Ain Shams University
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SPEED CONTROL OF A DC DRIVE BASED ON OPTIMAL PERFORMANCE

BY

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5140

UNDER SUPERVISION OF

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STATEMENT

This dissertation is submitted to Ain Shams University for the degree of M. Sc. in Electrical Engineering.

The work included in this thesis was carried out by the author in the department of Electrical engineering, Ain Shams University from November /1989 to May /1995.

No part of this thesis has been submitted for a degree or a qualification at any University or Institution.

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PRINCIPAL SYMBOLS

$N(t)$	:	rototional motor speed.
$T_L(t)$	:	constant load torque.
J	:	moment of inertia of the machine system.
K_t	:	torque coefficient.
K_e	:	counter electromotive force coefficient.
τ_m	:	mechanical time constant.
τ_a	:	armature time constant.
τ_f	:	field time constant.
L_a	:	inductance of armature circuit.
L_f	:	inductance of field circuit.
A_a	:	gain of the armature power converter.
A_f	:	gain of the field power converter.
$I_a(t)$	:	armature current.
$I_f(t)$	:	field current.
$V_a(t)$	:	armature voltage.
$V_f(t)$	:	field voltage.
P_o	:	output power.
η	:	efficiency.
L	:	machine losses.
P_a	:	armature circuit power loss.
$P_f(N)$	:	field circuit power loss.
$K_f(N)$	:	field loss coefficient.
K_a	:	armature loss coefficient.
I_{ao}	:	armature current at steady state.
I_{fo}	:	field current at steady state.
T_{mo}	:	generated torque at steady state.
β	:	optimal current ratio.
R_f	:	field resistance.
R_a	:	armature resistance.
dc	:	direct current.
RDE	:	reduced dynamic equation.
$R(k)$	:	desired signal.
$d(k)$	:	disturbance signal.
$e(k)$	:	error signal.
J_d	:	performance index.
$U(k)$	:	control input.
Q	:	weighting matrix.
R	:	weighting matrix.
G	:	feedback gain.
M	:	preview step.

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G_H	:	feedforward gain.
K, λ, γ	:	steady state solution of the Riccati equation.
S	:	Riccati gain.
C_p	:	proportional controller output.
K_p	:	proportional gain.
E_p	:	proportional error.
C_0	:	output with zero error.
$C_i(t)$	:	integral controller output.
K_i	:	integral mode gain.
$A_e(t)$	:	net area of error.
$C_i(o)$	:	integral controller output at t=0.
$C_d(t)$	:	derivative controller output.
$E_p(t)$	:	error at time t.
$E_p(t_0)$	:	error at time t_0.
K_d	:	derivative mode gain.
C_{pi}	:	proportional-integral controller output.
C_{pd}	:	proportional-derivative controller output.
C_{pid}	:	proportional-integral-derivative controller output.

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LIST OF FIGURES

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APPENDIX.

LIST OF USED SOFTWARE PROGRAMS:

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INTRODUCTION

1-1 Speed control of DC motors:

Great numbers of dc motors are still made today because their characteristics are so well suited to many variable speed drives. The performance of a modern drive is judged by its wide speed of response and the possibility of applying feedback. In all these respects the dc motor is still considerably superior to the induction motor, but its initial and maintenance costs are relatively high. Methods of control are in most cases simpler and less costly than methods of control of ac motors to obtain the same performance. However, on the other hand, the dc motor needs more maintenance than the induction motor because of the commutator which offer other limitations. There is brush wear from friction, arcing and sparking. As a conclusion, for the precise speed control, the dc motor is the good solution on the expense of the cost. This is not the case for very high speeds and large ratings, where ac drives are used successfully.

The principal parameter of interest in DC motor control systems is the speed of the machine. The speed can be controlled either by the control of armature voltage, field voltage, or both, depending upon the desired performance charateristics of the drive. Thus providing an additional degree of flexibility in the operating system.

1-2 Mathemtical models of physical systems:

Many dynamic systems, may be characterized by differential equations. The response of a dynamic system to an input (or forcing function) may be obtained if these differential equations are solved. The equations can be obtained by utilizing physical laws governing a particular system, for example, Newton's laws for mechanical systems, Kirchhoff's laws for electrical systems, etc [13].

1-2-1 Mathematical models:

The mathematical description of the dynamic characteristics of a system is called a mathematical model. The first step in the analysis of a dynamic system is to derive its model. We must always keep in mind that deriving a reasonable mathematical model is the

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most important part of the entire analysis.

Models may assume many different forms. Depending on the particular system and the circumstances, one mathematical representation may be better suited than other representations. For example, in optimal control problems, it is often advantageous to use a set of first-order differential equations. On the other hand, for the transient-response analysis or frequency-response analysis of single-input-single-output systems, the transfer-function representation may be more convenient than any other.

Once a mathematical model of a system is obtained, various analytical and computer tools can be used for analysis and synthesis purposes.

1-2-2 Simplicity versus accuracy:

In obtaining a model, we must make a compromise between the simplicity of the model and the accuracy of the results of the analysis. Note that the results obtained from the analysis are valid only to the extent that the model approximates a given physical system.

The rapidity with which a digital computer can perform arithmetic operations allows us to employ a new approach in formulating mathematical models. Instead of limiting models to simple ones, we may, if necessary, include hundereds of equations to describe a complete system. If extreme accuracy is not needed, however, it is preferable to obtain only a reasonably simplified model. In deriving such a simplified model, we frequently find it necessary to ignore certain inherent physical properties of the system. In particular, if a linear lumped parameter mathematical model (i.e. one employing ordinary differential equations) is desired, it is always necessary to ignore certain nonlinearities and distributed parameters (i.e. ones giving rise to partial differential equations) which may be present in the physical system. If the effects that these ignored properties have on the response are small, good agreement will be obtained between the results of the analysis of a mathematical model and the results of the experimental study of the physical system.

In general, in solving a new problem, we find it desirable first to build a simplified model so that we can get a general feeling for the solution. A more complete mathematical model may then be built and used for a more complete analysis.

1-3 Design principles of control systems:

1-3-1 General requirements of a control system:

The primary requirement of a control system is that it must be stable. In addition to absolute stability, a control system must

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error signals are considered important; the analysis and design of control systems are carried out using transfer functions, together with a variety of graphical techniques such as root-locus plots and Nyquist plots. The unique characteristic of conventional control theory is that it is based on the input-output relation of the system, or the transfer function.

The main disadvantage of conventional control theory is that, generally speaking, it is applicable only to linear time-invariant systems having a single input and a single output. It is powerless for time-varying systems, nonlinear systems and multiple-input--multiple-output systems.

1-5 Modern control theory:

The modern trend in engineering systems is toward greater complexity, due mainly to the requirements of complex tasks and good accuracy. Because of the necessity of meeting increasingly stringent requirements on the performance of control systems, the increase in system complexity, and easy access to large-scale computers, modern control theory, which is a new approach to the analysis and design of complex control systems, has been developed. This new approach is based on the concept of state.

State-space methods are the cornerstone of modern control theory. The essential feature of state-space methods is the characterization of the processes of interest by differential equations instead of transfer functions. This may seem like a throwback to the earlier, primitive, period where differential equations also constituted the means of representing the behaviour of dynamic processes. But in the earlier period the processes were simple enough to be characterized by a single differential equation of fairly low order. In the modern approach the processes are characterized by systems of coupled, first-order differential equations. In principle there is no limit to the order (i.e., the number of independent first-order differential equations) and in practice the only limit to the order is the availability of computer software capable of performing the required calculations reliably.

1-6 Modern control theory versus conventional control theory:

System design in classical control theory is based on trial-and-error procedures which, in general, will not yield optimal control systems. System design in modern control theory, on the other hand, enables the engineer to design optimal control systems with respect to given performance indexes. In addition, design in modern control theory can be carried out for a class of inputs, instead of a specific input function, such as the impulse function, step function, or sinusoidal function.

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A modern complex system may have many inputs and many outputs, and these may be interrelated in a complicated manner. To analyze such a system, it is essential to reduce the complexity of the mathematical expressions, as well as to resort to computers for most of the tedious computations necessary in the analysis. The state-space approach to system analysis is best suited from this viewpoint.

While conventional control theory is based on the input-output relationship or transfer function, modern control theory is based on the description of system equations in terms of n-first-order differential equations, which may be combined into a first-order vector-matrix differential equation. The use of vector-matrix notation greatly simplifies the mathematical representation of system of equations. The increase in the number of state variables, the number of inputs, or the number of outputs does not increase the complexity of the equations.

From the computational viewpoint, the state-space methods are particularly suited for digital-computer computations because of their time-domain approach.

In the design of a control system, it is important that the system meet given performance specifications. Since control systems are dynamic, the performance specifications may be given in terms of the transient-response behaviour to specific inputs, such as step inputs, ramp inputs, etc, or the specifications may be given in terms of a performance index.

1-7 Optimal & preview control:

The problem of optimal control have received a great deal of attention during the past 3 decade owing to the increasing demand for systems of high performance and to the ready availability of the digital computer. The concept of control system optimization comprises a selection of a performance criterion and a design which yields the optimal control system within limits imposed by physical constraints. Such an optimal control system differs from an ideal one that the former is the best attainable in the presence of physical constraints whereas the latter may well be an unattainable goal. In solving proplems of optimal coltrol systems, the goal is to find a rule for determining the present control decision, subject to certain constraints which will minimize some measure of deviation from ideal behaviour. Such a measure is usually provided by a criterion of optimization, or performance index. The performance index is a function whose value indicates how well the actual performance of the system matches the desired performance. In most practical cases, system behaviour is optimized by choosing the control vector in such a way that the performance index is minimized (or maximized) [4, 5, 7, 13].

The performance index is important because it, to a large

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degree, determines the nature of the resulting optimal control. That is, the resulting control may be linear, nonlinear, stationary or time varying, depending on the form of performance index. The control engineer formulates this index based on the requirements of the problem. Thus , he influences the nature of the resulting system. The requirements of the problem usually include not only performance requirements but also restrictions on the form of the control to ensure physical realizability. The optimization process should provide not only control policies, parameter configurations which are optimal, but also a measure of the degradation in performance by the departure of the performance index function from its minimum (or maximum) value which results from the use of nonoptimal control policies.

To a considerable degree, use of optimization theory in system design has been much hampered by the conflict between analytic feasibility and practical utility in the selection of the performance index. It is desirable that the criteria for optimal control originates not only from a mathematical but also from an applicational point of view. In general, however, the choice of a performance index involves a compromize between a meaningful evalution of the system performance and a tractable mathematical problem [12, 17, 20, 22].

A wide-class of commercial applications have been carried out by utilizing the optimal control theory. This theory can be implemented easily to cope with plants having constant parameters or even of slowly variation parameters. The off-line controller gain of this theory and its robustness, simplicity, applicability and the narrow space area required on memory of the microcomputer, encourage many designers to utilize it in several industrial applications.

Furthermore, there is a varity of applications that utilize the optimal control theory, some of them combining the preview feedforward control to improve the transient response.

It is a common knowledge that the rapid and revolutionary progress in microelectronics in the last decade has had a profound impact on all aspects of technology. The computing capability and low cost of microprocessors have made the implementation of complex control algorithms in practical systems of acceptable cost. In fact the world is rapidly approaching a stage where the scope of specific applications will be limited only by the existing theory and the imagination of the designer [24, 25, 26, 27].

1-8 Scope of work:

The obvious side of the present work is to investigate the properties of the optimal and preview feedforward controllers from the simulation results and from the structure of their control laws. The dynamic equation of a separately excited direct current

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motor is reduced on the basis of maximum efficiency over the whole control range. Accordingly, the control laws are simplified and the microprocessor's execution time is reduced. In addition, the optimum current ratio, ß, is calculated only once at any arbitrary operating condition and it is considered as a variable parameter of the dc motor, then there will be no need to detect or observe the field current. This results in reducing one current detector and one A/D channel of the microprocessor.

The expermintal results are carried out by designing and building an interface circuit and a 3 phase power converter, to compromise between the optimal and the PID controller.

Applications of the PID and optimal controller are carried out on the basis of the dynamic equation of a separately excited constant field current DC motor.

The preview feedforward controller is obtained by minimizing a selected performance criterion, utilizing the principle of optimality. Based on this controller, corresponding future values of desired and disturbance signals are obtained for improving robustness and control system performance.

This dissertation consists of five chapters.
The first one is an introduction that includes a brief description about this thesis and a theoretical background about its subjects.

Chapter two investigates the normal dynamic equation of the separately excited direct current motor, the derivation of the Reduced Dynamic Equation (RDE), and the dynamic equation of the same motor with constant field current. The remainder of this chapter indicates a novel error system technique and a feedforward compensation utilizing certain successive steps ahead of the desired signal of the dc motor. This is to attain best transient response and smooth speed response for several desired signals. The proporties of the optimal and the preview feedforward, applied for RDE and constant field motor, are given from the structure of their control laws and the simulation results.

Chapter three is the simulation results of the separately excited DC motor, constant field current, and Reduced Dynamic Equation. The results have been gathered with a sampling period T=.033 sec. at differernt weighting factors, R & Q, to investigate the robustness of the optimal controller schemes, with and without feedforward compensation. The disturbance and the reference signals have changed. The desired reference signal is selected to change either abruptly, ramp or sinusoidally from 1350 to 1500 RPM. The variable load torque represents the disturbance signal that is selected to be changed abruptly from 2.37 to 5.94 NM.

Chapter four is devoted for the experimental work and test results. It is divided into four sections.
The first section is building and constructing of the three phase six pulse power converter controlled either manually or automatically through the microprocessor to be applied on the

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