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TEST FACILITY FOR ADVANCED ELECTRIC ADJUSTABLE FREQUENCY DRIVES AND GENERATORS OF TYPICAL INDUSTRIAL RATINGS (DE-FG06-95TE00066)

1. INTRODUCTION – GENERAL BACKGROUND

The use of electrical adjustable speed drives (ASD) is rapidly growing in industry due to the increased energy efficiency and improved process control generally obtained from their application. The majority of ASDs are adjustable frequency induction motor systems although some alternatives, such as permanent magnet machines, are being used for specific applications and several new technologies are under development including the switched-reluctance motor and the brushless doubly-fed machine. Although the benefits of ASDs are well understood, several problems have arisen in the application of high switching speed electronic converters to induction machines. These include premature winding insulation failure, bearing failure, and electromagnetic interference with other equipment. The efficiency of uncontrolled induction motors is the subject of considerable current scrutiny following the passing of the National Energy Policy Act of 1992 (EPACT '92). The legislation, which came into effect in October 1997, specifies the efficiency that induction motors attain in order to be described as high efficiency. The problems that both manufacturers and users of motors face as a result need to be addressed. In particular, there are needs for both independent accredited test facilities and for nondisruptive methods of assessing the performance of motors in service in industrial environments.

In addition to efficient energy utilization, the development of renewable electrical energy sources is of on-going importance. Major efforts to exploit wind and wave energy still appear to hold the best short- and intermediate-term prospects for meaningful contributions; recent studies indicate that the contributions of wind energy to the nation's requirements will increase substantially if certain techno-economic factors can be overcome. Consequently, numerous forms of efficient variable-speed generators (VSG) are being proposed and developed worldwide. In order to be worthwhile, such VSGs must be of substantial rating, and must be robust and relatively simple while maintaining respectable efficiencies.

As a result of its previous work for the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE) – Bonneville Power Administration (BPA), the Department of Electrical and Computer Engineering of Oregon State University (OSU) was selected as the site for an independent test facility for both conventional and experimental ASDs and VSGs. Work began on the development and construction of the test laboratory, named the Motor Systems Resource Facility (MSRF), in early 1994. The MSRF was conceived as being the most flexible and most energy efficient test facility of a typical industrial rating in the nation. This requires both electrical and mechanical instrumentation that is adaptable, readily calibrated, and capable of

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handling electrical signals over a wide range of frequencies and mechanical measurements over a wide range of speeds. In addition, the equipment must be capable of being readily calibrated to ensure the accuracy of results that are commensurate with the legislated levels of efficiency. As the MSRF is a university-based facility, the repeated calibration functions must be simple enough to be performed by student workers rather than full-time technical staff. This, in turn, requires comprehensive documentation of procedures.

The equipment purchased under this DOE University Research Instrumentation Program award is in two basic categories: fixed equipment, that is permanently installed in the laboratory infrastructure, and portable equipment, that can be moved around the laboratory to serve short-term functions or to accommodate the specific needs of particular tests. The first category includes torque transducers and current, voltage, and power transducers that have been built into the laboratory switch gear, and the virtual-instrument, computer-based, data acquisition system. The second category includes oscilloscopes, power analyzers, and a multicalibrator. Details of the completed laboratory are covered in several papers, referenced later in this report, and can be viewed by visiting our web site: www.ece.orst.edu/~msrf.

2. EQUIPMENT – STATUS AND USAGE

2.1 Mechanical Transducers

The transmitted shaft torque and the speed of ASDs and VSGs are measured by noncontact (inductively coupled) strain-gauge transducers. For larger machines, 50 to 300 hp, mechanically interchangeable units rated at 1,000, 2,000, 5,000, and 10,000 lb.in. with speed capabilities up to 20,000 rev/min have been obtained. For smaller machines, transducers rated at 100, 200, and 500 lb.in. have also been purchased. All of these units are compatible with the same power supply and signal processing equipment. The torque sensing mechanism of these transducers is based on strain gauges bonded to a special shaft. These are prone to mechanical failure when subjected to overloads which sometimes occur with transients or unanticipated conditions. Repair time of these units is of the order of two months which would impose unacceptable delays for the laboratory's industrial customers. Consequently, duplicate units of the more frequently used torque transducers have been obtained.

In addition to the manufacturer's calibration recommendations, a complete end-to-end in-house torque calibration method has been developed appropriate to our function and accuracy requirements. This involves precisely matched (in length and mass) torque arms and a set of calibrated masses. These are used together with a unique shaft locking mechanism that permits adjustment, while under load, to maintain horizontal torque arms. Thus, accurately known torques are applied to the transducers and observations are taken in the data acquisition system. The procedures for these processes, which are far more comprehensive than those of the equipment manufacturer, have been carefully documented and refined after exposure to uninitiated student workers.

A small but significant discount of 6% was obtained from the manufacturer of the torque/speed transducers (Eaton-LeBow).

2.2 Voltage, Current, and Power Transducers

The proposal from OSU which resulted in this instrumentation award envisaged extensive use of individual voltage, current, and power transducers backed by power analyzers. However, since the preparation and submission of the proposal, significant progress has been made in the functional capabilities and accuracy of laboratory power analyzers. Based on this, we have elected to make minimum purchases of the transducers (from Ohio Semitronics) which are incorporated in the laboratory switchgear and have done comparison testing of some of the major laboratory power analyzers (from Valhalla [a Norma-Goertz derivative], from Yokogawa, and from Voltech). This shift was documented in our letter to Mr. R. Moody, dated October 24, 1995, which was acknowledged and approved October 27.

After the comparison test, based on functionality to our requirements, equipment maturity, and cost, we selected Voltech power analyzers and, to date, two high-end units have been obtained (PM3300) with three low-end (PM300) units for everyday functions. The power analyzers are rated to 600 V rms which is suitable for the normal operation of the laboratory (480 V and 575 V being the most common rated potentials for electric machines). The analyzers are limited to 30 A, however, which is well below the rated currents of the machines we wish to test (e.g., 350 A for a 300 hp motor). A range of current transformers (from Voltech and LEM) have been obtained to extend the range of the power analyzers and are calibrated in the measurement system.

Because of our use of these power analyzers in a university environment, the manufacturer (Voltech) enabled our purchase of the second PM3300 unit at a substantial (~60%) discount.

2.3 Laboratory Equipment

The proposal called for general laboratory equipment to observe the quality of the voltages and currents associated with ASDs and VSGs. These requirements have been met by the purchase of three 500 MHz oscilloscopes (Hewlett-Packard) augmented by high-current current probes and high-voltage differential voltage probes (Tektronics). The funding provided in this DOE award has been leveraged by equipment donation programs between OSU and both Hewlett-Packard and Tektronix. The provide purchase of equipment at discounts up to 90% in some cases. This has enabled the MSRF to obtain more equipment in the area of oscilloscopes and probes than was envisaged in the original proposal. Calibration of all transducers and instruments is done by a multi-calibrator (Fluke) and winding resistance measurements for large motors are obtained from two low-resistance, high-current, ohmmeters (Norma-Goertz).

2.4 Data Acquisition and Processing

Four identical computers (Dell, Pentium based) have been obtained for the basic functions of the laboratory. One unit is for data acquisition and basic laboratory control. This is interfaced to the instrumentation (National Instruments A/D and D/A using Labview software). The second is to be developed into a dynamic dynamometer control, with programmable functions. The third is used for data processing and report generation and also serves as a back-up in case of a failure of either of the other two computers. The fourth computer serves as a back-up unit for data acquisition and control functions. For reasons of laboratory security and operating safety, only the third of these units is Internet connected.

2.5 General

Throughout the development of the laboratory, over the last four years, its concepts and implementation have received praise and, in some cases, equipment support from US Electric Motors (Emerson), Marathon Electric, Bechtel, Electric League of the Pacific Northwest, in addition to our sponsors. We have hosted visitors from several overseas universities and agencies.

3. PROJECTS

The MSRF has completed the following projects in the last year:

- (i) Comparison of Switched Reluctance Motor and Induction Motor ASDs [1];
- (ii) Evaluation of a Wind-Turbine Generator (on-going) [2];
- (iii) Evaluation of In-Service Efficiency Estimation Techniques [1,3,4];
- (iv) Evaluation of a 60-hp Brushless Doubly-Fed Machine;
- (v) Investigation of the Effects of Pulse-Width Modulation on Induction Motors (on-going) [5-7];
- (vi) Evaluation of a 20-hp Single-Phase Motor (Written-Pole) [8].

In addition, the capabilities of the laboratory have been described in three conference papers [9-11].

Future projects which relate to evaluation of specially developed, high efficiency, motors for the pulp and paper industry (up to 300 hp) and a proposed high efficiency ceiling fan system (up to 1/10 hp) illustrate the broad range of capabilities that have been developed in the laboratory.

4. OPERATION AND MAINTENANCE PROVIDED BY OSU

The infrastructure of the MSRF laboratory became partially operational in late 1996 and was completed by early summer 1997. Throughout 1997 the laboratory has been connected to its own dedicated electric service from our local utility (Pacific Power). The connection charge is \$550 per month. Because of the energy recirculation concept of the MSRF design (dynamometer load is returned to the service utility rather than being dissipated), the facility has used approximately only 1000 kWhrs in its first year of operation which the university has funded at the rate of approximately 5¢ per kWhr.

OSU continues to maintain the building space for the MSRF which is approximately 2,300 sq ft for the laboratory itself, 300 sq ft for the control and data acquisition room, and 200 sq ft for an office.

During the first year of operation the following equipment has required repair: two torque transducers; the low resistance, high current ohmmeter. Total maintenance cost was of the order of \$2,000. In addition, there is a continuous need for laboratory consumables such as mechanical hardware and small hand tools and electrical hardware as well as basic materials and office support.

Operational funding of \$130,000 has also been provided by EPRI during 1996 and 1997.

5. FACULTY AND STUDENTS

5.1 Faculty

The laboratory and instrumentation are currently being used for both routine testing and research purposes by the following faculty: Alan Wallace, René Spée, and Annette von Jouanne. The fourth faculty, Dr. Corwin Alexander, has now retired. The capabilities of the laboratory will be a big asset in the recruitment of his successor.

5.2 Students

To date, five graduate students (T. Lewis, T. Rollman, A. Kemp, B. Koch, and A. Faveluke) have obtained M.S. degrees and two Ph.D. degrees (B. Ghorti and S. Bhomik) have been awarded while working with the equipment obtained under this award. Currently the following students are working towards their degrees in the MSRF using this equipment: H. Zhang (Ph.D. 1998), E. Wiedenbrüg (Ph.D. 1998), L. Chis (M.S. 1998), J. Paramesh (M.S. 1998), T. Rodriguez (M.S. 1998), P. Andrews (B.S. 1997), J. Duncan (B.S. 1999), and R. Jeffreys (B.S. 1999). The two undergraduate students are obtaining experience under work-study programs.

6. EXPERIMENTAL RESULTS AND BREAKTHROUGHS

6.1 Non-Intrusive In-Situ Efficiency Estimation

A project that was undertaken early in 1997, funded by Bonneville Power Administration and Pacific Gas & Electric Co., addressed the possibility of estimating the efficiency at which induction motors are operating in industrial environments [1-3]. Part of this project was an examination of three instruments specifically developed (in Germany, Canada, and New Zealand) for this purpose. It was found that, under certain circumstances, these instruments could perform well. However, when applied to machines which were running unbalanced or had been repaired outside the original specification, the accuracy of these existing instruments were not sufficiently accurate. The problems with accuracy were traced to two major factors:

- (i) all three instruments employed an idealized mathematical model of the motors;
- (ii) all three instruments required that the rotational speed of the shaft be measured by an optical (light or laser) or inductive pick-up.

It is believed by the author and a graduate research student (E. Wiedenbrüg) that these deficiencies can be overcome by techniques of motor terminal current signature analysis, which they were investigating for other purposes. This has led to a spin-off development of an efficiency estimator instrument which is now being funded by an equipment manufacturer (Baker Instruments of Ft. Collins, Colorado).

6.2 Passive Control of Variable-Speed Generation

The MSRF has tested two variable-speed generation systems intended for wind-turbine applications. These have been found to be either expensive (due to a dependence on power electronics for frequency control) or having a high maintenance requirement (due to the use of a slip-ring induction generator). A concept for an alternative, passive (i.e., non-power electronic) system without slip-rings has been developed. Initial trials of the system on an 80 kW unit have demonstrated the viability of the concept with a conversion efficiency between 85% and 92% depending on speed. Efforts are underway to refine the concept to improve these efficiencies.

The proposed system promises a combination of low capital cost, simplicity, and robust low maintenance equipment unique to the VSG industry.

7. REFERENCES

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