AC MOTORS FOR HIGH-PERFORMANCE APPLICATIONS

Analysis and Control

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SAKAE YAMAMURA

Professor Emeritus
University of Tokyo
Tokyo, Japan

and

Vice President
Central Research Institute of Electric Power Industry
Tokyo, Japan

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Preface

I have taught the principles of electrical machinery at the University of Tokyo for many years. My main interest is in analysis and control theories. For a long time I had felt that something was lacking in theories of electrical machinery, in spite of the fact that they were very numerous. Steinmetz's work was outstanding but was concentrated in the analysis of steady-state operation of electrical machines. Fortesque proposed a new analytical tool in the symmetrical component (or coordinate) method. Its analytical power extended to asymmetrical operation of electrical machines, but was still confined to analysis of steady-state operation. Kron tried to produce a unified or general theory of various electrical machines through tensor expressions and introduced the orthogonal two-phase coordinate system, but his theory did not produce any new findings. The orthogonal two-phase coordinate system is currently used in the matrix theory of machines, but matrix theories in the orthogonal coordinate system are similar to Kron's theory. They attempt to unify various machines theoretically, but are not particularly successful in analyzing transient phenomena in machines.

Advances in power electronics are making ac motors competitive and even superior, as control motors, to dc motors, and ac motors have begun to replace dc motors in high-performance control areas. It has been felt that transient phenomena in ac motors were not adequately or sufficiently investigated. Ac motor windings are more numerous than those of dc motors, and their electromagnetic transient phenomena are more complicated. Transient phenomena in ac motors must be further analyzed to suppress and prevent them from occurring in order to realize very quick control response.

For three years I have been working on the analysis of ac motors for quick control and have produced new tools of analysis: the phase segregation method and the decaying-vector symmetrical component method. With these new tools I have analyzed transient phenomena in ac motors, and based on the results of the analyses, new control methods for ac motors have been implemented.

I wish to thank the staff of Marcel Dekker for suggesting that I write a book on these new analytical tools.

Sakae Yamamura

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1

Introduction

The interesting history of the competition between direct current (dc) and alternating current (ac) might better be called a battle, the battleground being New York City and New York State. Thomas Edison built the first commercial power station in 1882 on the southern part of Manhattan Island in New York City. The project, which involved four generators driven by reciprocating steam engines, was very successful and Manhattan was soon electrified. Overhead distribution lines were constructed and underground cables were spread extensively throughout the city. Both arc lamps and Edison's bamboo filament lamps became very popular, and all power was supplied by dc motors. At about this time, Nikola Tesla came to the United States from Yugoslavia. He arrived in New York City in 1884, bringing with him his ideas regarding an ac power system and ac machines. He had worked on the idea of an ac system for some time but could not put his ideas into practice in Europe. In the United States he first worked for Edison, but they soon went their own ways. Edison's dc system was very successful, whereas Tesla believed firmly in the ac system. Although Tesla had invented the induction motor, no polyphase ac system was in operation, and he continued to work on the idea of the polyphase generator and the ac system. George Westinghouse recognized the importance of Tesla's polyphase ac system and bought his patents. In 1895, two 3725-kW ac generators based on Tesla's patents were installed at the Niagara Falls Hydroelectric Power Plant. The frequency used was 60 Hz, which was also Tesla's idea. Gradually the tide of the battle changed and the ac system advanced to the forefront, although it was many years before the dc system finally disappeared from New York City.

As a recipient of the Nikola Tesla Award of the Institute of Electrical and Electronics Engineers (IEEE), I highly esteem Tesla's contributions to the birth and growth of the ac system and admire him very much. I have worked for some time on induction motor theory, and received the Tesla Award for my work on the theory of the linear induction motor (17). Receiving the award was a great honor, and I feel a close relationship with Tesla through my work on the induction motor.

Although the ac system, including the induction motor, was on the winning side of the battle, the dc motor survived the battle because of its superior controllability. The ac motor cannot match the dc motor in controllability. Railway trains are still driven by dc motors, numerical-controlled machine tools are driven by dc motors, most robots are operated by dc motors, and the small motors in computer accessories, recorders, and so on, are dc motors. Dc motors continue to increase their share of the motor market.

For a century ac motors have suffered from problems regarding their controllability. Both induction motors and synchronous motors are awkward in their start and stop operations: they are inferior in speed control, their torque control response is not as quick as that of the dc motor, and ac commutator motors are inferior to the dc motor in structure and performance.

The basis of these limitations does not lie in ac motors themselves but in ac power supplies. In the past, the voltage and frequency of ac power supplies were fixed and difficult to change, whereas dc power supply voltage was easier to change by means of motor-generator sets and mercury-arc rectifiers. The advent of thyristors has helped the dc motor more than the ac motor, by increasing the controllability of dc power supplies and by reducing their cost.

Further development of power electronics is rapidly changing the situation with regard to power supplies. The appearance of gate-turn-off thyristors and bigger power transistors, together with better techniques for thyristor control, are advancing inverter techniques very remarkably. The pulse-width-modulation inverter has become practical and has greatly advanced ac power supply controllability with respect to voltage and frequency. The inferiority of the ac motor to the dc motor is thus disappearing, because it lies in the power supply, not in the motor itself.

Ac motors have begun to replace dc motors on many fronts, where controllability is of primary importance. Induction motors have begun to drive steel mills, are driving spindles of lathes without reduction gears, and are being tested to drive railway cars and locomotives.

Unfortunately, it is not well recognized that the origin of their poor performance lies in the ac power supply, not in the ac motor. Even some of the newly developed ac motor control theory does not recognize this fact. One example is that of transvector control theory of the induction motor, developed in West Germany (11), (18) and also popular in Japan (11). Transvector control theory appears to view the origin of the poor performance as being in the induction motor itself and attempts to make the induction motor behave as much like a dc motor as possible (10), (11), (13). In transvector control theory, the torque-producing mechanism of the dc motor is introduced to the induction motor, and spatial orthogonality between stator magnetic flux and rotor magnetomotive force is assumed, as in the dc motor. The assumed orthogonality couples transvector control to the (d, q)-axis coordinate system, in which the axes are orthogonal to each other. However, the coordinate transformation from a three-phase system to a two-phase system does not assist the analysis of electromagnetic transient phenomena in the induction motor.

For quick torque control response in the electrical motor, analysis of electromagnetic transient phenomena is essential. It is necessary to know how disturbing transient phenomena are to torque control of the motor and, if possible, an attempt should be made to find control methods that do not cause electromagnetic transients or which at least minimize them. In controls that require quick response, such as those of robots and machine tools, the decay-time constant of electromagnetic transients of the motor becomes comparable with that of dynamic transients in driven machines. Unfortunately, ac motor transients are much more complicated than those of dc motors, because ac motors have a greater number of windings. Electromagnetic transient phenomena of both induction motors and synchronous motors have not been analyzed sufficiently.

In much of ac motor control theory, including transvector control theory, coordinate transformation from three-phase to orthogonal two-axis coordinates [(d, q)-axis coordinates] has been introduced to facilitate ac motor analysis, but it has not helped. The coordinate transformation reduces the number of phases from three to two, but two are still too many, because this corresponds to a four-mesh circuit. Inductor motor transient phenomena still remain virtually unanalyzed. In transvector control, (d, q)-axis coordinate transformation does provide orthogonality between the flux and the magnetomotive force to produce torque, but since transient phenomena are not well analyzed, the theory does nothing to change the inferiority of the ac motor with respect to quick torque control response.

This book provides the complete analysis of ac motor transient phenomena which has been missing in previous control theories. Both the field theory approach and the circuit theory approach to the problem of ac machine analysis have been used by the author in past research. In the former approach, Maxwell's field equations have been solved for transient phenomena of the air gap field of the induction motor (3). Although both approaches appear to be very successful, in this book only the circuit theory approach will be used, because most readers are more familiar with the circuit theory of ac motors than with the field theory. In the circuit theory, coordinate transformation will not be used; rather, state variables of the motor will be used directly.

A new method of analyzing transient phenomena of ac motors is proposed, in which only one phase is used to represent three phases of the ac motor, as is the case in the analysis of ac motor steady-state operations. This method, termed the phase segregation method, is used extensively in this book. It is very powerful in analyzing three-phase ac motors in symmetrical or balanced operation. The phase segregation method provides equivalent circuits for both the steady and transient states of ac motors. The approach may seem rather classical, but the equivalent circuits are very useful in analyzing and understanding transient phenomena of ac motors and are also very helpful in finding the best control methods to use with ac motors. In induction motor control it was found that transientless response could be realized and that the induction motor could be made to respond more quickly than the dc motor.

The decaying vector symmetrical component method is proposed for the analysis of transient phenomena of ac machines under both balanced and unbalanced operations. This is a type of expanded symmetrical component method, and it will be shown that its analytical power is very strong and it will fill a large vacant area in the theory of ac machines.

Analyses of electromagnetic transient phenomena of both induction and synchronous motors constitute the main part of this book. Based on the results of transient analyses, new control methods are proposed to provide the quickest response to ac motor torque control.

2

Induction Motor Control

2.1 MOTOR CONTROL: PAST AND PRESENT

The induction motor is used extensively in homes and in industry. It is the most popular electrical motor and more are produced each year than any other motor. However, its applications are limited to those that do not require a high level of control of speed, torque, and/or starting/stopping operations. The induction motor is an ac motor fed by an ac power supply. Ac power systems are widely used throughout the world and are essentially fixed-voltage, fixed-frequency systems. Because of the constraints of a fixed-voltage, fixed-frequency system, the induction motor has remained essentially a constant-speed motor, and its control capabilities have been markedly inferior to those of the dc motor, so dc motors are widely used for high-level control applications.

The situation has begun to change since the advent of semiconductor power electronics. Thyristors and power transistors have made variable-voltage, variable-frequency power supplies practical and economical, and with the constraints imposed by the ac power supply disappearing, the induction motor has begun to invade applications areas in which the dc motor had formerly been used exclusively.

The induction motor has begun to replace dc motors as a spindle motor of the lathe; is going to replace dc motors in the steel industry, as drive motors in steel mills and conveyor rolls; and is being tried as a primary motor in railway locomotives and electric trains. But these are applications where very quick control response is not necessarily required. Applications where really quick control response is required await continued development of the induction motor for use in robots, machine tools, and sophisticated drives in industry.

Induction motors for quick response control are three-phase motors. Single-phase induction motors are not suitable for quick control because their performance is not good, especially at low speeds. They are not necessarily small motors, but may be large motors. Control techniques for quick response are the same for both small and large motors.

The induction motor itself is a very superior electric motor, being simple in structure, robust and easy to maintain, and very reliable. But its performance is dependent on the power supply and the control method used. When the power supply is of fixed voltage and/or fixed frequency, its performance is rather limited and it is inferior in control performance to the dc motor. When the power supply is of variable frequency and variable voltage, its performance is enhanced and its control performance becomes notably superior, although it is dependent to a large extent on the control method and theory. At present the hardware techniques used in power electronics are well advanced, making available variable-voltage, variable-frequency ac power supplies that provide quick response. The pulse-width-modulation inverter is best suited as the ac power supply providing quick response control of ac motors. It now appears that the theoretical side of control techniques for the induction motor is the area where further improvement is most needed before the induction motor can develop its full control capability. The induction motor has the potential to be much quicker in its response to torque control than the dc motor. One of the aims of this book is to introduce control theory for the induction motor that has been developed by the author over a period of several years (3)-(10).

2.2 STATE OF THE ART INDUCTION MOTOR CONTROL

The induction motor had been considered to be essentially a constant-speed motor. Control of its speed has been possible, but the method and equipment have been awkward and its control performance inferior, the principal reason being that the variable-frequency ac power supply was expensive and uneconomical. Motor-generator sets and mercury-arc rectifiers were the first to be used, but even thyristor inverters were awkward, and the response of the ac power supply, which made use of these power conditioners, to frequency control was not quick. It is because of the awkward ac power supplies that the induction motor has been limited in its control performance, although the induction motor itself has a very high control capability. When first used, control of the induction motor was restricted to speed control, which was by means of frequency and/or voltage control. By changing the frequency of the power supply, synchronous speed of the induction motor could be changed. By changing the terminal voltage of the induction motor, its speed under load could be changed. If the frequency and voltage were changed proportionally to each other, the magnetic flux density could be kept almost constant, resulting in better control performance. The object of these controls was mainly motor speed adjustment under steady state; transient phenomena between successive steady states were of no concern. With respect to quick motor control response, the induction motor was far inferior to the dc motor, and the latter was used predominantly in applications where quick response was required. This was the state of the art of classical induction motor control.

It should be pointed out that control of the electrical motor is actually control of the power supply. The motor can be controlled only through the power supply. If the power supply is controlled properly, the motor responds properly. Controllability of the power supply is more important, because that of the motor is not a limiting factor. For the classical period of induction motor control, controllability of the ac power supply was very inferior to that of the dc power supply. This was only one reason that the dc motor was used so predominantly for quick response purposes, in spite of the fact that the dc motor itself was so awkward in its structure and capability. It has many performance constraints, caused by commutation with brushes and commutators, limited momentary overload capacity being one example.

Now the situation has changed. With the progress in power electronics, controllability of the ac power supply has been advanced dramatically, ac motor control performance has improved considerably, and a new era in ac motor control has begun. It is very important to know that the constraints on ac motor control arising from the ac power supply have disappeared. The problem now is that ac motor control theory is not adequate and is imposing constraints on the control capability of the ac motor. However, it appears that efforts have begun on developing appropriate ac motor control theory for quick response. The vector or transvector control theory, which deals with quick response in the induction motor, is one such development.

Generally speaking, high-level control of the electric motor is torque control. It may or may not be closed-loop control, but motor torque is the target state variable of the motor, whose value must be controlled precisely to obtain a high level of control. However, in classical induction motor control, the target state variable was often not clear; it might have been motor speed or else torque value being left uncontrolled. In the days of classical control of motors, torque control could be performed quickly only for the dc motor. The induction motor was thus placed in a very inferior position compared with the dc motor.

Transvector or vector control was proposed to overcome this problem. Its theoretical basis is to treat the induction motor and the dc motor in the same way. In the dc motor the mechanism of torque generation is the cross product of the magnetic flux and the magnetomotive force of the armature current, which are spatially orthogonal to each other. The vector control theory tries to view the mechanism of the induction motor in the same way. To realize spatial orthogonality in the induction motor, a coordinate transformation is made to transform the three-phase induction motor into a two-phase induction motor which has phase windings along the direct and quadrature axes, which are orthogonal to each other. The transformation makes the control circuit more complicated than necessary and does not help the analysis of induction motor transient phenomena nor that of control (11),(12).

Transvector control theory is still being revised and made more sophisticated. It is in great fashion in Japan, where the most sophistication has probably been achieved. Although there is not enough space in this book to explain all the details of transvector control theory, it seems appropriate to point out the following.

As stated above, the coordinate transformation between two phases and three phases in transvector control makes control computation more complicated than necessary and does not help the analysis of transient phenomena of torque control in the induction motor. The equivalent two-phase induction motor is still difficult to analyze, so transient phenomena are not adequately taken into account. Because of lack of knowledge of transient phenomena, the full capability of the induction motor with respect to torque control is not recognized by transvector control. The theory does not pay attention to voltage-type control (9),(10) where primary terminal voltage is a controlling input variable to the induction motor, but treats only current-type control, where primary current is a controlling input variable to the induction motor. As explained later, voltage control has many advantages over current control.

The author has contrived a new approach to the analysis of induction motor transients. Based on the results of this analysis, a new control method, called the field acceleration method (FAM), has been developed. A number of technical papers on FAM control have been published and it is appropriate at this time to organize them into a book.