

IEEE Guide for Evaluation of Torque Pulsations During Starting of Synchronous Motors

Sponsor

Electric Machinery Committee
of the
IEEE Power Engineering Society

Approved 7 August 2000

IEEE-SA Standards Board

Abstract: A uniform method for calculating and measuring torque pulsations that occur during starting of synchronous motors is provided. Synchronous motors, as discussed in this guide, applies to all types of excited synchronous motors, including laminated or solid, salient or nonsalient machines, as well as nonexcited synchronous-reluctance motors.

Keywords: air gap torque, angular acceleration, electromagnetic, motor, pulsation, rotational velocity, salient, speed sensing, starting stator resistance, synchronous, torque, winding volt-second ampere (VSA) method

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2000 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 29 September 2000. Printed in the United States of America.

Print: ISBN 0-7381-2524-4 SH94867
PDF: ISBN 0-7381-2525-3 SS94867

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

IEEE is the sole entity that may authorize the use of certification marks, trademarks, or other designations to indicate compliance with the materials set forth herein.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; (978) 750-8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Introduction

(This introduction is not part of IEEE Std 1255-2000, IEEE Guide for Evaluation of Torque Pulsations During Starting of Synchronous Motors.)

As the size of large synchronous motors began to increase in the early 1960s to multimewatt ratings, shaft breakage began to be a major concern, particularly in applications requiring a long starting interval. Torque pulsations resonating with the natural mechanical frequency of the shaft and load were blamed for these breakages, but theoretical as well as experimental techniques for evaluating this phenomenon were lacking at the time. Technical discussions concerning this problem were scheduled at several conferences in the mid 1960s.

This guide for evaluating these torque pulsations is the result of a more than 30-year effort of a Working Group formed under the auspices of the Synchronous Machines Subcommittee of the Power Engineering Society (PES) Electric Machinery Committee, formed sometime around 1968. The work of many participants over the years is acknowledged, including Jack Imbertson, William Flora, K. C. Cooley, Radhey Mathur, Azad Mesrobian, William L. Billington, L. A. Ferrano, Ernest I. Pollard, J. P. Povlock, John F. Szablya, Jay C. White (deceased), and particularly, former chairperson Gurney Godwin.

Participants

The following is a list of the Working Group members for this guide:

Thomas A. Lipo, Chair

Paul L. Dandeno
James H. Dymond
Nirmal K. Ghai

Ronald Hedin
William Jackson

James Oliver
Edward Owen
Michel Poloujadoff

The following members of the balloting committee voted on this guide:

Vaino Aare
Michael P. Baldwin
Paul L. Dandeno
James H. Dymond
James S. Edmonds
Ahmed M. El-Serafi
Nirmal K. Ghai
Brian E. B. Gott

Thomas J. Hammons
Ronald Hedin
Richard A. Huber
Innocent Kamwa
Ali Keyhani
Thomas A. Lipo
Azad Mesrobian

J. R. Michalec
Daleep C. Mohla
Nils E. Nilsson
Michel Poloujadoff
Manoj R. Shah
Jan Stein
John F. Szablya
Paul Dieter Wagner

The final conditions for approval of this guide were met on 7 August 2000. This guide was conditionally approved by the IEEE-SA Standards Board on 29 June 2000, with the following membership:

Donald N. Heirman, *Chair*

James T. Carlo, *Vice Chair*

Judith Gorman, *Secretary*

Satish K. Aggarwal
Mark D. Bowman
Gary R. Engmann
Harold E. Epstein
H. Landis Floyd
Jay Forster*
Howard M. Frazier
Ruben D. Garzon

James H. Gurney
Richard J. Holleman
Lowell G. Johnson
Robert J. Kennelly
Joseph L. Koepfinger*
Peter H. Lips
L. Bruce McClung
Daleep C. Mohla

James W. Moore
Robert F. Munzner
Ronald C. Petersen
Gerald H. Peterson
John B. Posey
Gary S. Robinson
Akio Tojo
Donald W. Zipse

*Member Emeritus

Also included is the following nonvoting IEEE-SA Standards Board liaison:

Alan Cookson, *NIST Representative*
Donald R. Volzka, *TAB Representative*

Yvette Ho Sang
IEEE Standards Project Editor

Contents

1. Overview.....	1
1.1 Scope.....	1
1.2 Purpose.....	1
1.3 Limitations	1
2. Reference	2
3. Problem description	2
4. Synchronous motor equivalent circuit	4
5. Calculation of pulsating and average electromagnetic torque	7
6. Mechanical measurement of electromagnetic air gap torque	7
6.1 Measurement of angular acceleration	8
6.2 Measurement of rotational velocity	9
6.3 Torque shaft method	14
7. Electrical methods for measuring electromagnetic air gap torque	14
7.1 Search coil method.....	15
7.2 Measurement of electromagnetic torque using terminal voltage and current sensing.....	16
7.3 Measurement of electromagnetic torque using input power sensing.....	17
7.4 Measurement of torque using electrical power input and speed sensing.....	19
Annex A (informative) Sample calculation of per unit air gap torque.....	23
Annex B (informative) Operational reactances.....	25
Annex C (informative) Bibliography	26

IEEE Guide for Evaluation of Torque Pulsations During Starting of Synchronous Motors

1. Overview

1.1 Scope

This guide provides a uniform method for calculating and measuring torque pulsations that occur during starting of synchronous motors. Synchronous motors, as discussed in this guide, applies to all types of excited synchronous motors, including laminated or solid, salient or nonsalient machines, as well as nonexcited synchronous-reluctance motors.

1.2 Purpose

This guide

- a) Defines electromagnetic torque pulsations that occur during starting of synchronous motors.
- b) Recommends an equivalent circuit that can be used to describe analytically the behavior of a laminated, salient-pole synchronous motor during starting.
- c) Provides the definitions and information necessary to properly determine the circuit parameters of the equivalent circuit.
- d) Supplies equations, derived from the circuit, that can be used to calculate the magnitude of the torque pulsation that would occur during starting.
- e) Presents several alternative techniques for the on-line measurement of torque pulsations during starting.

1.3 Limitations

Although this guide recommends specific calculation methods and testing techniques, it does not suggest nor imply suitability of the methods for all machine designs or operating conditions. In particular, magnetic hysteresis, eddy currents in the stator, changes in stator resistance due to skin effect, and armature tooth saturation could cause significant deviations.

In modern installations, direct current is applied to the field winding by means of slip rings from a static exciter, or by a rotating brushless excitation system, to establish synchronous operation; the field is typically shorted through a starting resistor during the starting phase of operation. In modern excitation systems, the shorting of the exciter is frequently accomplished by means of a crow-bar thyristor. The action of this device produces a dissymmetry in the induced field current, which must be taken into account.

2. Reference

This guide shall be used in conjunction with the following publication. When the following publication is superseded by an approved revision, the revision shall apply.

IEEE Std 115-1995, IEEE Guide: Test Procedures for Synchronous Machines, Part I—Acceptance and Performance Testing, Part II—Procedures for Parameter Determination for Dynamic Analysis.

3. Problem description

The synchronous motor and its connected load can be represented by a torsional system of interconnected springs and masses, with a large number of springs and masses external to the motor itself. As in any mechanical system, resonances occur at the system natural frequencies, which are algebraically related to the spring constants and masses of the system. In many cases, the connected load has sufficient damping or is sufficiently stiff that these resonances are not of concern. Some systems are inherently flexible and have relatively low resonant frequencies. Such a system is sensitive to impressed torques that could excite the system at one of its mechanical resonant frequencies. The problem is especially pronounced in a synchronous motor, since the torque produced typically sweeps the frequency range from zero to twice the line frequency as it accelerates from rest during starting. Overstressed shafts and couplings, abnormal gear tooth wear, loss of interference fits, and other problems can result when a motor and the equipment coupled to it are subjected to excessive torsional oscillation.

Unlike lateral vibrations that can be readily sensed by touch and measured with relatively common instruments, torsional oscillations can exist with considerable amplitudes and yet be undetectable except by special instrumentation. Since torsional oscillations are so difficult to detect and measure, and yet cause disastrous consequences, it is particularly important that torsional stresses be evaluated when synchronous motors are to drive other equipment.

All synchronous machines develop the following three major components of electromagnetic torque during starting:

- A unidirectional or time-averaged component
- An initial transient (decaying) pulsating component
- A persistent (nondecaying) pulsating component

The unidirectional component is the useful component that acts to accelerate the machine, and results from the forward rotating components of the rotor current interacting with the air gap flux in the same manner as a squirrel cage induction machine. The torque definitions given in the IEEE Standard Dictionary of Electrical and Electronics Terms [B8]¹ refer to the time-averaged torque. The transient component results from the initial asymmetrical component of inrush current, which interacts with the symmetrical alternating component of air gap flux in the same manner as a squirrel cage induction motor. The resulting frequency of torque pulsation is essentially equal to the line frequency (i.e., 50 Hz or 60 Hz). The steady pulsating component is

¹The numbers in brackets correspond to those of the bibliography in Annex C.

the result of asymmetry of the rotor electrical and magnetic circuits. This guide is concerned primarily with the continuous pulsating component of torque that occurs during asynchronous operation due to the effects of rotor asymmetry.

In general, the persistent pulsating component arises from both rotor geometry variations that repeat once per pole pitch or that reappear once for every two poles. The following are the three causes of rotor asymmetry for which the geometry repeats once per pole pitch:

- a) Magnetic permeance variations, which are the result of the salient poles being relatively more easily magnetized at the center of the pole and relatively less easily magnetized at the center of the interpolar space.
- b) Main field winding, which encircles only the direct axis and not the quadrature axis.
- c) Nonuniform bar placement and composition of the amortisseur or damper winding. The amortisseur winding, which consists of short-circuited bars inserted into slots in the rotor, serves to start the motor in much the same manner as do the rotor bars of a conventional squirrel cage induction motor.

These geometric variations result in a torque pulsation at twice the slip frequency (twice the difference between the synchronous speed and the rotor speed multiplied by the number of pole pairs). When the main field winding is excited by direct current, the electromagnetic geometry repeats once for every two poles, and there exists an additional component of continuous torque pulsation at slip frequency. In most cases, the field winding is shorted either across the terminals or through a resistor. If the motor accelerates without the field excitation already applied, the frequency of the pulsating torque then varies nearly linearly from twice the line frequency at standstill to zero frequency at synchronous speed. However, should the field excitation be applied before the synchronizing speed is reached, an additional large component of pulsating torque appears with a frequency one-half of the original component (i.e., at the slip frequency).

One of the functions of the motor field excitation control circuit is to prevent the application of excitation until the synchronizing speed is close to synchronous speed. Another function is to remove the field excitation and reconnect the discharge resistor should the motor pull out of step after synchronism is reached. For motors with brushless excitation, the design of the excitation system attempts to avoid unnecessary or an unexpectedly large amount of torque pulsation. There are a number of different exciter circuits available from motor manufacturers. Experience has indicated that, with proper operation, the inherent amount of slip-frequency torque pulsation during starting is only a fraction of twice the slip-frequency torque pulsation, and is, therefore, not critical. Hence, this guide is concerned primarily with the starting torque pulsation at twice the slip frequency and not with the premature application of field excitation.

The magnitude of the pulsating torque is essentially determined by the degree of asymmetry of the rotor circuit. A rotor structure that has no significant asymmetry will not have a significant torque pulsation during asynchronous operation. Although the magnitude of twice the slip-frequency pulsating torque varies depending upon the rotor design parameters, experience indicates it is not practical to eliminate this pulsation. Furthermore, the reductions in the magnitude of the pulsating torque that are theoretically possible often can not be obtained in practice because it is necessary to meet other requirements of the drive.

In addition to the torque pulsation, asymmetry of the rotor typically causes a loss in average torque above half speed. This reduction in average torque is the result of the backward traveling component of air gap flux interacting with the stator circuit and creating a braking torque. The greater the degree of asymmetry in the rotor, the larger the amount of torque pulsation and the greater the loss in average torque for operation above one-half synchronous speed. A rotor structure that is extremely asymmetrical, such as a machine having no effective winding on one axis, will develop extreme torque pulsations and will not accelerate beyond one-half synchronous speed. A solid pole design most nearly approximates the single winding case when pole tip connections are not used.

While the factors that affect excitation of most modes of torsional oscillation are primarily contained in the design of the synchronous motor, the design of the external equipment to which it is mechanically connected must also be considered. When the manufacturer of the driven equipment makes a torsional analysis of the complete assembly, the motor manufacturer should be consulted for the motor design data for speed ranges of critical interest that affect torsional vibration. The manufacturer of the driven equipment, in turn, should advise the motor manufacturer of the results of this torsional analysis to permit the design of the motor rotor to be satisfactorily completed. When the driven machine starting requirements are not severe, the motor designer may have some latitude to adjust the motor torque characteristic. An increase in damping to avoid excessive torque pulsations or a shift of the mechanical resonance can improve the drive.

4. Synchronous motor equivalent circuit

The analysis of synchronous motors is generally based on the two-axis (d - q) theory developed by R. H. Park. The framework of differential equations, called “Park’s Equations,” forms the basis of most analyses of synchronous machines (see Park [B15]). Using the motor convention for current flow and the notation and terminology of Concordia [B2], Park’s equations are written in a reference frame rotating synchronously with the rotor and in per unit form (see Harris et al. [B6]) as shown in Equation (1) through Equation (6)

$$e_d = p\psi_d - \psi_q p\theta + r i_d \quad (1)$$

$$e_q = p\psi_q + \psi_d p\theta + r i_q \quad (2)$$

$$0 = p\psi_{1d} + r_{1d} i_{1d} \quad (3)$$

$$e_{fd} = p\psi_{fd} + r_{fd} i_{fd} \quad (4)$$

$$0 = p\psi_{1q} + r_{1q} i_{1q} \quad (5)$$

$$T_e = \psi_d i_q - \psi_q i_d \quad (6)$$

where

e_d	is the instantaneous value of the armature (i.e., stator) direct axis voltage, in per unit
e_{fd}	is the instantaneous value of the armature quadrature axis voltage, in per unit
e_q	is the instantaneous value of field voltage, in per unit
i_d	is the instantaneous value of the armature direct axis current, in per unit
i_q	is the instantaneous value of the armature quadrature axis voltage, in per unit
i_{1d}	is the instantaneous value of direct axis amortisseur winding current, in per unit
i_{1q}	is the instantaneous value of quadrature axis amortisseur winding current, in per unit
i_{fd}	is the instantaneous value of field current, in per unit
p	is the derivative operator $d/d(\omega t)$, where ω is the base frequency and t is time
r	is the per unit armature resistance per phase (including external resistance)
r_{1d}	is the per unit direct axis amortisseur resistance (referred to the stator winding)
r_{1q}	is the per unit quadrature axis amortisseur resistance (referred to the stator winding)
r_{fd}	is the per unit field resistance (including discharge resistance during starting and referred to the stator winding)