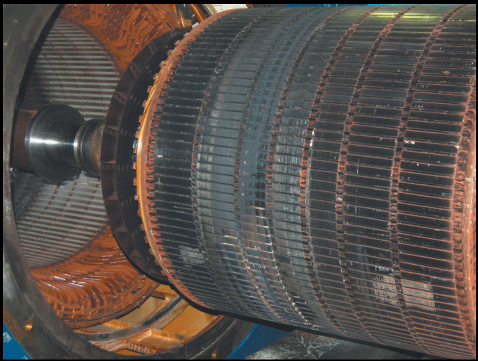
Current Signature Analysis for Condition Monitoring of Cage Induction Motors

Industrial Application and Case Histories



WILLIAM T. THOMSON
IAN CULBERT

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ABOUT THE AUTHORS

William T. Thomson was born in Scotland in 1946 and started his working life in 1961 as a maintenance electrician until 1970. Evening class study provided the vocational qualifications to enter the University of Strathclyde (Glasgow, Scotland) in 1970. In 1973, he graduated with an Honors degree in Electrical and Electronic Engineering specializing in electrical machines. He was an R&D engineer from 1973 to 1977 with Hoover Ltd. in Glasgow, working on the reduction of noise and vibration from electric motors. In 1977, he was awarded a Master's degree from the University of Strathclyde for a research thesis titled "Reduction of Acoustic Noise and Vibration from Small-Power Electric Motors."

From 1977 to 1979, Thomson was a Lecturer in Electrical Power Engineering at the Hong Kong Polytechnic, and from 1979 until 2001 he was a Lecturer (1979–1983), Senior Lecturer (1983–1990), and Full Professor (1990–2001) at the Robert Gordon University in Aberdeen, Scotland. His research focused on the design, operation, and condition monitoring of induction motors, and in 1980 he initiated research into Motor Current Signature Analysis to detect cage winding breaks and abnormal levels of airgap eccentricity in cage induction motors. This led to his first industrial case history in 1982.

He left academia in 2001 to set-up EM Diagnostics Ltd. and the company now has a team of professional electrical engineers and provides consulting services on the design, operation, and condition monitoring of induction motors. He has published 72 papers on condition monitoring of induction motors in a variety of engineering journals such as *IEEE Transactions* (USA), *IEE Proceedings* (UK), and also at numerous International IEEE and IEE conferences. He is a senior member of the IEEE, a fellow of the IEE, and a Chartered Professional Engineer registered in the UK.

Thomson was awarded the Queen's award for technological achievement in 1992 for his input of knowledge to the development of "Motor monitor" for diagnosing broken rotor bars in 3-phase induction motors via current signature analysis, marketed by Entek of Cincinnati, USA.

In 1999, Thomson provided access to his knowledge on MCSA, via a license from the Robert Gordon University, Scotland to Iris Power (now Iris Power-Qualitrol) Canada for the development of the CS meter (CS meaning current signature) and the third generation of this instrument called the MDSP (Motor Digital Signal Processor) was released by Iris Power-Qualitrol in 2014. The Robert Gordon University and EM Diagnostics Ltd. share (50:50) the royalty payments (in perpetuity) from Iris Power-Qualitrol to the Robert Gordon University.

Ian Culbert was a rotating machines specialist at Iris Power-Qualitrol since April 2002 until his very untimely death on September 8, 2015. At this company he provided consulting services to customers, assisted in product development, trained sales and field service staff, and reviewed stator winding partial discharge reports. Culbert also advised customers on Motor Current Signature Analysis and analyzed complex case histories. Before joining Iris Power he was a motor and small generator specialist with Ontario Hydro/Ontario Power Generation from 1977 to 2002 and prior to that time, a motor designer with Parsons Peebles, Scotland and Reliance Electric, Canada.

Culbert was a Registered Professional Engineer in the Province of Ontario, Canada and a senior member of IEEE. He has co-authored two books on electrical machine insulation design, evaluation, aging, testing, and repair and was principal author of a number of Electric Power Research Institute reports on motor repair. Culbert also co-authored a number of papers on motor electrical component on-line and off-line motor diagnostics testing and actively participated in IEEE, IEC, and ISO standards development working groups.

OBITUARY TO IAN CULBERT (1943–2015)

A POEM by Robert Burns expresses the thoughts of Ian's family, his many friends, and co-workers whom he met during his professional life.

William T. Thomson

Robert Burns (1759–1796), Scotland's National Bard
"Epitaph on my own friend and my Father's friend Wm. Muir in Tarbolton Mill"
(April 1784)

An honest man here lies at rest,
As e'er God with his image blest:
The friend of man, the friend of truth,
The friend of age, and guide of youth:
Few hearts like his – with virtue warm'd,
Few heads with knowledge so inform'd:
If there's another world, he lives in bliss;
If there is none, he made the best of this.

Ian was born on February 10, 1943 in Perth, Scotland and started his career as an electric motor designer with Parsons Peebles, Scotland. He emigrated to Canada with his family in February 1974 to take up a position as an electrical machines designer with Reliance Electric, Canada. From 1977 to 2002 Ian was an electrical machines specialist with Ontario Hydro/Ontario Power Generation. In April 2002, Ian joined Iris Power as a Rotating Electrical Machines Expert until his very sad and untimely death on September 8, 2015. At Iris Power he provided consulting services to customers, assisted in product development, trained sales and field service staff, and reviewed stator winding partial discharge reports. Ian also advised customers on Motor Current Signature Analysis and analyzed complex case histories.

Ian was a Registered Professional Engineer in the Province of Ontario, Canada and a Senior Member of IEEE. He co-authored two books on electrical machine insulation design, evaluation, aging, testing, and repair and was principal author of a number of Electric Power Research Institute reports on motor repair. Ian also co-authored and presented papers at IEEE international conferences and published papers in IEEE Transactions on the off-line and on-line testing of electrical machines to diagnose problems in stator and rotor windings and stator core problems. He actively participated in IEEE, IEC, and ISO standards development working groups. Ian was an excellent electrical engineer who set very high standards and was also a gentleman of wit and humor and was very proud of his Canadian citizenship and his native country, Scotland and is very sadly missed by all who knew him. It was indeed a great pleasure to be the co-author of this book with Ian and his input is testament to his knowledge and experience.

To quote Ian's daughter, Georganne "My Dad was a man who lived his life authentically. What you saw was what you got. The generous, intelligent and caring man I knew as my father was the same man his co-workers and friends knew."

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Thomson and Ian dedicate this book to their respective wives, Mary Thomson and Anne Culbert, for their irreplaceable support throughout their careers which made the writing of this book become a reality, without them, it would not have been possible.

William T. Thomson
Ian Culbert

FOREWORD

For decades the motor industry associated with squirrel cage induction motors (SCIMs) has been developing, as part of condition monitoring, a process called Motor Current Signature Analysis (MCSA) to determine if the rotor cage winding has broken rotor bars or the motor has an abnormal level of operational airgap eccentricity. Since the 1970s, research, testing, evaluation, and technical papers have been published on this form of condition monitoring and how and where to apply it. Unfortunately, few of these studies and resulting papers have had any significant amount of actual case histories containing enough useful data to assist in the conduction of an accurate analysis.

The authors of this unique book, William T. Thomson and Ian Culbert, have presented 50 industrial case histories, 35 of these are on MCSA to detect broken rotor bars in "Cage Induction Motors," which also include what is referred to as "false positives." These are cases where there are no broken rotor bars but the test data indicate that there are. There are also 15 industrial case histories on MCSA for diagnosing abnormal levels of operational airgap eccentricity including successful and "unsuccessful" cases.

On the surface, false positives may not seem a major issue. One may even breathe a sigh of relief that they do not have to rebuild the rotor. This is the issue with this approach that the authors discuss in great detail. First, if there turns out not to be broken rotor bars in a large, high voltage SCIM and the user shuts down the operation, pulls the motor, transports it to a qualified repair facility, disassembles the motor and then finds nothing wrong, the expense to do so and the loss in production can add up to a greater cost than a new motor! The end user is a very dissatisfied customer and inevitably loses all faith in MCSA as a credible condition monitoring technique. In many cases the "false positive" that drove this decision may indicate a serious problem with the driven equipment that still has not been identified and corrected when the motor is re-installed.

The authors do a great service to industry by identifying the source of many of these false positives. If it is wrongly concluded that there is a "false positive" and the motor is kept in operation, then the danger is that in some cases a broken rotor bar may find its way into the stator winding and cause a catastrophic failure or in some cases may actually exit the motor and cause physical harm to operating personnel, or in a hazardous area may lead to an explosion.

Because of these possibilities there has previously been some hesitance to rely on MCSA as an effective tool for condition monitoring and conducting a "Root Cause Failure Analysis." However, the proper use of this methodology proposed by the authors combined with the case studies now greatly minimizes the possibility of an incorrect root cause failure analysis. The final chapter starts with a very useful flow chart taking the user through a step-by-step process of conducting an MCSA test, which is followed by sections on "*strengths, weaknesses, external constraints, and very importantly the lessons learned*."

For those who choose to use MCSA as a tool there are some considerations as to where best to apply MCSA as pointed out by the authors. A review of broken rotor bar failures reveals that most broken bars occur on fabricated rotors and not on die-cast rotors which are normally used in smaller motors. The motors with the highest probability of having broken bars are those that have been in service for many years, those that are frequently started, or have high inertial loads. The actual loading of the motor or high ambient temperature conditions can also be a factor.

MCSA is proposed as a useful tool to benchmark the motor prior to shipment to the job site or upon start up. Unfortunately, there are some cases where the original rotor design was not acceptable for its application and therefore has a built in propensity for broken rotor bars during the motor's normal life cycle. There are other cases where, in the process of rebuilding the rotor, adequate steps have not been taken to minimize future bar breakage. The authors have woven into this book the basic knowledge to identify and deal with most of these issues.

When purchasing future motors, especially those with fabricated rotors, the authors recommend that the motor manufacturer also supply the actual motor speed at different loads and the correct number of rotor bars. It is also helpful to know the shaft configuration and whether end ring retaining rings cover the extended bars and end rings area. This additional information will help to ensure a more reliable MCSA diagnosis of cage winding problems. The book contains valuable details as to why this additional information is useful. If the motor is dismantled for repair much of this information can be obtained then.

Another feature of the book is that it contains useful information on basic SCIM theory to assist those who may be technical people, such as mechanical, maintenance, and instrumentation engineers and technicians but who may have had no prior training on basic induction motor theory. At the end of each chapter there are 10 questions that make the book useful in the training process.

This book can be very beneficial for those who design, install, operate, maintain, troubleshoot, and repair SCIMs. The authors have many years of experience in all of these areas and have chosen to include information pertaining to this vast array of users. I would also recommend it to university or trade schools as a training tool and a reference book.

It is quite apparent that the time spent to obtain and study the material presented by the authors is more than offset by the costs and time spent to avoid just one catastrophic motor failure. This book will be a valuable asset in the library of those who have to deal with SCIMs in any of the many aspects from design through to successful operation.

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PREFACE

CONDITION MONITORING of 3-phase squirrel cage induction motors (SCIMs) is now extensively used by end users to prevent catastrophic failures, unscheduled downtime with consequent loss of income, and hazardous conditions that may lead to major accidents. This book is dedicated to one condition monitoring technique, namely, Motor Current Signature Analysis (MCSA) and although its content is focused to suit the needs of industry it should also be of interest to academia.

The content is uniquely different from all other books on condition monitoring of electrical machines and also those with a part content on the use of MCSA, since it documents 50 industrial case histories on the application of MCSA to diagnose broken rotor bars, unacceptable levels of airgap eccentricity, and abnormal drive dynamics downstream of the motor. A key feature of the case histories is that, wherever possible, they seek to close the loop between diagnosing a problem and strip down of the motor, to provide photographic evidence that the diagnosis was correct or incorrect. MCSA case histories of motors with power ratings from 127 kW (170 HP) to 10,000 kW (13,340 HP) and operating voltages from 415 to 13,800 V are presented.

The reason for this book arises from the nature of the existing literature. Since the late 1970s there have been hundreds of research papers on MCSA which have been predominantly published by academia, with the test results obtained from small power SCIMs operating under controlled experimental conditions. These papers justify their research on the basis that MCSA is required by the end users and this is perfectly acceptable; however, the number of papers containing actual industrial case histories amount to only about 2% of the total. There was therefore an overwhelming need for a book on MCSA that focused on industrial case histories. Since 1982 the authors have applied MCSA in industry, William T. Thomson for 34 years and Ian Culbert for 14 years. Further, the authors' have 108 years of combined experience in the installation, maintenance, repair, design, manufacture, operation, and condition monitoring of SCIMs.

The successful application of MCSA requires the engineer to understand the operation of SCIMs, have an appreciation of the design, construction, and manufacture of cage rotors, the causes of breaks in cage windings, and the fundamentals on the use of MCSA to detect broken rotor bars. These topics are covered in Chapters 1 to 4, respectively. Chapters 5 and 6 contain case histories on MCSA used to assess the operational condition of different designs of cage windings when SCIMs are driving steady mechanical loads. Chapter 7 reports on case histories where MCSA attempts to diagnose broken rotor bars when cyclical disturbances from the mechanical loads are reflected back into the motor, which reflection can cause an incorrect diagnosis of broken rotor bars, referred to as a false positive.

Chapter 8 presents case histories, which include false positives of broken rotor bars due to the reflected mechanical dynamics from the combination of low speed gearboxes and fluctuating loads from conveyors and crushers. Chapter 9 presents miscellaneous MCSA case histories on the detection of broken rotor bars. For example, cases in which the number of spider support arms on the shaft (and axial ducts) of a cage rotor is equal to the number of poles, since this design can give a false positive of cage winding defects; the detection of slack and worn belts in belt driven cooling fans and the detection of imperfections in the caisson of a submersible seawater lift pump driven by a SCIM. Chapter 9 also includes case histories on the application of MCSA to inverter-fed SCIMs.

Chapter 10 covers the definitions and practical causes of different types of airgap eccentricity and discusses the resulting unbalanced magnetic pull (UMP) that can cause a rotor to stator rub. The predictor equations required to detect the unique current signature pattern, which is a function of the combination of static and dynamic airgap eccentricity, are presented and the diagnostic strategy for the signal processing is explained. The interpretation of the current spectrum and methodology used to estimate the operational airgap eccentricity are also included in Chapter 10. Chapter 11 presents industrial case histories on the application of MCSA to estimate the operational airgap eccentricity, including successes and failures.

The MCSA case histories are deliberately presented in "*great detail*" since a "*broad brush, superficial presentation*" that leaves the reader wondering how the diagnosis was achieved is meaningless. The inclusion of cases, when MCSA was not successful, is in complete contrast to the hundreds of research papers published on MCSA, which tend to only report on successful laboratory-based experiments. Each case history in this book stands alone so that the reader does not need to scroll backward and forward to find information and inevitably, there is repetition of formulae and other relevant knowledge. It is the authors' opinion that the style of presentation of the case histories is advantageous to the readers and particularly to engineers who apply MCSA technology. Root Cause Failure Analysis (RCFA) investigations are very time consuming, expensive, and normally delay the repair of motors, which the end user wants to get back in service as soon as possible. Consequently, RCFA investigations for each of the 50 industrial case histories were certainly not carried out by the end users but by the authors only when requested to so do. These requests were very infrequent, but any investigations are reported.

Chapter 12 presents an appraisal on the reasons why end users have not been receptive to the application of MCSA to diagnose shorted turns in LV or HV stator windings or faults in roller element bearings in SCIMs. Chapter 13 starts with a flow chart on the application of MCSA, which is formulated in a practical style, directly applicable for industrial engineers. This is followed by an appraisal on the strengths, weaknesses, external constraints, and very importantly the lessons learned by the authors spanning a period of 34 years.

The identities of manufacturers and end users of the motors in the case histories are not given and neither are the motors' serial numbers. At the start of the chapters on case histories (5–9 and 11) a list is presented to assist the reader to select the ones of personal interest contained therein. For completeness, metric and imperial units are included since the latter are used by electrical machine manufacturers, motor repair companies, and end users in the USA and also by the NEMA MG1: “Motors and Generators,” 2012, USA, and API 541, USA, 5th edition, December 2014 standards. Immediately after the list of contents there are lists of symbols, abbreviations, and relevant units of equivalence between SI, metric and Imperial units The equations in each chapter are presented after Chapter 13. There are 10 questions at the end of each chapter (except Chapter 13)—the publisher should be contacted directly to obtain access to the answers.

William T. Thomson
Ian Culbert

NOMENCLATURE

Quantity	Quantity Symbol	Unit	Unit Symbol
Angular frequency	ω	Radians per sec	rad/sec
Angular position around circumference	θ	Degrees	deg
Airgap—radial design value	g	Millimeters/inches 10^{-3}	mm/mils
Airgap as a function of time and angle	$g(\theta,t)$	Millimeters/inches 10^{-3}	mm/mils
Airgap eccentricity—static	e_s	Millimeters/inches 10^{-3}	mm/mils
Airgap eccentricity—dynamic	e_d	Millimeters/inches 10^{-3}	mm/mils
Backward rotating field from the rotor	N_{sb}	Revolutions per minute	r/min
Equivalent broken rotor bar factor at any operating slip below full-load slip	BB_f	Number	–
Equivalent broken rotor bar factor at operating slip	BB_{fs}	Number	–
Broken rotor bar correction factor	BB_c	Number	–
Broken rotor bar index at full-load current and slip	n	Number	–
Broken rotor bar index at any operational slip below full-load slip and current	n_{fs}	Number	–
Ball diameter in roller element bearing	BD	Millimeters	mm
Centrifugal force	CF	Newtons/pounds force	N/lbsf
Coil distribution factor	k_d	Number	–
Coil span factor	k_s	Number	–
Current (rms)	I	Ampere	A
Current magnitude of supply frequency component	I_p	Ampere	A
Current magnitude of $f - 2sf$ at any slip	I_{LSB}	Ampere	A
Current magnitude of $f + 2sf$ at any slip	I_{USB}	Ampere	A

Quantity	Quantity Symbol	Unit	Unit Symbol
Current magnitude of $f - 2sf$ at any slip but referred to full-load slip	I_{LSBr}	Ampere	A
Current components sum of $f \pm 2sf$ at full-load	I_n	Ampere	A
Current input per phase	I_i	Ampere	A
Current—no-load per phase	I_o	Ampere	A
Current in rotor per phase	I_r	Ampere	A
Current in rotor bar	I_{rb}	Ampere	A
Current per phase due to core losses	I_c	Ampere	A
Current per phase—magnetizing	I_m	Ampere	A
Current per phase in rotor referred to stator	I'_r	Ampere	A
Contact angle on bearing raceways	β	Degrees	deg
Diameter of rotor core	D_r	Millimeters/inches	mm/inches
Decibel difference between $f - 2sf$ and f	N	Decibels	dB
Decibel difference (average) between $f \pm 2sf$ and f	N_{av}	Decibels	dB
Decibel difference—the corrected average of measured N_{av} at reduced load and slip between $f \pm 2sf$ and f referred to full-load slip	N_{cav}	Decibels	dB
Decibel difference (average) between f_{rs} and $f_{rs} \pm f_r$	N_{ec}	Decibels	dB
Electromotive force (instantaneous)	e	Voltage	V
Electrical degrees	θ_e	Degrees	deg
Flux per pole	ϕ_p	Webers	Wb
Frequency of mains supply	f	Hertz	Hz
Frequency of rotor emf and current	f_2	Hertz	Hz
Frequency of lower sideband	f_{sb}	Hertz	Hz
Frequencies of upper and lower sidebands	f_s	Hertz	Hz
Frequencies of rotor slotting current components	f_{rs}	Hertz	Hz
Frequency of oscillation of mechanical load	f_c	Hertz	Hz