MOTOR EFFICIENCY IMPROVEMENT EXPERIMENTS

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ABSTRACT

This paper describes experiments developed while teaching in the former Waterbury State Technical College. It show how all experiments, however performed, have the same seven fundamental steps. Two things are demonstrated: That original work can be done in a two year school, and to both encourage teachers and professors and explain how original experiments can be performed.

These DC motor experiments, scaled up to diesel electric locomotive traction motors, proved able to clarify and resolve problems known to manufacturers and the AAR (Association of American Railroads) but were unable to explain. The AC experiments show potential efficiency improvements not yet covered in the literature.

I. Introduction

Electric motor fundamentals go back to the pioneering experiments of Michael Faraday, who discovered that a conductor carrying current, when immersed in a magnetic field, produced a lateral force. All motors (and generators) whether AC or DC use this principle, regardless of their specific size or configuration.

DC motors need some form of synchronized current switching to reverse current in the rotor coils as they pass though a magnetic field which reverses at least once per revolution. Traditionally this switching has been done by a rotating metallic commutator and stationary brushes. The commutator is a segmented copper cylinder which sequentially offers access, one coil at a time, to carbon “brushes” which transfer current to that coil, forming a rotating switch.

Only in the past decade or so, have various solid state devices replaced this commutator + brushes package to dynamically route current to/from the optimum rotor coil for smaller motors.

Both AC & DC motors are still evolving; the average household has more AC motors than light bulbs. Late model cars average about 15 DC motors, one Mercedes has sixty! Skilled technicians and engineers are needed to design, develop, install, control and service these motors. Back in Connecticut, local industry protests loudly when they cannot find new employees that understand motors.

II. Perspective

While preparing my notes for the 1998 ASEE National Conference I realized that all new work in all fields from Anthropology to Zoology follows a process which has the same fundamental steps:

a.) PROBLEM: Recognizing and identifying a need for answers to a new situation or the need for further development of a field of study.

b.) DESIGN: Defining the experimental apparatus and procedures to accomplish the desired result. This may involve standard instruments and apparatus or something entirely unconventional.

c.) DATA: Recording the experimental procedure. These records may be written, recorded on-line, photographed, or even deduced from old records. They may be numerical or subjective.

d.) INTERPRETATION: Selecting, sorting, filtering, or reducing to a logical sequence of data of the significant part of the raw data.

e.) DECISION: Determining what step is next or what conclusion may be drawn.

f.) IMPLEMENTATION: Carrying out the next step in whatever form is required whether a new design or new related construction.

g.) REPORT: Publishing results whether as a student lab report, a formally published scientific journal article or a prepared record for the agency that sought the experimental work.

These step names are not standardized or even recognized by most faculty. Yet, we will show that these steps are always there in new original work! Most undergraduate lab work, even using real physical experiments, does not show the student this seven step process. Some published industrial procedures use similar but not identical steps.

In reality we train undergraduate or graduate students to do original work. The same goes for a laboratory or experimental technician whether at the two year associate level or as a four year technologist. These people are not wanted for repetitive work; they are hired and put to work on some facet of a project that has original development as an integral part of its content. In order to illustrate this process to an ECCD audience, I have selected a few developments from my own experience in college teaching and private consulting. After changing careers to college teaching in 1969 the wide variety of projects that I took on in the Aerospace industry, faded away. It took a while to fully familiarize myself with the electrical machines lab at the old Waterbury State

Technical College (WSTC). Soon it became obvious that this was a well equipped laboratory that had not been fully developed. The apparatus was versatile but the laboratory experiments were being presented to the students only by using the Hampden Inc. apparatus prepared lab directions. These were the usual post WW II connection charts that did not use a schematic format. This meant that while the students could get the apparatus to function, they could not generalize from the results.

One by one I rewrote the various laboratory syllabi to present the information in schematic fashion. As a result, the students could be expected to connect, operate and test the same type of motor or generator of any size and brand within reason. This step-by-step upgrading had a few results, both planned and unplanned.

First, it became obvious that the students were much more interested in realistic laboratory operations. Also, when I was working in the lab while not scheduled for student contact, various students would drop in to see what was going on. If I said that I was trying to develop a particular test procedure and did not yet know how well it was going to work they immediately wanted to help and would contribute time to do so.

Second, I had a dean who took no interest in what any of the faculty were doing. On the other hand, my department head was most supportive and encouraging and gave me full freedom to shape my lecture and lab work. Only two other members of the Electrical Technology Dept. had ever had an electrical machines lab, they were post-Grinter Report students themselves.

Third, I soon started to prepare a full scale Electrical Machines Laboratory Manual because nothing in that line had been published since WW II. The only lab manuals were specific hook-up charts sometimes with prepared fill-in-the-blanks format. This sort of procedure does not prepare a student to earn his or her living as a creative engineer or lab technician.

Fourth, I had long been interested and professionally involved in energy saving developments and wanted to develop my own electric vehicle. Nothing at the time (1970-1980) promised an electric car which would serve as a commuting vehicle to handle my own commute. I commuted 25 miles each way each day to school, most of it on a four-lane divided highway. Thus, a car that could cruise at 60 mph for 50 miles plus a reserve on battery power was not available but seemed within reach. As a result, I started my own laboratory tests to see what could be done about direct current motor efficiency and performance in the range of 20-25 horsepower at about 2500 rpm. This required tests of armature circuit power loss, rotational losses, etc. that were not available to me from motor manufacturers. The next eight years produced the following:

III. Armature Circuit Power Loss Test Procedures - “Forgue's Method”

Most college rotating machinery texts simply estimate a nominal one volt drop across each brush in a DC machine. They also suggest using an ohmmeter to measure the resistance of the commutator segments, making allowances for number of poles and armature winding pattern. None of these tests accurately pinpoint the loss mechanism, but the worst is measuring the brush-to-brush resistance with an ohmmeter, while slowly moving the armature by hand. This type of reading varies wildly, but since the armature circuit loss is the largest in a DC motor this topic needs further study.

Early in this study one of my students, John Forgue sought make-up work, so I assigned him a lab project, testing a small dynamometer generator to find its armature circuit resistance by as many ways as he could think of. He tried all of the ways we discussed in class and recorded data which, were in wild disagreement.

After another professor went into the lab to find out what Forgue was doing, Forgue tried yet another method, which later turned out to be so effective that it eliminated the traditional fudge factor called "stray load loss":

FORGUE'S METHOD for Armature Circuit Loss.

a.) PROBLEM: To get basic data to determine true armature circuit power loss in watts.

b.) DESIGN: While rotating the armature by an external torque, measure the voltage generated from its residual field magnetism. Using a separate field excitation source hooked up in reverse, buck out the residual field until the armature shows zero voltage generated. Then, by use of prepared switching, with an external direct current source, force current through the moving armature and measure the impedance by the voltmeter-ammeter method. This is sensitive and accurate for low resistance circuits. Remember that the brush-to-commutator connection is through a plasma when significant current is flowing.

c.) DATA: Forgue set up and took one data point and rechecked it a few times.

d.) INTERPRETATION: None of us fully realized the broad implications of this data. We decided to broaden the scope of this test from one point to a range of data as the input current was varied.

e.) DECISION: I prepared a new lab syllabus, and in the next lab period the fifteen students in that section performed the test in slightly different ways on various machines.

f.) IMPLEMENTATION: The class plotted data which showed a linear relationship between armature current and voltage drop, with the exception of the lowest currents. This plot, projected back to zero current, intercepted the y-axis at a point which we decided was the elusive brush voltage drop[1]. Fig. 1. confirms Forgue's Method. The spread between the two groups' data probably is due to winding temperatures.

g.) REPORT: No formal report was yet produced but class and lab excitement ran high when I announced that we were collectively involved in something outside the literature of the

[1] a.k.a. stray load loss

field, and that I wanted help to expand this concept. I think I convinced the class that we should, at the same time, continue with the rest of our class and lab syllabus but extra work was to be welcomed.

Follow up on Forgue's Method came step by step. Tests at various rotating speeds showed conclusively that a family of fan spreading straight lines was produced and that the ordinate intercept also varied a bit. The armature circuit power loss is clearly affected by the inductance of the armature coils as their polarity is reversed by the commutator. To a lesser extent the armature circuit losses are affected by the magnetic steel losses in the armature laminations and this loss affects the power required to turn the armature whether generating or not.

The next step was to determine other forms of motor losses to closer limits. I was particularly bothered by traditional "stray load" losses which were assigned various quantities by various authors. Over the next few years many various tests were tried to enable more realistic and specific motor efficiency tests to be standardized at a better level.

The IEEE *Standard for Rotating Electric Machinery for Rail and Road Vehicles* [i] does not recognize the inductive losses in an armature. They specify the I^2R losses as if this was a pure direct current situation. However, Forgue's Method clearly shows that it is not. The IEEE specifies 1.5% "stray load losses" and lets it go at that.

IV. Finding Rotational Losses

This is defined as all of the power into the rotating part, the armature, in a direct current motor when it is rotating but not driving a load. There turns out to be a family of losses depending on speed and field excitation. These losses include bearing loss, windage loss, commutator friction and some magnetic loss.

a.) PROBLEM: Determine comprehensively the Rotational Losses in a direct current motor or generator. Remember that any DC motor can act as a generator or a generator as a motor. Traditionally one point is selected at rated rpm.

b.) DESIGN: Various motors in the lab were instrumented for voltage and current into the armature. Field current was separately adjusted and measured as was rotating speed.

c.) DATA: Various motor runs were made by adjusting to a series of speeds. At each speed the field current was adjusted then the armature voltage changed until the chosen rpm was achieved. Then armature voltage and current were recorded as the power at that speed and field current. A whole family of data was recorded within predetermined speeds and current limits.

d.) INTERPRETATION: As suspected, whole families of curves emerged when the data was plotted. From these curves the rotational power loss could easily be determined at any speed and field current. Most textbooks speak of a single loss measurement at rated speed and power and that is not satisfactory for a vehicle design such as an automobile or a locomotive. Figure 2. is a typical Rotational Loss curve.

e.) DECISION: This type of procedure was adopted as our lab course standard.

f.) IMPLEMENTATION: More of these tests were made on different size motors and with different lab groups.

g.) REPORT: The procedure was written up and refined and ultimately became a part of my text "*Laboratory Operations for Rotating Electric Machinery and Transformer Technology*" [ii], now in its second edition.

This type of lab work is still fading away. My own Electric Machinery course held at a full three terms a year for awhile, was cut to two terms, and ultimately to one. It has not been taught at WSTC since I retired in 1980.

These two preceding experimental procedures cried out for proof. One way is to test for Armature Circuit Loss and Rotational Loss and to add them. These losses are added to the field or fields losses and all subtract from the input power of the motor under test. The remaining shaft output power can be verified on a dynamometer or a Prony Brake. We found the total input power minus the losses above checked with the measured output mechanical shaft power. The errors were usually below one percent and sometimes under a tenth of a percent. This raised the issue of stray power losses, which we had ignored, and it seems that the sensitive loss tests included all losses.

V. Losses in Larger Machines

A typical mid-sized US automobile needs 20 horsepower or more at cruise, and 60 to 80 hp for a reasonable acceleration. Our WSTC dynamometers could only test to 5 hp and 4000 rpm. Thus it was determined to upgrade the historic Kapp Back-to-Back Test [iii] using our newly developed loss tests. In a Kapp test, a motor and a generator are connected shaft to shaft. The generator is set to feed back its output into the motor and thus the power supply need only supply the total of the losses of the two machines. The two machines need not be of the same frame size and rating as Kapp specified. In fact, he recommended that the rotational and armature circuit losses be split 50-50 between the two machines. This is now known to be wrong because even if the two machines were identical the motor would be drawing more current than the generator produced and our curves clearly showed it would have greater losses.

KAPP BACK-TO-BACK TEST to reconcile losses.

a.) PROBLEM: Determine if the Kapp Back-To-Back Test can be used for sensitive testing at higher power levels.

b.) DESIGN: The WSTC machine stand No.9 had two face-to-face (or back-to-back) DC machines but of different frame sizes although the same voltage rating. They appeared ideal for proof of concept tests although of only 1.5 horsepower rating each. Suitable instrumentation and circuit switching was planned with student involvement.

c.) DATA: Separate tests using small student volunteer groups repeated the now familiar Rotational Loss Tests and Armature Circuit Loss Tests on each machine, recording data as they went. Then other larger and different groups performed the full Back-to-Back Test under various speeds and loads. They used the same instruments as the separate tests as far as possible to minimize errors.

d.) INTERPRETATION: Each involved group placed their data in chart form on the laboratory blackboard for all to see. Step-by-step, with plenty of discussion, the individual losses were worked out and plotted.

e.) DECISION: The combined losses for each machine when totaled together matched the input power from the lab source usually within one percent or less. The whole procedure, "warts and all", is developed in an appendix in my laboratory text mentioned above.

f.) IMPLEMENTATION: In this long test development many variations were tried but it is still the only facing pair of DC machines we had at WSTC. The full implementation came with 900 horsepower diesel locomotive motors at the national Transportation Test Center in Pueblo, CO after I retired. It came as an unsolicited consulting assignment in 1984. This is discussed after some AC experiments.

g.) REPORT: Our original test results are generalized and discussed in my lab text mentioned above and in my lecture text "*Rotating Electric Machinery and Transformer Technology*" [iv] now in its fourth edition. It was very, very satisfying doing original work with the students.

VI. Efficient Use of AC Motors

We studied a few AC motors and found some surprises. As a new teacher I was constantly upgrading the Electric Machines Laboratory to make it both more interesting and realistic. In my experience almost all new projects for engineers and technicians involved experimental work. If it wasn't new it didn't need the skills of project engineers and associated technicians. Some of what we did follows:

Three Phase Induction Motor - Low load tests

These motors are used everywhere and are long lasting if correctly applied and occasionally serviced.

a.) PROBLEM: Efficiency when operating at partial loads and supply voltages.

b.) EXPERIMANTAL DESIGN: Use laboratory dynamometer to measure performance of a 3 hp, 3 phase induction motor with various line voltages.

c.) DATA: Different student sections recorded data with different line voltages.

d.) INTERPRETATION: On 220 V peak efficiency was 87% at 1.6 hp tailing off to 83% at 3 hp. At 127 V, peak efficiency was still 87% but at 0.8 hp and 1.6 hp it dropped to 81%. At 110 V, maximum observed efficiency was 82% at 0.6 hp. Line current and winding heating were greatly reduced at low loads. The current at 220 V was 8.8 A for 3 hp, and 5.5 A for 1.6 hp. The power factor at 3 hp was 82% tapering to 80% at 1.6 hp. Larger benefits were found at lower line V when at low loads because the lagging coil excitation current is reduced. See Fig. 3. for Reduced Voltage Efficiency Gains vs. Load. Note that at 0.75 hp, for example, running this 220 V motor at 127 V, the efficiency gain was about 10%, and the current dropped about 20%. Also at 0.75 hp and 127 V input, the speed held up almost as well as with rated voltage input, and the power factor improved from 44% to 74%.

e.) DECISION: Recognizing that in many installations such as a turret lathe, the drive motor does not operate at full power much of the time, we decided to look further to find the benefits of using lower line voltage while running light or unloaded, such as for a low torque center drill operation.

f.) IMPLEMENTATION: Another class checked the no load or running light characteristics.

g.) REPORT: Each student submitted his own report with discussion, data, calculations and curves. Still another group repeated f.) above and found the motor running light would hold speed at 30 V but would not accept a sudden load increase. At 55 V or 1/4 the rated voltage, the speed did not drop seriously and only 1.2 A and 30 watts was used. See Fig. 4 - No-Load Motor Characteristics at Reduced Voltage.

A heavy turret lathe might need full power on one or two turret stations but could well be operated on 110 V or 127 V at partial loads and 55 V on the turret position when feeding the bar stock. Probable total wattage savings for a group of machines are as much as 30%. In a large production factory that would be a substantial saving of the total electricity use. On a ship, plane or satellite payload, the reduced power consumption is even more significant.

Switching from 220 to 110 V or 440 to 220 V is standard. Many shops have both 440 and 220 V bus service. The 220 V usually is used for the occasional two speed motors. The 55 V with its much lower current is easily accomplished. Frequently the full installed power is not needed at all and the lower voltage is sufficient.

We found similar savings in single phase motors. With capacitor-run motors, a 1/2 hp motor uses less wattage than a 1/3 hp split phase motor when both are loaded. This is because it operates as if it were a two phase motor. A capacitor run motor actually draws less current delivering its rated 1/2 hp than a 1/2 hp split phase motor running light! The capacitor run motor runs cool and split phase motors may be too hot to touch.

I use capacitor-run 1/2 and 1/3 hp (quasi two phase) motors in my home solar heat system. The 1/2 hp motor driving the air handler blower runs about 10 hours a day in summer and 6 hours a day in the winter. This hot air system heats part of the domestic hot water and supplies about 55 to 60% of the space heating in a Connecticut winter, and all of the hot water in the summer.

We continually emphasized AC and DC efficiency experiments and the students were enthusiastic. I firmly believe that more of this type of lab instruction should be offered.

VII. Full size DIESEL LOCOMOTIVE TRACTION MOTOR Loss Tests.

The Association of American Railroads, (**AAR**), operates the Transportation Test Center (**TTC**) in Pueblo, CO. The TTC was working unsuccessfully on a traction motor reliability problem. It seems that many railroads used either General Electric's 3900 horsepower locomotive or the General Motors Electromotive Diesel (**EMD**) locomotive of the same power. In either case, the individual traction motors that are geared to the driving axles, were rated at 900 hp each. Between AAR member railroads, at the time, there were some 15,000 of these locomotives or 60,000 motors in service. Both makes shared the same problem.

Both new motor types shared long successful service records although occasional burnouts occurred due to various causes. Rebuilt motors, using the appropriate GE or EMD factory-prepared rewinding coils, had an average life only one third as long. The cause of these premature failures was unknown.

An electrical consultant, Joseph Schmidt, was chosen because as the recently retired Chief Electrical Engineer of Amtrack, he was familiar with railroad traction motors. He studied the problem and found that the cause was consistent overheating of the new windings and determined to find out where the additional heat was coming from. The motor winding current was essentially the same either new or rebuilt.

Mr. Schmidt found a copy of my text and, with the approval of the AAR chiefs, called me to see if these three types of tests would be applicable to his problem. At this time both GE and EMD factory efficiency tests had been tried without showing anything special. As subcontractor to Mr. Schmidt I traveled to Pueblo and the TTC to investigate. We concluded that a whole series of Rotational Loss Tests, Armature Circuit Loss Tests and Kapp Back-to-Back Tests should be carried out on both GE and EMD motors using both new and rebuilt samples.

This was essentially a fully-instrumented, massive scale-up of the three tests we developed at WSTC. But this time, all instrumentation was analog-to-digital and all calculations were done on computers in real time. Most of the problems were in the set-ups and transducers.

The AAR test chief, Mr. Ray Washburn, Mr. Schmidt and I worked closely and harmoniously, perhaps because we were pre-WW II students and had experienced lab tests. Both GE and EMD representatives were extremely skeptical, especially of the efficacy of Forgue's Method, with which they were unfamiliar.

In various tests a GE motor would drive an EMD motor as a generator or vice versa. The set-up was massive and the machines, which weighed a few tons apiece, could only be moved with the overhead traveling crane. All connecting wiring had to handle up to 2000 amperes. Current measurements were by use of calibrated shunts with sensitive voltage drop readings.

A 1000 ampere power source was available although it proved difficult to adjust. The coupling alignment between the motors gave trouble. After a period of preliminary testing for transducer range adjustments and so on, serious testing began.

Armature Circuit Charactersitics

Forgue's Method tests were used on General Electric model 752E4 and Electromotive Model D77 traction motors. Tests were repeated many times on a number of motors by a standardized technique.

a.) PROBLEM: Find the armature circuit characteristics with sufficient detail and accuracy to help find the cause(s) of premature burnouts.

b.) EXPERIMENTAL DESIGN: Motors were set up shaft-to-shaft end-on, coupled and aligned. This general set-up was used for all types of planned tests. Current shunts were inserted where measurements were needed and low-range digital voltmeters were placed across the current shunts. High range digital voltmeters measured voltages directly. High-current, pneumatically-operated switches were used for circuit changes. Rotational speeds were read by strobe lights; temperatures were read by attaching the transducers directly to the field windings. Armature temperatures were determined by voltmeter-ammeter methods with the armatures stationary.

c.) DATA: Each motor was tested over a range of speeds and armature circuit currents and related data recorded digitally. A mass of data accumulated for each run of each motor.

d.) INTERPRETATION: Each data run was computer analyzed, and data was delivered via computer-plotted curve families. In the few cases that I checked by pocket calculator, reasonably close agreement of the results was shown.

My data reduction, on one Electromotive D77 motor, after root mean squared reduction on various rpm showed that:

$$\mathbf{E_a = (RPM)^{0.526} \times (0.027811 + 0.0013638\, I_a)}$$

where E_a is the armature circuit voltage drop and I_a is the armature current. Power loss in kilowatts is $\mathbf{P_a = E_a \times I_a \times 10^{-3}}$.

Similar data runs for the GE model 752E4 motor showed that:

$$\mathbf{E_a = (RPM)^{0.576}\ (0.017796 + 0.00080705\, I_a).}$$

Note that each brand of new motor was different but only by a small amount. However, rebuilt motors showed small differences from the new counterparts. See Fig. 5. for Armature Circuit Characteristics of a General Electric model 752E4 Locomotive Traction Motor.

e.) DECISION: Decisions were deferred until all other tests were performed in this program.

f.) IMPLEMENTATION: Similarly, no changes were made until the completion of the program.

g.) REPORT: The records of the Forgue's Method tests were compiled so that each motor's test data and curves were available for later work.

VIII. Rotational Loss Tests

a.) PROBLEM: To prepare and compile a full range of self powered rotational loss tests on various new and rebuilt motors of both makes.

b.) EXPERIMENTAL DESIGN The couplings between the motor shafts were removed for separate self-powered tests. High range ammeter shunts were removed and suitable low range units installed after heated debate with technicians trained in setting up digital circuit measurements. They did not understand that current readings with increasing rpm and increasing field currents should increase as smoothly as did other independent variables. Readings were running 7.36, 7.36, 7.36, 11.4, 11.4, 11.4, 15.3, etc. When using the high current shunt, these steps in the data turned out to be the minimum possible readings on the digital current recorder system. After the three of us "old timers" insisted, the shunt was changed and smooth data resulted.

One of the major reasons for this campaign for real lab work with students is so that they might recognize a data problem such as this. The digital technicians hadn't a clue and preferred to believe their numbers.

c.) DATA: Again many motors new and rebuilt were tested and data automatically recorded over the desired range of speeds and field currents.

d) INTERPRETATION: My hand calculated root-mean-squared reduced data produced a family of curves that when plotted showed a surprise.

When plotted, each curve had a few reversals. For field currents of 200 - 800 amp @1000 rpm, we found these results:

EMD model D77: $P_{rot} = 0.77714 + 0.0035655\, I_f + 0.000008631\, I_f^2$.

GE model 752E4: $P_{rot} = 1.4000 + 0.0095624\, I_f$. **(same conditions):**

Field currents, I_f, of **0 - 200** amps, **200 - 800** amps, and **800 - 1800** amps followed three distinct equations. The original TTC digital program tried to fit all field currents to the same equation and when plotted large excursions showed between the calculated curve and plotted data. Again the digital computer program was too simplified and again arguments ensued. It was shown to be reasonable that the field current dependent data should show a change above about 800 amperes when the field went into increasing saturation. Rotational loss curves for these motors were plotted on 17 by 22 inch 3 decade semi-log paper and are much too detailed to reproduce here. However, they show what was expected, judging from earlier work, namely that the actual rotational losses could be closely predicted for specific conditions rather than using the traditional single “fudge factor” for a generalized estimate of losses.

e.) DECISION: Other than changes in current shunts and computer procedure final decisions had to wait for other tests.

f.) IMPLEMENTATION: The changes above were carried out and carefully checked. No motor rebuild procedure change was yet evident.

g.) REPORT: The various motor rotational loss data was refined by further test, compiled along with rotational loss curves and equations and held for further procedures. The difference in rotational losses between new and rebuilt motors was again apparent but not yet understood.

IX. KAPP Back-to-Back Tests - Locomotive Traction Motors

While Kapp's original work was apparently done between belt-connected motors where the individual motor shafts weren't directly facing each other, in modern terminology this test should really be called a face-to-face test.

a.) PROBLEM: To test locomotive traction motors up to and beyond their rated 900 horsepower. By using refined Kapp techniques the drive motor supplied shaft power and the driven motor served as a generator and thus contributed its output current to the motor drive bus. The external power supply produces just enough current to supply the sum of losses.

b.) DESIGN: The same set-up was used but now with motor and generator shafts connected and a strain gauge torquemeter wrapped around one shaft. Shaft alignment techniques needed refinement because at high torques the coupling would growl loudly and overheat. The original alignment was by a builder's transit with a laser beam "hairline" in the telescope. This was used both sighting horizontally from the floor and vertically from an overhead traveling crane. The alignment achieved was rarely better than 1/32 of an inch. This is fine for a builder laying out a foundation but not in a high power mechanical coupling. I showed them how to align the couplings with a six inch micrometer which showed that both ends of the coupling were the same diameter then with a micrometer depth gauge which allowed alignment to 1/1000 of an inch very quickly. Again the technicians lacked real world experience so they did not realize how simple the alignment proceedure would be.

c.) DATA: A number of runs of the same group of new and rebuilt motors was tested and all related current, voltage, speed and temperature readings were recorded. This was complicated by the request for the hurried return of one of these borrowed motors, because the contributing railroad had run out of spares owing to the same burnout problem of a rebuilt motor that had been the cause of this investigation in the first place.

d.) INTERPRETATION: It was soon found that for any one pair of motors on this Kapp test that its input power supply current almost exactly matched the sum of the two specific motor armature losses (Forgue's Method), and the two rotational losses at the same speed. Now we had accurate data, so that if further testing was done, we could use these results.

That a rebuilt motor always had slightly higher losses, could now be believed. Some of the Kapp test data matched the sum of the four losses to less than one part in one thousand!

e.) DECISION: With now accepted loss data it was decided to see if rotational loss data and Forgue's method data could be broken down further to separate the losses into their components.

f.) IMPLEMENTATION: Rotational losses were broken down by performing a set of mechanical rotational loss tests. These were done by running a motor with a known drive source while it is open circuited. This input power is the sum of the bearing losses, windage losses and brush drag losses. Then the total self powered rotational loss includes mechanical and armature circuit electrical losses. Therefore, when these two lesser losses are subtracted from the total loss the remainder is the magnetic circuit losses of hysteresis and eddy currents. The real problem was that the only drive available was another motor, rather than a dynamometer. However, mechanical loss tests were scheduled and performed with the facing motor. The small power it drew above its full rotational loss was determined to be the mechanical loss of the unpowered motor it was driving. This result and the armature circuit loss was subtracted from its full rotational loss and the remainder, while not complete and pure, was determined and treated as the combined magnetic losses.

g.) REPORT: It immediately became obvious that the average of the so-called magnetic losses of rebuilt motors, while small, was nearly three times the magnetic losses of the average of new motors under comparable conditions and this disturbing fact was reported to the AAR.

Now the question was why the magnetic properties of the armature were so disturbed by the rebuilding process? A review of the motor rebuilding processes as they changed over time found the culprit. Early on a burned out armature would have its pinion, its commutator, and bearings removed and be placed in an outdoor furnace. The insulation would literally be burned off in the process. When cooled the now bare thumb sized windings could be easily lifted out of the core laminations.

Then the EPA entered the scene and prohibited the outdoor burning and its dense black smoke. The process was modified and settled on the following: The armature would be mounted in a large lathe and the large windings would be turned off at either end of the laminations. These stub windings were then driven out of the laminations with an air hammer. Finally the armature was chemically cleaned and the rewinding started. This was the clue that we needed.

Armature and field core laminations have been progressively refined down the years. The original pre turn-of-the-century laminations were annealed low carbon steel. Progressively the lamination steels have had more and more silicon alloying and could be used to higher and higher magnetic flux density. This, together with the improvements in insulating materials, are the major reasons why a traction motor size which started out before WW II at 125 horsepower can now deliver 900 hp. They run at higher magnetic flux density and much higher current. Therefore they run much hotter even though ambient air at is blown through them at hurricane velocities, for cooling.

These high-silicon alloy steels are vibration and impact sensitive and the air hammer process thoroughly disturbed the magnetic properties of the steel. As a result the motors ran farther into saturation and the laminations were hotter as a result. This higher temperature was enough to cook the windings which were running on the edge of failure anyhow because of the high current heating.

There is a simple fix: Armatures are now annealed *after* the air hammer process and thus restored to their design-level, i.e. "normal" magnetic properties.

This whole process took about six months and, although I was not in on all of it, I was kept up to date by phone and extensive correspondence. Ray Washburn retired and left no forwarding address. Joe Schmidt has also retired and I have heard no more on the subject.

The seven step process developed here resembles some modern business multi-step problem solving procedures. Ford Motor Co. uses a proprietary and copyrighted process called *Eight Disciplines* or 8D [v]. It cannot be described here because it is a confidential internal multi-step procedure but it is mentioned because it is a business world implementation.

Step-by-Step Problem Solving [vi], uses six steps to solve business-related problems. Both of these references, while differing, show that business problems that need solutions can be broken down to identifiable steps. In both of these last two references, many steps are identified with the same labels as we use. Ford's eighth step involves rewarding the creator of the successful idea, while Chang and Kelly ignore the seventh or report step. However their steps are not the same, because they involve using existing knowledge and business procedures, rather than the search for new principles.

Again all experiments, however diversified they may be, can be subdivided into these seven steps. After compiling this record of my own experiences I'm quite sure that my experiences are not unique. Many practicing engineers have experienced the same sort of thing because we were trained to do this kind of work. I sincerely hope that school curricula can be modified to allow the young men and women to realize that behind all the wonderful computer simulations are real world elements that must be recognized, especially when they are involved in break-through work.

The United States continues to be a leader **in research** but has already lost and continues to lose more of its **technological** superiority. We are becoming more and more a second rate manufacturing nation as more of our work goes overseas.

This we allow at our peril as a free nation.

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