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Abstract

Although the relatively poor transient response of open loop induction motor drive controllers is adequate for most purposes, applications frequently arise which could benefit from faster response but which must retain the low cost advantages of an open loop speed controller. This paper describes a new type of field orientation control system which has been developed which does not require the use of additional tachometers or transducers. The control is accomplished with flux feedback using additional taps utilizing already existing motor coils. This system is shown to demonstrate good transient as well as steady state behavior.

INTRODUCTION

The large majority of industrial motor drives involve applications where precise speed regulation or rapid torque response are not essential for satisfactory operation of the drive. For such applications it is usually cost effective to operate the inverter in an open loop mode in which the inverter frequency is set indirectly by means of a dc bus voltage command. Constant volts per hertz operation is ensured by utilizing the dc bus voltage as an inverter frequency command as shown in Fig. 1. The frequency of the inverter sets the motor synchronous frequency in turn sets the motor speed. Since, the motor speed varies from the synchronous condition with load due to motor slip, the effects of slip are frequently compensated by increasing the inverter frequency command as a function of the dc link current. In effect, both measurement of dc bus voltage and current accomplish feedforward rather than feedback regulation so that the motor speed is not tightly controlled and can vary substantially with changes in motor parameters. In addition, response to changes in speed command varies substantially with operating speed and load. The response of such controllers is relatively sluggish since the controller gains must be set to ensure stable operation for all speed and load conditions and for use with any motor of a given rating.

While good torque and speed performance is frequently not a primary concern there exist many applications where improved performance could yield great dividends. For example, while a conveyor drive is basically a straightforward speed control application, use of a variable speed motor drive involving a very long belt requires the careful programming of motor torque during the starting phase to avoid setting up oscillation between the motor inertia and the effective spring due to the conveyor belt compliance.

Greatly improved transient response can be obtained using the principle field orientation [1,2]. However this method is complex and expensive to implement in hardware. In particular, some means of locating the flux position is required for the implementation of field oriented drives making the addition of expensive position encoders or special flux sensors necessary. The added expenses involved with field oriented control typically make it impractical for use in many cost sensitive applications. A system that could approach the transient performance of a field oriented drive without a substantial cost penalty over an open loop drive would be a very attractive alternative in numerous applications. A presentation of one such alternative is the subject of this paper.

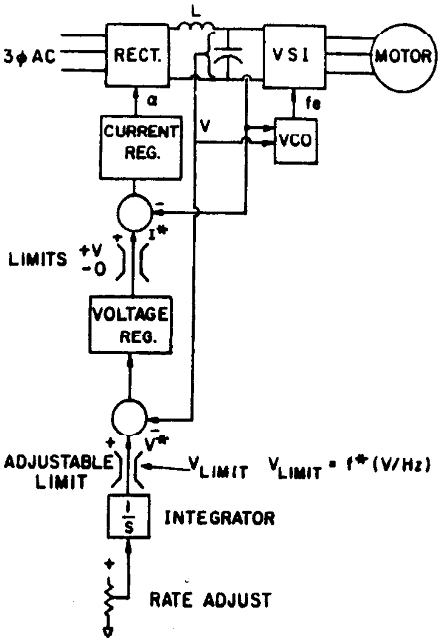


Fig. 1 Block Diagram of Conventional Open Loop Speed Controller.

FIELD ORIENTATION PRINCIPLES

The objective of field orientation is essentially to accomplish a decoupling of the control over excitation flux and torque in a manner similar to DC machines [3]. To accomplish this task in an induction motor the flux linked by the rotor should be regulated to be positioned at right angles to the MMF produced by the rotor current. This is accomplished, in turn, by supplying an appropriate stator current to provide not only the reactive power required for exciting the rotor flux but also the real power required by the rotor component of current and thus by the load. In a DC machine this positioning action is automatically accomplished by means of the commutator. In an induction machine, however, the rotor flux rotates relative to both the stator and the rotor and some method of locating the instantaneous position of the rotor flux is required.

Two distinct methods have been employed in locating the flux position. The most popular method, the indirect method, utilizes measurement of the rotor rotational angle and calculates the position of the flux from this angle. This method requires the addition of an external position encoder to determine the rotor position. Such a device, unfortunately, can add considerably to the cost. In addition, calculations done with this method depend heavily on the motor parameters. Errors in estimation of these parameters can affect the performance of the drive [4].

The angular position of the rotor flux can clearly be found more directly by using some type of flux sensor. These sensors usually consist of flux coils or hall sensors implanted in the stator slots to measure the air gap flux [5]. Field orientation derived by measurement of rotor flux is generally called direct field orientation. Rotor flux can then be calculated by approximating the distribution between the stator and rotor leakage inductances. Such sensors unfortunately require specially modified motors which adds to the cost and are considered fragile. A third method which is commonly employed is to measure the terminal voltage and subtract the stator IR drop to obtain the voltage component due to the time rate of change of stator flux. Again the rotor flux can then be calculated if the leakage inductances are known. While this method works well at higher speeds, at lower speeds errors in the IR calculation can overshadow the flux voltage and produce sizable errors [6].

TAPPED STATOR WINDING METHOD OF FLUX SENSING

In a recent paper it has been shown that by bringing out additional taps from the stator windings of the induction machine an improved flux sensing method can be developed [7]. The method employed is similar to that of using terminal voltages sensing except with the additional taps the IR drops in the coils can be cancelled. In addition, since the stator leakage inductance drops are also cancelled the voltage sensed is a direct measure of the air gap voltage. Since actual motor windings are used, the system is much more robust than systems using flux coils or hall sensors. An additional advantage of the tapped winding method is that only minor modifications are needed during motor manufacture so that the additional expense involved in bringing out the additional winding taps is minimal. In effect, the tap points required are already available within the motor and it takes little additional expense to make them available to the controller.

An illustration of how the taps have been implemented for one phase of a motor under test is shown in Fig. 2. By utilization of the terminals made available by the taps, the voltages across individual coils can now be measured. Since, the voltage in each coil is dependent on both the flux linking the coil and the IR drop in the coil, we have for one of the coils

$$v_1 = i\,r + d\lambda_1/dt$$

and, for the another coil in a phase belt

$$v_2 = i\,r + d\lambda_2/dt$$

Since the two coils are identical, the resistance in each coil will be the same. In addition, since the two coils are in the same phase, the current is identical in both coils. This feature makes the IR drop as well as the slot leakage reactance drop of both voltages the same. Hence, the difference in the two voltages is dependent only on the difference in the fluxes which is, in turn, nearly proportional to the air gap flux [7].

A pictorial example of how such coils might be physically related to air gap flux is shown in Fig. 3. In particular, if the coils are considered to be portions of a phase belt corresponding to phase A, the component of the flux in each coil can be considered as the vector sum of the projection of each coil along the magnetic axis of phase A together with the projection of the flux along an axis perpendicular to phase A magnetic axis. The scalar difference between these coil voltages clearly cancels the component in the direction of the phase A leaving only the component perpendicular to the phase A flux linkage (λ_{ap}). Hence, a flux linkage corresponding to air gap flux in a direction normal the the phase A magnetic axis can be obtained using the integral of the voltage

$$\lambda_{ap} = k(\lambda_1 - \lambda_2) = k_2\int(v_1 - v_2)\,dt$$

By use of similarly tapped windings for the B phase, a flux perpendicular to the B phase axis can also be found (λ_{bp}). Assuming a balanced three phase system it is not necessary to use taps on phase C since the desired perpendicular component of flux can be calculated from the other two phases.

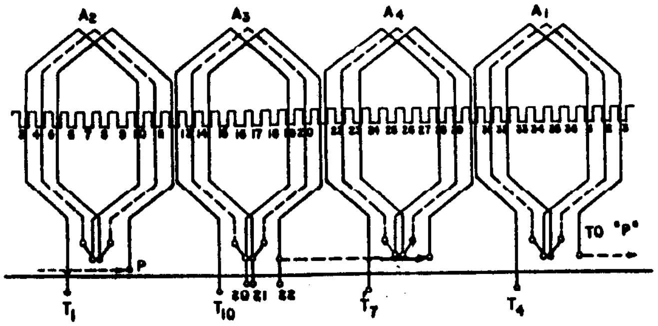


Fig. 2 Coil Placement and Taps on One Phase of a Double Layer Lap Winding Having a 7/9 Slot Pitch.

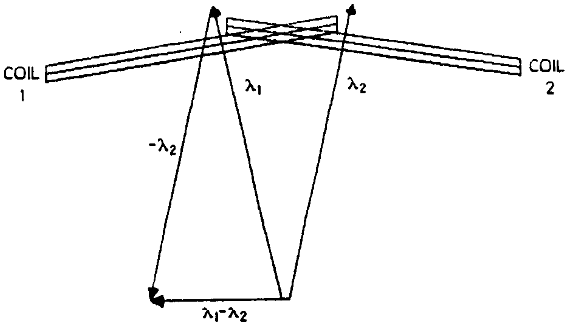


Fig. 3 Phasor Diagram of Voltage Across Coils n_1 and n_3 Relative to the Voltages Induced in the Three Stator Phases.

SYSTEM IMPLEMENTATION

An implementation of a field oriented induction motor control utilizing tapped stator windings has been implemented in the laboratory. The implementation consists of three major components; a squirrel cage induction motor having tapped stator windings of the form illustrated in Fig. 2, a current controlled PWM inverter, and a microcomputer which used to carry out all of the control procedures. A simplified block diagram of the overall control structure is given in Fig. 4.

Except for the additional taps on the stator, the motor used for this experiment was a standard 10 horsepower Marathon Electric induction machine. The current controlled PWM inverter utilizes GTO's as its power switching devices. The pulse width waveform is generated from the difference between the current command and the actual waveform using a ramp comparator [8]. Since this type of control has a lag in its response, a synchronous PI controller has been added to the system to correct for the inherent phase shift [9]. Although the computation of the current commands from the flux voltages and line currents is relatively complex, the field oriented control algorithm can be implemented fairly easily with a microprocessor.

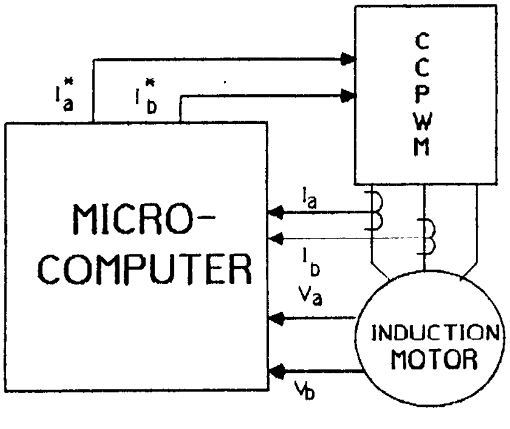


Fig. 4 Simplified Block Diagram of System Implementation.

The Microprocessor Controller

The central control device for this system has been realized using an IBM AT personal computer. Although such a system is not viable for a commercial application, it has many attractive features for use in the laboratory environment. As a development system, a personal computer allows considerable flexibility for use in multiple projects. Since there is a large variety of software available, the computer can be used for analysis as well as development. Also, there is also a large availability of general purpose hardware which can save a considerable amount of development time compared with specialized prototypes. However, computational speed is sacrificed compared to special purpose microprocessor chips. The control software has been written in assembly language to allow for maximum utilization of the Intel 80286 processor. The program has a structure which can be divided into two major sections, the interrupt drive real time control and the user interface.

User Interface

A major portion of the program is not used in the actual control of the motor but is employed to accomplish such tasks as initialization and user interface. Since these tasks do not require real time operation, they are calculated during the time between interrupt routines. An initialization section of the program is run before the interrupt control is started. The purpose of this portion of the program is to carry out various functions such as setting the interrupt controller and initializing the A/D and D/A boards. The user interface program operates throughout the operation and runs in the time between the end of one interrupt and the arrival of the next interrupt. The process is stopped during the time of the interrupt and continues when the interrupt is complete. Its function is to allow the user control over speed and termination of the program through the keyboard. The implementation of this section uses the DOS system resident on the personal computer. This feature allows for easy interfacing to the screen for displaying messages and to the keyboard for accepting commands.

Interrupt Driven Control

In order to achieve consistent control over the system, the control portion of the program must be executed at exact time intervals. To accomplish this task the control routine is initiated by a clock drive interrupt. For the controller that has been implemented, the interrupt time is set at 1 millisecond. During the interrupt routine all the major functions used in the field orientation control algorithm are performed. A block diagram of these functions are shown in Fig. 5. They consist of a flux calculator, torque calculator, a sine and cosine calculator, a frequency compensator, a proportional-plus-integral (PI) controller, and a phase and reference frame transformation.

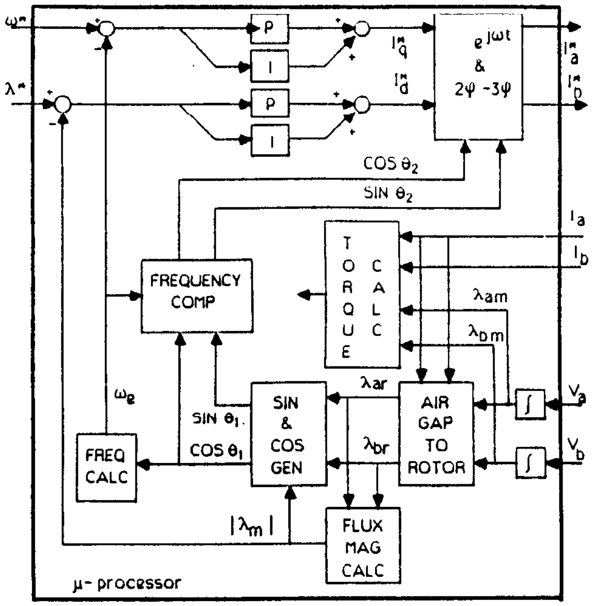


Fig. 5 Microprocessor System Implementation of Field Oriented Controller Utilizing Tapped Stator Windings.

After reading in the flux voltages and phase current, the first operation to be performed is an air gap flux calculation. This calculation is accomplished by integrating the input voltages using a standard trapezoidal method. This method, however, results in a considerable integrator drift so that an additional digital filter has been added to reduce DC gain. Rotor flux is derived from air gap flux by first scaling the air gap flux by the ratio of rotor inductance to magnetizing inductance and then subtracting the product of the stator current and leakage inductance [3,4].

In order to generate the required sine and cosine functions and to regulate the flux command a flux magnitude calculation is needed. Since the perpendicular elements of flux (d-q components) are not directly available, the scaled magnitude of flux is calculated using the equation

$$|\lambda| = \sqrt{\lambda_{ap}^2 + \lambda_{bp}^2 + 2\lambda_{ap}\lambda_{bp}}$$

A "pencil and paper" method described by Flores [10] is employed to calculate the square root.

Although the d-q components λ_q and λ_d were not directly available as measured values, the calculation for the sine and cosine components of the flux angle is still straightforward. By simply replacing the d-q flux linkages, λ_q and λ_d, by their equivalents in terms of λ_{ap} and λ_{bp} the resulting equations become

$$\cos\theta_1 = -\lambda_{ap}/|\lambda|$$

$$\sin\theta_1 = -(\lambda_{ap} + 2\lambda_{bp})/|\lambda|$$

A special note should be made about start up conditions. When the inverter is first started there is no available flux and therefore the above calculations are indeterminant. Thus for starting a forced sine and cosine wave is generated to fit a low frequency flux wave.

Since one of the major goals of this drive system was to give reasonable transient response without any additional speed or position sensing devices added to the motor shaft, a software based method for deriving the frequency from the data input was derived. This speed measurement was accomplished by calculating the time between zero crossings of the generated cosine wave. The frequency is calculated is then filtered and used for speed regulation and also to compensate for steady state phase error due to digitization [3,11]. To compensate for this phase error in the sine and cosine waves, the angle for the flux wave (θ_1) has to be increased by the delay angle $\theta_d = \omega T$. The sine and cosine of the new angle θ_2 are then calculated using the equations

$$\sin \theta 2 = \sin(\theta_1 + \theta_d) = \sin \theta_1 \cos \theta_d + \cos \theta_1 \sin \theta_d$$
$$\cos \theta 2 = \cos(\theta_1 + \theta_d) = \cos \theta_1 \cos \theta_d - \sin \theta_1 \sin \theta_d$$

The sine and cosine of θ_1 are calculated using the air gap fluxes while the sine and cosine θ_d are found from a table lookup based on a scaled value of the calculated speed. The compensated value of sine and cosine are used to convert the current commands i_{qs}^{e*} and i_{ds}^{e*}, to the stationary reference frame. The value of the d-axis current i_{ds}^{e*} directly controls the flux in a field oriented controller and therefore is derived by performing a proportional-plus-integral (PI) control on the flux error. Similarly, the q-axis current i_{qs}^{e*} is derived from a PI control of the speed error.

Once calculated, the command currents must be transformed into stationary phase coordinates for use with the PWM inverter. This transformation is accomplished in one step by using the equations

$$i_{as}^{*} = i_{qs}^{e*} \cos \theta_2 + i_{ds}^{e*} \sin \theta_2$$
$$i_{bs}^{*} = (\sqrt{3}\, i_{qs}^{e*} - i_{ds}^{e*}) \sin \theta_2/2 - (\sqrt{3} i_{ds}^{e*} + i_{qs}^{e*}) \cos \theta_2/2$$

These values can then be outputted to the inverter through a D/A board completing the field oriented control task. There is, however, one other major calculation performed during the control sequence. This calculation concerns the computation of electrical torque from air gap flux and stator current. Presently, this torque calculation is only being used as a method of checking response to the torque command, but it could easily be used to incorporate an actual torque loop in the control.

EXPERIMENTAL RESULTS

A major objective of this motor drive was to obtain a steady state performance which is at least comparable to an open loop drive in regard to steady state speed accuracy and with improved transient response. Tests to check both steady state and transient response were therefore performed on this system. It should be noted here, however, that the PWM inverter used in the tests had a considerably smaller rating than the motor. Since the output is measured from the motor, the per unit values seem small even though the inverter is being pushed to its limits.

In order to test the steady state performance, speed variations were measured as a function of load changes at various commanded speeds. The results in Fig. 6 show little difference in the speed torque characteristics of this drive compared to the open loop controller. The drive is, therefore, equally suitable for obtaining the desired steady state response.

Tests to determine the transient response were based on two tests involving step changes in load torque and in speed command. First, with the motor running using a constant speed command, a step change in load torque was added. The speed response to such load changes is shown in Fig. 7. From this figure it can be seen that the speed recovery to such a load change is fairly fast. Another transient response tested was the response of the system to a step change in speed under different loading conditions. This test is relatively important since open loop con-

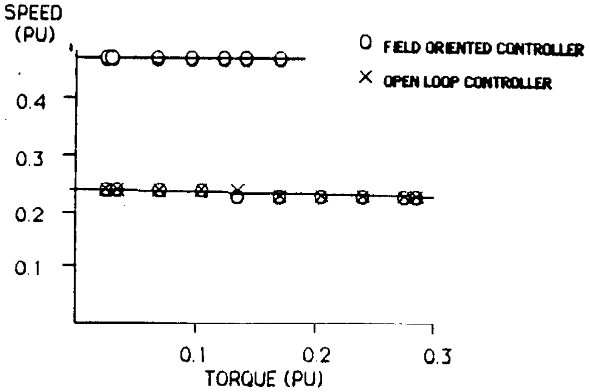


Fig. 6 Comparison of Steady State Characteristics of Field Oriented Controller and Open Loop Controller.

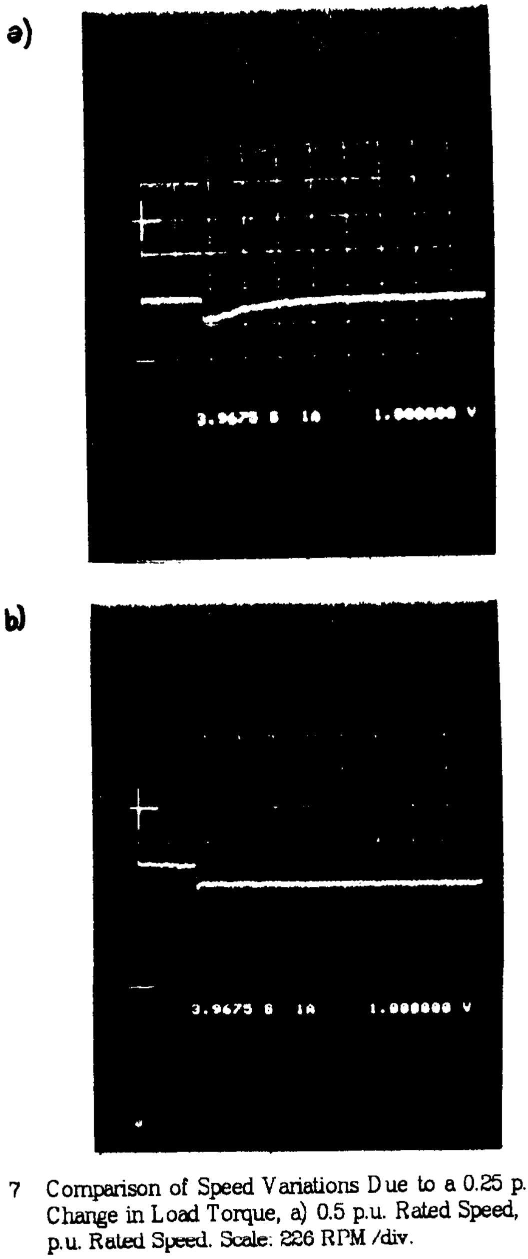
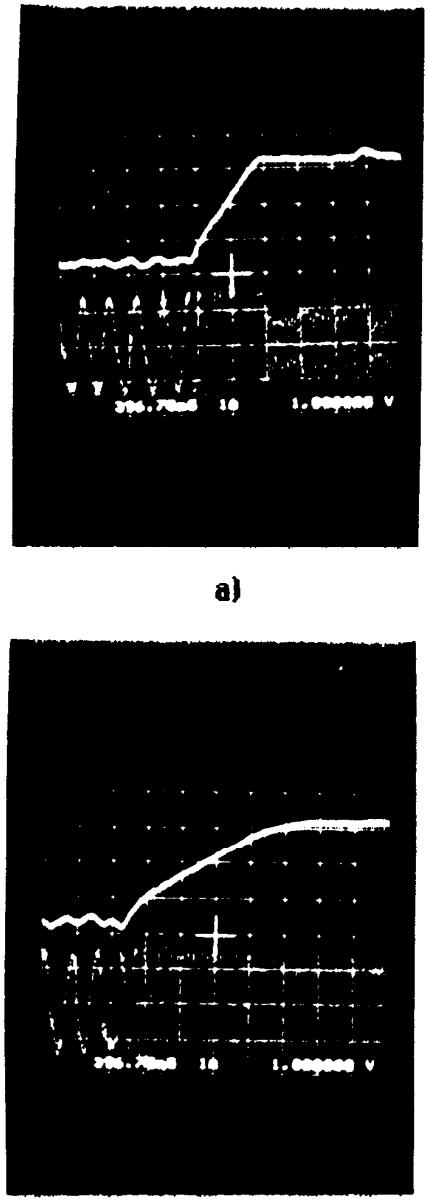


Fig. 7 Comparison of Speed Variations Due to a 0.25 p.u. Step Change in Load Torque, a) 0.5 p.u. Rated Speed, b) 0.25 p.u. Rated Speed. Scale: 226 RPM/div.



a)

b)

Fig. 8 Run Up Time from 100 to 900 RPM. a) No Load, b) Load Proportional to Speed (0.2 p.u. Torque at 900 RPM). Top Trace - Speed - 226 RPM/div., Bottom Trace - Stator Current - 10.9 Amps/div.

trollers generally require programmed speed responses and do not respond well under different load conditions. With the field oriented controller, however, the system was able to respond well under various loading conditions as seen in Fig. 8. The duration of the response time was observed to be limited mostly by the current capability of the inverter.

CONCLUSION

This paper has described a new type of field oriented control system using tapped motor windings which provides good speed regulation and speed response without the use of added speed or position sensors. In particular, the transient response of such a system is shown to be considerably improved over open loop systems. Since the motor uses the stator winding itself for flux measurements, it is more robust and less expensive then other direct or indirect field oriented systems. In applications where low cost but moderate performance is required, this system is shown to have important advantages over more conventional approaches.

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