually with a rotor position sensor, and the required current is injected into the windings aligned with the q axis generating the required torque.

With torque control implemented, speed and position control can be added with further outer feedback loops. For speed control, the speed is measured from the position information and compared with the required speed, with the difference used to adjust the applied torque using a proportional + integral controller. If position control is required, the position is measured and compared with a set point position, with the difference used to adjust the required speed usually using a proportional only controller.

In a so-called sensorless motor drive, the rotor position must still be measured to determine the q axis direction, but it is achieved by means other than using a rotor position sensor. By far the most common method is to measure the motor winding voltages, subtract estimates of the current caused voltage drops to determine the back emf voltages, then use these back emf voltages to determine the rotor position. The problem with this method is that the back emf cannot be measured at zero speed, requiring the motor to be started by injecting a rotating fixed magnitude current into the windings to rotate the motor up to a speed at which the back emf can be measured. This makes the motor very slow to start and makes adding a position control loop very difficult. Also, stable, very low speed operation is precluded.

Feed forward torque control uses a new method of controlling the torque which does not require knowledge of the rotor position. The new torque control method, which is more complex than the standard torque control method of Figure 1 is illustrated in Figure 2 below.

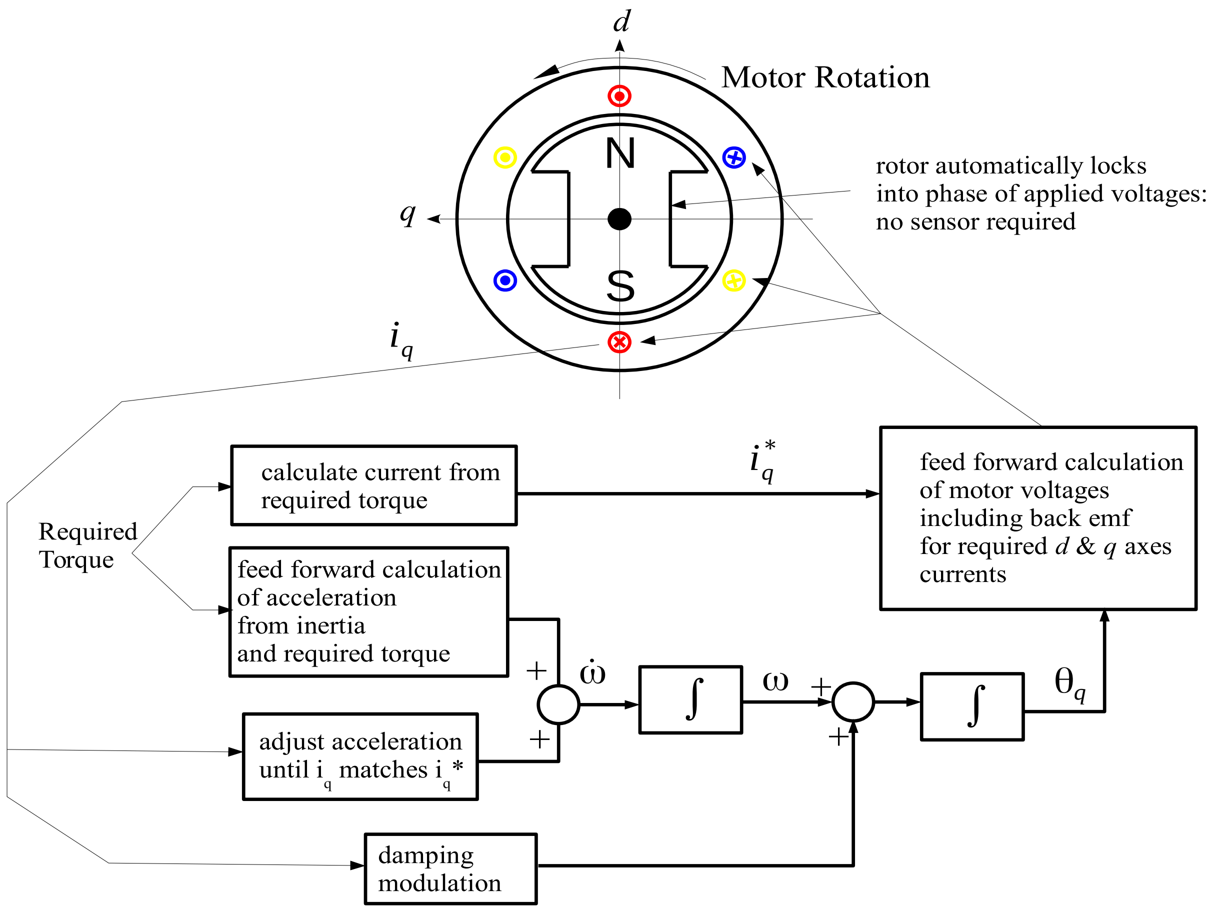

Figure 2. Torque control method for feed forward torque control.

In the new torque controller, the need to know the rotor position is eliminated by applying fixed voltage waveforms to the motor rather than fixed current waveforms as used in the standard torque controller. In a permanent magnet motor, the rotor will automatically lock in to a rotating voltage waveform. This effect, greatly enhanced by added feedback, is used in the new torque controller to keep the rotor locked onto the rotating voltage with an accuracy typically of one or two electrical degrees. At zero and low speeds the voltage lock-in effect is augmented by adding a *d* axis current which locks in the rotor in a similar way to the holding current applied to a stepper motor.

The required torque input is used to directly calculate the *q* axis current i_q^* as before and also the rotor acceleration $\dot{\omega}$ from an estimate of the inertia ($\dot{\omega}$ =torque/inertia). The *q* axis current together with the rotor *q* axis phase angle θ_q , derived from $\dot{\omega}$, are used to calculate the required motor voltages. Phase angle θ_q is derived from $\dot{\omega}$ by first integrating $\dot{\omega}$ to get speed ω then integrating again to get phase angle θ_q . Before integrating, rotor acceleration $\dot{\omega}$ is corrected for added load torque and any inertia mismatch by comparing i_q^* with the measured *q* axis current i_q . Also, the i_q measurement is also used to derive a damping modulation term which is added to the speed ω before integrating. This prevents the rotor from oscillating about its locked in angle θ_q .

The correction of the acceleration rate from the difference between the measured current i_q and the reference current i_q^* only occurs at speeds where the back emf is high enough to cause this current error. The current error disappears at low speed and standstill. At these speeds, the torque control relies on the estimated inertia to provide the correct value of acceleration and the application of positive *d* axis current to keep the rotor aligned. This results in reduced sensitivity to load variations at low speeds and no sensitivity at zero speed but does not affect damping and dynamic response times to torque command changes. Of interest is that a rotor position sensor could be used to provide the missing torque error information at low and zero speed by measuring the error between the actual rotor position and the reference position angle θ_q .

Of interest is the robustness of the drive to stalling. If the rotor braked to standstill whilst a positive torque is set, the high current error between i_q and i_q^* will drive the controller speed setting ω down to a very low value resulting in a slowly rotating voltage and thus a rotating current being applied to the motor. As a result the motor torque will slowly oscillate between positive and negative. As soon as the motor is allowed to spin, the positive torque intervals will predominate and drive the motor speed back up.

Note that apart from not requiring a rotor position sensor, the big difference between the standard torque controller and the new torque controller is that with the standard controller the required torque is translated into a forced rotor torque by injecting a matching *q* axis current resulting in a rotor acceleration depending in the inertia. With the new torque controller the required torque is translated into a forced rotor acceleration which is then adjusted until the rotor torque as measured by the *q* axis current matches the required torque.

Although not directly obvious from the illustration in Figure 2, feed forward torque control has a number of other advantages over the standard torque control method apart from not requiring a rotor position sensor. These include:

- Voltage control rather than current control allows much smoother waveforms to be applied to the motor resulting much lower torque ripple and much lower audible noise.
- With current feedback only used for damping and acceleration adjustment, current sensors need only be low bandwidth reducing hardware requirements compared with current control.
- The availability of immediate and noise free values of speed and acceleration allows the use of a much faster outer speed controller which requires only a proportional gain term in its feedback loop. This results in much faster speed response times and corresponding much faster position response times.
- The availability of immediate and noise free value of rotor position allows position control without chatter at standstill, normally unavoidable with standard servo controllers.
- The current feedback adjustment of acceleration errors allows the controller to operate with large parameter errors. In particular, the new controller is largely unaffected by resistance errors at standstill and low speed, which prevent back emf position sensing methods working at these speeds.

- Because the controller is stabilised by controlling the acceleration rather than by controlling the current, the drive can operate at maximum output voltage. The voltage headroom required for current control loops is not needed.
- Because the motor is voltage controlled, it is easy to add fast flux weakening for over-speed operation that maintains maximum output voltage and thus maximum efficiency at all times. Also, extreme flux weakening for very high over-speed ratios (> 4:1), especially necessary for hybrid stepper motors, is easily and stably obtained. This is not possible with back emf sensing schemes.

In conclusion the new feed forward torque control scheme has many advantages over existing current control schemes with no disadvantages. it is expected that the new control scheme will mostly replace the existing current control schemes especially for sensorless applications.