Adjustable Speed Drive Power Quality
Evaluation Program
Second Phase, 1995-1996
FINAL REPORT

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Chapter 1

Introduction

A combination of an Adjustable Speed Drive (ASD) with an induction motor results in a highly efficiency system. The ensuing reduction in operating cost, and the accompanying flexibility makes the combination very attractive in an industrial environment. But the use of ASDs entails the following problems:

- A Pulse Width Modulated (PWM) ASD has a Full Wave Rectifier at its input stage. Here, an incoming AC voltage is converted to a Direct Voltage. Since each phase of the supply carries a non-sinusoidal current, the current flowing into the ASD has high harmonic content. As this current flows, it causes corresponding harmonic-rich voltage drop across the utility transformers and transmission line impedances. This results in harmonic distortion in the voltage supplied to other users.

- The Utility capacitors switch in and out of the power system to ensure acceptable voltage levels and to provide reactive power. This capacitor switching has been a major cause of disrupting the operation of ASDs.

- A third concern is the disruption of ASDs when the supply voltage dips for a fraction of a second and then returns to normal. This voltage sag disruption is a very common problem.

Michigan State University undertook a project, funded and managed by Detroit Edison, Consumers Power and Drive manufacturers to evaluate the operational characteristics of PWM ASDs, in order to help commercial and industrial users in selecting a drive best suited to their needs and environment. Mr. Van E. Wagner from Detroit Edison’s Power Quality Services and Dr. Tim Unruh from Consumers Power provided technical guidance, while Ms. Heidi Muir from Demand Side Management of Detroit Edison provided administrative guidance.
From MSU Ms. Nicole Anderson, Mr. Brian Easton and Mr. John Kelly developed the testing facility and conducted the experiments.

Marathon kindly provided the Inverter Duty Motors used in the testing.

At this stage the drives tested were limited to PWM type rated at 460V.

The following manufacturers participated in this stage of tests with the following drives:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>20HP</th>
<th>3HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABB</td>
<td>ACS 500 20HP</td>
<td>ACS 501 3 HP</td>
</tr>
<tr>
<td>Baldor</td>
<td>ID15H420 and Series 21H, 20HP</td>
<td>ID15H405-E</td>
</tr>
<tr>
<td>Allen Bradley</td>
<td>1336plus, 20HP</td>
<td>1336plus, 3HP</td>
</tr>
<tr>
<td>Furnas/Vee Arc</td>
<td>Micro 7000, 20HP</td>
<td>Micro 7000, 3HP</td>
</tr>
<tr>
<td>Reliance</td>
<td>GV3000, 20HP</td>
<td>GV3000, 3HP</td>
</tr>
</tbody>
</table>

Of the units supplied, the 20HP Furnas/Vee Arc Micro 700 would operate supplied from a three-phase or a six-phase. Such a transformer was supplied by Furnas, and was used for the harmonic and efficiency testing. The transformer was not used during the sag and capacitor testing.

The series 21H, 20HP drive provided by Baldor uses a PWM inverter at the input, which is operating at a frequency of 4kHz. Baldor also requested additional testing, including a three-phase inductor in series with the input of the 20HP (0.8 mH) and 3HP (3mH) Drives.

The results of testing of these either modified or non-typical drives are reported separately.
Chapter 2

The Testing Protocol

2.1 Objectives and Scope

Adjustable speed drives are susceptible to power quality problems and generate such problems themselves. Three of these problems are:

- Utility capacitor switching transients disrupt the operation of ASDs.
- During voltage sags, i.e. when the voltage of the line drops to a portion of its nominal value for less than a second, the operation of the drive is disrupted.
- The drives generate harmonics that can resonate with capacitors and inductances in the system disrupting their operation or the operation of nearby drives, or causing capacitor fuses to blow.

The testing of drives performed at MSU was at present limited to Pulse Width Modulated Variable Frequency Drives for Induction Motors.

The objectives of this testing were to evaluate the performance and robustness of industrial PWM drives for induction motors, under steady state and specific transient supply conditions. In particular the following operating conditions were imposed:

1. The load of the PWM drive was set at various levels up to 100%, at or close to 60Hz and at rated voltage. Efficiency and harmonics were measured.
2. The frequency and the load torque of the motor was varied, and efficiency was measured again.
3. The drive started operation as in 1., and a signal of 500Hz frequency and of given amplitude and duration is imposed on all three phases. The performance of the drive was monitored.
4. The drive started operation as in 1., and voltage sags were imposed to all three phases for prescribed periods of time. The performance of the drive was monitored.

2.2 Equipment and Technical Issues

2.2.1 Drive Programming and External Connections

The drives were sent to the MSU Machines and Drives Laboratory as they are delivered to the end users, without any modifications. The manufacturer also supplied a document outlining the setup procedure for the drive prior to testing. Besides setting the motor for constant torque load etc., this document was to outline the procedure to set the carrier frequency to $4kHz$. All tests were performed at this carrier frequency.

In addition, when necessary, the drive was connected to appropriate external equipment, which included a two-wire switch (maintain start) and an appropriate potentiometer for speed control.

2.2.2 Laboratory Equipment and Characteristics

For all the tests the drive was connected to an induction motor (3HP, 4 pole, 460V rated, or 20HP, 4 pole, 460V rated), through:

- Current and voltage Hall effect probes,
- Equipment for the generation of transients.

Appropriate controllers, (on/off buttons, potentiometers etc.) were connected to the drive.

The induction motor in the MSU Machines and Drives laboratory turns a 20HP DC regenerative drive through an in-line torque sensor. The speed of the motor is monitored through an optical encoder with 1024 pulses/revolution and a frequency counter.

The DC regenerative drive was computer controlled to provide a preset counter-torque to the induction motor. This DC drive uses an 240/480V transformer to feed the regenerated power back to the power system.

Sampling at a rate of several $kHz$ through A/D converters, the data acquisition board on the computer recorded:
Figure 2.1: Schematic of the test set-up
• Line current and voltage of the drive,
• Shaft torque.

Through a counter and GPIB board it sensed:

• Shaft speed.

Through its digital outputs, the data acquisition board controlled the starting and stopping of the regenerative DC drive and initiated and stopped the transients. Through D/A converters it controlled the counter-torque produced by the DC drive.

From the sampled data the host computer of the data acquisition system calculated and displayed:

• RMS values of the input currents and the input power to the drive,
• Current harmonics as percentages of the fundamental,
• Input (electrical) and output (mechanical) of the PWM drive/motor system.

2.3 Test 1: Performance under Rated Line Voltage

The drive and the regenerative load were powered up. The computer set the regenerative drive to a torque limit of 100% of its maximum and zero actual torque. The drive and motor were left to operate at this load level for 15 min, in order for the drive to reach operating temperature.

The regenerative drive was adjusted to produce $60 Hz$ and the load torque was increased to 25% of rated ($3HP$ or $20HP$). Current and voltage to the PWM drive under test were measured, as well as harmonics, input power and output power. The data were recorded along with any observations.

The power was increased to 50%, 75% and 100%, and the same data were taken. Plots of the harmonics were recorded and THD was calculated.

2.4 Test 2: Efficiency

The drive was programmed to run at three different speeds at specific torque loads. The input power to the drive was calculated using time integration of the product of the input currents and voltages. These were measured through the current and voltage sensors.
The same high efficiency induction motor was used for all testing of the same size drives. Output power was computed from the torque the motor delivered and the motor speed.

Efficiency is reported at 60Hz, 45Hz and 30Hz, at 100%, 75%, 50% and 25% of rated torque.

2.5 Test 3: Capacitor Switching Emulation

During capacitor switching a waveform similar to figure 2.2 is applied to all three terminals of the drive. This waveform consists of a high frequency component superimposed on the 60Hz fundamental.

![Figure 2.2: Typical capacitor switching transient](image)

During the testing the transient voltage was produced by a solid state generator. It consisted of a programmable 3-phase power source and the desired voltage was simulated by it.

The computer initiated a recording of currents and voltages and gave a start command to the programmable power source to produce a decaying waveform of 500Hz.

After a preset time the command to the power source was removed and the recording was stopped. The transient was applied to the drive operating at no load, half load and full load. The performance of the drive during these tests (errors, interruptions etc.) was recorded.

2.6 Test 4: Voltage Sags

The testing equipment was inserted before the measuring system. It consisted again of a 3-phase programmable power source, controlled by the computer through the
A test run consisted of the following steps: The computer commanded the programmable source to provide rated voltage. The drive and the regenerative were are powered up. The computer set the regenerative drive to a torque limit of 100% of its maximum, and zero actual torque. The torque command from the computer to the regenerative drive was increased slowly to the desired value and the output power of the drive was measured. The drive was left to operate at this load for 15 min to reach steady state temperature.

The computer initiated a recording of currents and voltages and commanded the source to produce a three-phase sag of appropriate duration and value. After a preset time the voltage of the source was returned to the rated value.

Table 2.1 gives the depth and duration of all the voltage sags applied to the drive at zero, half rated, and rated load torque.

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0% of rated</td>
<td>1/30s</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
<td>1/10s</td>
</tr>
<tr>
<td>3</td>
<td>70%</td>
<td>1.0s</td>
</tr>
</tbody>
</table>

Table 2.1: Duration of Voltage Sags

The following were recorded for each of the 9 accurate applications of sags:

- Torque, speed, and output power,
- Rms values of currents and voltages,
- Input Power to the drive,
- Plots of the line voltage,
- The performance of the drive and possible diagnostic outputs.
Chapter 3

Comments on the Protocol

3.1 Computing Efficiencies

Efficiency of a drive alone is a rather vacuous term. The drive/motor system has to be considered as a whole, and the total system efficiency has to be computed. Because of this, the selection of the motor plays a significant role in the computation of the efficiency. The choice of motor here is not necessarily that of an application, and it is possible that the order of efficient drives will change with the load. The efficiency results are presented here as a crude guide to efficiency estimation.

A meaningful comparison of efficiency could only be obtained if efficiency were computed at many combinations of speed and load. The raw efficiency data are presented here for many operating points. The interested applications engineer can arrive at the effective efficiency of the drive-motor system for a particular application by calculating a weighted average of the efficiencies reported.

3.2 Voltage Sag Tests

Aside from the case when a drive stops and cannot restart except through manual resetting, it is very difficult to differentiate between the performances of drives and quantize these differences. One drive may slow down for a few milliseconds during a voltage sag, while another may be unable to bring the load back to the original speed, unless the load torque is decreased.

These two extremes are nothing more than manifestations of the same phenomenon, that the voltage of the DC bus decreases during a sag and that may cause a temporary interruption of operation. Whether a drive will ‘ride through’ a sag depends on the type of load used and on how accurately the drive parameters have been tuned.
to the characteristics of a particular load.

During the laboratory tests the load torque was held constant during the sags, while
the moment of inertia of the motor-dynamometer system was low. This meant that
when the motor was not producing torque, the rotor speed would decrease rapidly,
and the rotation might even reverse before the drive had a chance to recover. This
made it difficult for the drive to ‘catch’ the motor, even in the case when the drive
was equipped with a ‘flying restart’ option.

In practical terms the most important characteristic of the drive for the user or
the applications engineer is the reliability of the drive during a sag, i.e. whether the
drive has to be reset to restart, or whether a transient causes a failure. Furthermore,
to optimize the drive performance, the applications engineer will have to tune the
parameters of the drive to the load characteristics.
Chapter 4

Test Results

4.1 Summary

To make the tables of results more legible the drives were represented by letters according to the table below. The nonstandard drives are separated from the standard ones through double lines.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Drive</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen Bradley</td>
<td>1336plus, 20HP</td>
<td>G</td>
</tr>
<tr>
<td>Baldor</td>
<td>ID15H420, 20HP</td>
<td>H</td>
</tr>
<tr>
<td>Reliance</td>
<td>GV3000, 20HP</td>
<td>I</td>
</tr>
<tr>
<td>ABB</td>
<td>ACS 500 20HP</td>
<td>J</td>
</tr>
<tr>
<td>Baldor</td>
<td>ID15H420 20HP with a 3-phase 0.8mH line inductor</td>
<td>K</td>
</tr>
<tr>
<td>Baldor</td>
<td>Series 21H 20HP</td>
<td>L</td>
</tr>
<tr>
<td>Furnas/Vee Arc</td>
<td>Micro 7000, 20HP</td>
<td>M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Drive</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliance</td>
<td>GV3000, 3HP</td>
<td>h</td>
</tr>
<tr>
<td>ABB</td>
<td>ACS 501 3HP</td>
<td>i</td>
</tr>
<tr>
<td>Allen Bradley</td>
<td>1336plus, 3HP</td>
<td>j</td>
</tr>
<tr>
<td>Baldor</td>
<td>ID15H405-E, 3HP</td>
<td>k</td>
</tr>
<tr>
<td>Baldor</td>
<td>ID15H405-E, 3HP with a 3mH line inductor</td>
<td>m</td>
</tr>
<tr>
<td>Furnas/Vee Arc</td>
<td>Micro 7000, 3HP</td>
<td>l</td>
</tr>
</tbody>
</table>
4.2 **Voltage Sags**

Below follows a description of the performance symbols for the voltage sag testing:

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The speed of the motor was only decreased momentarily.</td>
</tr>
<tr>
<td>B</td>
<td>The speed of the motor was decreased to zero or reversed, but the system recovered.</td>
</tr>
<tr>
<td>C</td>
<td>The motor speed became negative, and the drive was unable to restart the motor. After the load was removed, the motor accelerated back to the original speed.</td>
</tr>
<tr>
<td>D</td>
<td>Power to the motor was interrupted, and the drive did not recover after the load was removed.</td>
</tr>
</tbody>
</table>

The ability of a drive to take the load after a sag depends both on the drive and on the load characteristics. In our tests we used an active load, i.e., the induction motor being driven by the ASD under test drove a DC dynamometer that fed the power back into the mains through a regenerative drive. Loading of the induction motor was accomplished by applying a constant torque to the motor.

The 70% voltage sag caused a momentary disruption of the operation of almost all the ASDs. When the voltage returned to its rated value, the ASDs marked with a B or C in the corresponding tables resumed operation. In the meantime the load torque had caused the Induction Motor to decelerate rapidly and even to rotate in a direction opposite to the direction it was turning before the sag. In order to let the ASD accelerate the induction motor, the load torque had to be removed in the tests marked with C.

According to the testing protocol, the manufacturers were encouraged to adjust the characteristics of their drives to match the load, and this was done in several cases.

In practical situations the loads depend on speed and, in many cases, the load torque drops to zero at zero speed. Drives marked with a B or C, i.e., the ones which came back on line after their operation was disrupted by the sag, should be able to take such a load (e.g., a fan) if their acceleration time is programmed to match the load.
Table 4.2: Performance of the 20HP Drives During Voltage Sags.

<table>
<thead>
<tr>
<th>Sag type</th>
<th>Load Torque</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>50%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100%</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>0%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>D</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>C</td>
<td>D</td>
<td>C</td>
</tr>
<tr>
<td>2</td>
<td>100%</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>C</td>
<td>D</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>0%</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>D</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>50%</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>A</td>
<td>D</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>100%</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>C</td>
</tr>
</tbody>
</table>

Note: Letters refer to the performance categories in Table 4.1; Torque as a percent of rated.

Table 4.3: Performance of the 3HP Drives During Voltage Sags.

<table>
<thead>
<tr>
<th>Sag Type</th>
<th>Load Torque</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>50%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100%</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>0%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>50%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>100%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>0%</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>50%</td>
<td>A</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>3</td>
<td>100%</td>
<td>B</td>
<td>A</td>
<td>C</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>

Note: Letters refer to the performance categories in Table 4.1; Torque as a percent of rated.
4.3 Efficiency and Harmonics

4.3.1 20 HP Drives

Table 4.4: Total Harmonic Distortion of the Line Current of 20HP Drives

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Torque</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.25</td>
<td>0.95</td>
<td>1.43</td>
<td>1.53</td>
<td>0.86</td>
<td>0.83</td>
<td>&lt;0.01</td>
<td>0.19</td>
</tr>
<tr>
<td>60</td>
<td>0.50</td>
<td>0.79</td>
<td>1.25</td>
<td>1.27</td>
<td>0.60</td>
<td>0.73</td>
<td>&lt;0.01</td>
<td>0.14</td>
</tr>
<tr>
<td>60</td>
<td>0.75</td>
<td>0.65</td>
<td>1.23</td>
<td>1.19</td>
<td>0.45</td>
<td>0.60</td>
<td>&lt;0.01</td>
<td>0.12</td>
</tr>
<tr>
<td>60</td>
<td>1.00</td>
<td>0.54</td>
<td>1.12</td>
<td>1.10</td>
<td>0.39</td>
<td>0.49</td>
<td>&lt;0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>45</td>
<td>0.25</td>
<td>1.10</td>
<td>1.44</td>
<td>1.51</td>
<td>0.92</td>
<td>0.88</td>
<td>&lt;0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>45</td>
<td>0.50</td>
<td>0.85</td>
<td>1.30</td>
<td>1.37</td>
<td>0.73</td>
<td>0.77</td>
<td>&lt;0.01</td>
<td>0.13</td>
</tr>
<tr>
<td>45</td>
<td>0.75</td>
<td>0.76</td>
<td>1.21</td>
<td>1.35</td>
<td>0.53</td>
<td>0.69</td>
<td>&lt;0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>45</td>
<td>1.00</td>
<td>0.65</td>
<td>1.15</td>
<td>1.16</td>
<td>0.48</td>
<td>0.57</td>
<td>&lt;0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>30</td>
<td>0.25</td>
<td>1.08</td>
<td>1.55</td>
<td>1.52</td>
<td>0.98</td>
<td>0.98</td>
<td>&lt;0.01</td>
<td>0.14</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>0.93</td>
<td>1.43</td>
<td>1.48</td>
<td>0.82</td>
<td>0.85</td>
<td>&lt;0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td>0.86</td>
<td>1.35</td>
<td>1.33</td>
<td>0.72</td>
<td>0.78</td>
<td>&lt;0.01</td>
<td>0.10</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
<td>0.80</td>
<td>1.27</td>
<td>1.30</td>
<td>0.59</td>
<td>0.71</td>
<td>&lt;0.01</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Frequency in Hz, torque as a percent of rated.

Table 4.5: Efficiency of 20HP Drives

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Torque</th>
<th>G</th>
<th>H,K</th>
<th>I</th>
<th>J</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.25</td>
<td>71.51</td>
<td>77.77</td>
<td>75.09</td>
<td>79.23</td>
<td>69.39</td>
<td>60.7</td>
</tr>
<tr>
<td>60</td>
<td>0.50</td>
<td>84.44</td>
<td>83.54</td>
<td>83.06</td>
<td>87.18</td>
<td>78.23</td>
<td>75.5</td>
</tr>
<tr>
<td>60</td>
<td>0.75</td>
<td>87.34</td>
<td>86.16</td>
<td>86.24</td>
<td>88.23</td>
<td>81.14</td>
<td>79.31</td>
</tr>
<tr>
<td>60</td>
<td>1.00</td>
<td>88.39</td>
<td>86.41</td>
<td>85.94</td>
<td>88.66</td>
<td>83.35</td>
<td>80.53</td>
</tr>
<tr>
<td>45</td>
<td>0.25</td>
<td>68.49</td>
<td>78.87</td>
<td>71.26</td>
<td>78.65</td>
<td>75.52</td>
<td>65.78</td>
</tr>
<tr>
<td>45</td>
<td>0.50</td>
<td>83.42</td>
<td>83.49</td>
<td>82.94</td>
<td>85.80</td>
<td>77.93</td>
<td>80.03</td>
</tr>
<tr>
<td>45</td>
<td>0.75</td>
<td>86.69</td>
<td>83.48</td>
<td>85.01</td>
<td>87.91</td>
<td>80.44</td>
<td>82.77</td>
</tr>
<tr>
<td>45</td>
<td>1.00</td>
<td>86.59</td>
<td>85.73</td>
<td>87.11</td>
<td>87.44</td>
<td>82.03</td>
<td>84.18</td>
</tr>
<tr>
<td>30</td>
<td>0.25</td>
<td>68.96</td>
<td>74.19</td>
<td>76.83</td>
<td>79.69</td>
<td>61.68</td>
<td>67.82</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>82.32</td>
<td>82.26</td>
<td>83.91</td>
<td>87.73</td>
<td>75.06</td>
<td>81.79</td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td>84.69</td>
<td>82.54</td>
<td>85.00</td>
<td>87.42</td>
<td>77.30</td>
<td>85.04</td>
</tr>
<tr>
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<td>84.85</td>
<td>82.40</td>
<td>85.44</td>
<td>85.76</td>
<td>77.50</td>
<td>85.70</td>
</tr>
</tbody>
</table>

Frequency in Hz, torque as a percent of rated.

Drives H and K had efficiencies that differed less than 1 percentage point.
4.3.2 3HP Drives

Table 4.6: Total Harmonic Distortion of the Line Current of 3HP Drives

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Torque</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
<th>l</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.25</td>
<td>2.00</td>
<td>1.06</td>
<td>1.69</td>
<td>1.78</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td>60</td>
<td>0.50</td>
<td>1.79</td>
<td>0.80</td>
<td>1.63</td>
<td>1.73</td>
<td>0.63</td>
<td>0.84</td>
</tr>
<tr>
<td>60</td>
<td>0.75</td>
<td>1.71</td>
<td>0.74</td>
<td>1.60</td>
<td>1.64</td>
<td>0.52</td>
<td>0.76</td>
</tr>
<tr>
<td>60</td>
<td>1.00</td>
<td>1.69</td>
<td>0.58</td>
<td>1.55</td>
<td>1.59</td>
<td>0.43</td>
<td>0.72</td>
</tr>
<tr>
<td>45</td>
<td>0.25</td>
<td>1.90</td>
<td>0.90</td>
<td>1.81</td>
<td>1.98</td>
<td>0.86</td>
<td>1.05</td>
</tr>
<tr>
<td>45</td>
<td>0.50</td>
<td>1.90</td>
<td>0.90</td>
<td>1.63</td>
<td>1.81</td>
<td>0.74</td>
<td>0.93</td>
</tr>
<tr>
<td>45</td>
<td>0.75</td>
<td>1.74</td>
<td>0.78</td>
<td>1.63</td>
<td>1.71</td>
<td>0.62</td>
<td>0.85</td>
</tr>
<tr>
<td>45</td>
<td>1.00</td>
<td>1.73</td>
<td>0.74</td>
<td>1.59</td>
<td>1.66</td>
<td>0.52</td>
<td>0.79</td>
</tr>
<tr>
<td>30</td>
<td>0.25</td>
<td>1.97</td>
<td>1.08</td>
<td>1.76</td>
<td>1.80</td>
<td>0.99</td>
<td>1.08</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>1.76</td>
<td>0.94</td>
<td>1.69</td>
<td>1.78</td>
<td>0.83</td>
<td>0.93</td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td>1.76</td>
<td>0.91</td>
<td>1.65</td>
<td>1.78</td>
<td>0.76</td>
<td>0.88</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
<td>1.79</td>
<td>0.83</td>
<td>1.61</td>
<td>1.72</td>
<td>0.63</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Frequency in Hz, torque as a percent of rated.

Table 4.7: Efficiency of the 3HP Drives

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Torque</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k,m</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>0.25</td>
<td>54.30</td>
<td>49.60</td>
<td>27.19</td>
<td>48.97</td>
<td>40.08</td>
</tr>
<tr>
<td>60</td>
<td>0.50</td>
<td>72.08</td>
<td>79.40</td>
<td>60.01</td>
<td>74.20</td>
<td>64.03</td>
</tr>
<tr>
<td>60</td>
<td>0.75</td>
<td>77.19</td>
<td>80.86</td>
<td>69.01</td>
<td>77.69</td>
<td>70.92</td>
</tr>
<tr>
<td>60</td>
<td>1.00</td>
<td>79.44</td>
<td>80.84</td>
<td>74.72</td>
<td>79.89</td>
<td>74.17</td>
</tr>
<tr>
<td>45</td>
<td>0.25</td>
<td>50.16</td>
<td>67.72</td>
<td>11.37</td>
<td>43.77</td>
<td>45.21</td>
</tr>
<tr>
<td>45</td>
<td>0.50</td>
<td>72.24</td>
<td>72.63</td>
<td>53.90</td>
<td>69.10</td>
<td>72.70</td>
</tr>
<tr>
<td>45</td>
<td>0.75</td>
<td>76.01</td>
<td>80.61</td>
<td>64.53</td>
<td>74.80</td>
<td>75.77</td>
</tr>
<tr>
<td>45</td>
<td>1.00</td>
<td>80.33</td>
<td>77.18</td>
<td>79.96</td>
<td>78.60</td>
<td>75.97</td>
</tr>
<tr>
<td>30</td>
<td>0.25</td>
<td>36.90</td>
<td>24.68</td>
<td>9.32</td>
<td>27.06</td>
<td>46.50</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>70.37</td>
<td>63.60</td>
<td>53.23</td>
<td>60.90</td>
<td>72.05</td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td>71.92</td>
<td>71.88</td>
<td>60.87</td>
<td>69.36</td>
<td>75.29</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
<td>73.96</td>
<td>76.08</td>
<td>68.33</td>
<td>72.33</td>
<td>75.64</td>
</tr>
</tbody>
</table>

Frequency in Hz, torque as a percent of rated.
Drives \(k\) and \(m\) had efficiencies that differed less than 1 percentage point.
4.4 Capacitor Switching Emulation

All the drives tested were immune to this test.
Chapter 5

Comments on Individual Drives

Efficiency results for the Baldor Drives $H$ and $K$, were very similar, within 1 percentage point. The same was true for Baldor drives $k$ and $m$. The reader is reminded that the $K$ and $m$ drives are the same as the $H$ and $k$ correspondingly, with the addition of line inductors. Line inductors are standard stocked products of Baldor. The performance during transients of the drives with inductors was identical to the performance of the same drives without inductors.

The Baldor 21H-series 20HP drive showed no appreciable harmonic content in the range of frequencies tested (up to the 19th harmonic). This was expected due to the $4kHz$ PWM scheme at the input rectifier. This drive had to be reset in order to resume operation, after the sag tests marked D.

Allen Bradley drives required a standard auxiliary board to allow startup after an interruption of service.

Furnas provided a standard 3-phase/6-phase transformer for the efficiency and harmonic tests of the Micro 7000 20HP Drive. Although the efficiency of the system may vary with other six-phase transformers, the harmonic content is not expected to change dramatically.
Chapter 6

Recommendations for Future Testing

Regarding future testing of drives that are becoming more complex, the following issues should be considered:

- Explore alternatives to capacitor switching techniques. This transient can be reproduced through a variety of techniques, including synthetic testing (i.e. developing a capacitive circuit to simulate reality) to using an inverter switching at high frequency (above 15kHz) to supply the desired waveform.

- When evaluating the response of the drives to voltage sags, implement other load torque and load speed profiles, simulating fan or friction loads. Although this can be accomplished easily with a regenerative dynamometer, the choice of these profiles should be thoroughly discussed.

- Control the phase angle of the voltage during the sag initiation, and evaluate its effect on performance.

- Although we consider the use of a ‘stiff’ source the preferred method for current harmonic measurement, it may be useful to determine a specific value of source impedance, which would be considered typical.

- All the tests were performed at the nominal value of the line voltage. Experience has shown that a drive is more susceptible to capacitor switching transients when the voltage is at the high end of the acceptable voltage range. Specifying at what level of line voltage these tests should be conducted may affect the results.
Appendix A

Test Equipment

A.1 Load

In these tests, the load on the induction motor was provided by an Emerson DC dynamometer with the following specifications:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>20 HP</td>
</tr>
<tr>
<td>Speed</td>
<td>1750 rpm</td>
</tr>
<tr>
<td>Line-line voltage</td>
<td>240 V</td>
</tr>
<tr>
<td>Frame</td>
<td>259 AT</td>
</tr>
</tbody>
</table>

Table A.1: Load Data

The Emerson DC drive control Model ES-2300RG, which is a regenerative adjustable speed DC motor controller, produced braking torque by absorbing energy from the induction motor. Its DC output current varies as a function of an reference voltage. This reference voltage was set at the computer and supplied by the data acquisition and control card.

A.2 Induction Motors

Marathon Inverter Duty 3 Phase, 60Hz Induction Motors were used with the following nameplate data:

- 20 HP Motor:
Model: 2J 256TTFN6026EE R142
Frame: 256T
Voltage: 230/460V
Current: 48.2/24.1A
Speed: 1775rpm

3 HP Motor:
Model: 2J 182TTF6026AV R142
Frame: 182T
Voltage: 230/460V
Current: 7.4/3.7A
Speed: 1775rpm

A.3 Personal Computer
- Gateway 2000 Pentium, 120MHz

A.4 Data Acquisition and Control
- Hardware
  Keithley Metrabyte DAS 1802HC card with the following specifications:
    - 64 single ended or 32 differential analog inputs
    - 2 channel analog outputs
    - 4 bit digital input
    - 8 bit digital output
    - 333 thousand samples/s maximum single channel input rate
    - 12 bit resolution
    - 1 K word FIFO
    - 16-bit DMA with single and dual channel modes
- Software
  Keithley Metrabyte’s application software package VIEWDAC was used to develop the software for the testing.

A.5 IEEE 488 Instrument Interface

Computer Boards CIO PC2A board with its accompanying DRVR-PC2A drivers.
A.6 Current and Voltage Sensors

- LEM Modules LV 25-P were used for sampling voltage signals.
- LEM Modules LA 50-S were used for sampling current signals.

A.7 Speed Sensor

A BEI Shaft Encoder model H25D-SS-1024-ABC-7406R-LED-SM18 was used. It produced 1024 pulses per revolution of the motor shaft. The pulses were counted using PHILIPS PM6666 Programmable Timer/Counter. This counter was controlled via the IEEE Bus. Speed was calculated from the pulse count given by the counter.

There was a DC tach generator mounted on the Emerson DC dynamometer which produced 50V DC at 1000 rpm. This speed was displayed on the Emerson drive controller enclosure.

A.8 Capacitor Switching and Sag Emulation Equipment

California Instruments bank of three 4500L-PT Invertron Power System, controlled through an GPIB bus.