OAK RIDGE
NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
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PERFORMANCE TESTING THE SERIES MACHINE FROM DELPHI APRIL 2004

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Oak Ridge National Laboratory

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Engineering Science & Technology Division

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. PURPOSE

This report documents the testing of the deliverable series electric machine from Delphi. The tests were performed on behalf of the Department of Energy (DOE) to evaluate the overall performance capabilities of the prototype motor developed for the Automotive Electric Motor Drive (AEMD) task. Tests were performed at the development dynamometer test cell at Delphi during April 2004.

2. DESCRIPTION OF THE AEMD UNIT

The deliverable prototype electric motor was developed by Delphi for potential traction motor applications in hybrid electric vehicles. The electric motor is a 12-pole 3-phase permanent magnet (PM) machine with an outer-rotor configuration. The machine has a nominal voltage rating of 325 V with a continuous power rating of 30 kW and a peak power rating of 55 kW. The AEMD unit operates at a base speed of 6000 rpm at 325 V with a maximum rated speed of 12,000 rpm. The motor is liquid-cooled and has a thermistor embedded in the stator to allow the stator temperature to be monitored. The insulation of the electric motor is Class H and is rated at up to 180° C. Figure 1 shows Delphi's deliverable series machine.

Fig. 1. Deliverable series machine from Delphi.

3. TEST DESCRIPTION

The configuration of the series electric machine that was tested included a reduction gear assembly and lubrication fluid. The electric machine was driven by a development inverter from Delphi, Global 2000, with a maximum output of about 430 A. Torque versus speed mapping of the machine was performed with dc link voltages of 325 and 200 Vdc. The machine was tested from 500 to 12,000 rpm in intervals of 500 rpm with torque loads of 100%, 80%, 60%, 40%, 20%, and 10% of rated torque. These short-duration tests were performed without allowing the stator temperature to stabilize. The inlet cooling temperature was maintained at 20ºC while the

machine was being mapped. The machine mapping data are presented in Tables 1 and 2 for 325 and 200 Vdc respectively. Plots of the mapping data are shown in Figs. 2 and 3.

Table 1. Short-duration testing of Delphi series machine with 325 Vdc link

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
516	4.4	60.3	1091.1	94.7	9.2	9.2	9.2	41.7	42.1	41.5
518	4.4	119.6	2194.8	95.6	9.4	9.5	9.5	81.5	81.8	81.3
514	4.4	238.0	4350.6	91.6	10.1	10.1	10.0	161.8	161.9	160.9
513	4.4	357.1	6507.6	86.8	10.8	10.8	10.8	244.4	244.2	242.9
514	4.4	478.2	8721.1	81.5	11.8	11.8	11.8	329.9	329.1	327.3
516	4.4	596.9	10936.7	74.6	13.1	13.1	13.0	418.4	416.6	414.6
1010	8.6	59.6	2138.7	93.4	18.3	18.3	18.3	41.9	42.0	41.4
1038	8.8	119.2	4399.9	97.3	18.6	18.6	18.5	82.1	82.1	81.3
1034	8.8	238.3	8770.6	95.7	19.4	19.4	19.4	162.7	162.4	161.3
1032	8.7	356.9	13102.4	93.1	20.5	20.5	20.4	245.0	244.8	242.8
1029	8.7	477.6	17443.0	89.4	21.8	21.8	21.8	330.9	329.8	327.8
1008	8.5	596.8	21366.8	84.5	23.4	23.3	23.3	417.1	415.6	413.6
1532	13.0	59.4	3239.5	93.2	27.4	27.4	27.3	42.8	42.6	41.9
1535	13.0	120.1	6527.2	95.5	27.8	27.8	27.8	82.9	82.7	81.8
1532	13.0	238.6	12972.3	95.1	28.8	28.9	28.8	163.4	163.3	161.5
1502	12.7	359.3	19133.8	92.5	30.1	30.2	30.1	245.5	245.0	242.6
1502	12.7	478.0	25468.3	90.4	31.8	31.8	31.7	330.7	329.4	326.4
1505	12.8	598.0	31931.0	87.4	34.0	34.0	33.9	420.1	417.3	415.7
2028	17.2	60.0	4314.9	91.9	36.3	36.4	36.3	43.6	43.3	42.5
2030	17.2	119.5	8619.2	94.7	36.7	36.8	36.7	83.8	83.3	82.4
2029	17.2	238.7	17194.0	95.0	37.9	38.1	37.9	165.1	164.2	162.8
2020	17.1	357.7	25626.8	93.6	39.6	39.7	39.5	248.3	246.9	244.9
2021	17.1	477.9	34229.9	92.1	41.8	41.8	41.7	334.7	332.8	330.1
1994	16.9	596.8	42238.3	89.2	44.4	44.3	44.3	420.8	418.9	417.8
2525	21.4	59.9	5364.7	91.3	45.0	45.1	45.0	44.2	43.3	43.2
2530	21.4	119.5	10717.4	94.5	45.4	45.6	45.4	84.6	83.7	82.9
2524	21.4	239.2	21392.6	94.9	47.0	47.1	46.9	166.1	165.3	163.7
2518	21.3	358.2	32029.7	94.1	49.0	49.1	48.9	250.5	248.6	246.7
2514	21.3	477.5	42611.8	92.8	51.6	51.7	51.4	336.9	334.3	331.4
2496	21.2	597.6	52938.5	91.2	54.6	54.6	54.5	421.0	419.0	417.7
3020	25.6	52.9	5648.5	89.3	53.7	53.8	53.8	39.7	39.0	39.0
3023	25.6	105.1	11240.8	93.3	54.2	54.4	54.2	75.0	74.2	73.8
3023	25.6	209.2	22493.9	94.9	55.6	55.7	55.5	146.7	145.3	144.7
3025	25.6	314.5	33762.6	94.6	57.5	57.6	57.3	220.6	218.3	217.3
3015	25.6	419.4	44889.7	93.5	60.0	60.1	59.8	296.0	293.2	291.5
3009	25.5	523.8	55935.1	92.3	62.9	62.9	62.6	373.4	370.1	367.7

Table 1. Short-duration testing of Delphi series machine with 325 Vdc link (cont.)

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
3518	29.8	45.0	5603.3	87.2	62.4	62.5	62.3	34.9	34.1	34.0
3524	29.9	90.1	11277.2	92.5	62.8	63.0	62.8	65.7	64.3	64.3
3524	29.9	180.1	22508.2	94.6	64.0	64.2	63.8	127.5	125.3	125.5
3520	29.8	269.5	33663.6	94.6	65.7	65.9	65.6	189.6	187.7	186.6
3514	29.8	359.3	44843.1	94.1	67.9	68.1	67.7	253.8	251.4	249.7
3511	29.8	449.5	55984.5	93.4	70.5	70.6	70.2	319.5	316.3	314.2
4035	34.2	39.4	5644.9	85.9	70.8	70.9	70.8	31.3	30.7	31.0
4043	34.3	79.0	11305.7	92.1	71.1	71.3	71.1	58.2	57.0	57.3
4042	34.3	157.3	22561.4	94.6	72.4	72.5	72.2	112.2	110.1	110.9
4038	34.2	236.0	33832.8	95.1	73.9	74.1	73.7	167.2	165.0	164.5
4032	34.2	314.6	45011.5	94.9	75.9	76.0	75.6	223.2	219.4	219.6
4032	34.2	393.6	56288.1	94.4	78.2	78.5	77.9	280.2	277.0	274.8
4533	38.4	35.5	5654.0	85.5	78.0	78.1	78.0	28.7	28.2	28.3
4535	38.4	70.5	11329.3	90.3	79.7	79.9	79.7	53.1	52.0	52.2
4544	38.5	139.8	22611.5	94.0	80.8	80.8	80.5	101.5	99.1	99.7
4541	38.5	210.0	33861.1	95.1	82.1	82.3	81.9	149.3	147.1	147.2
4542	38.5	279.4	45062.1	95.2	84.0	84.1	83.6	198.7	195.1	195.8
4541	38.5	348.7	56294.5	95.0	86.1	86.2	85.7	248.7	245.1	245.1
5019	42.5	32.3	5703.3	81.1	87.5	87.6	87.5	27.4	26.9	27.0
5025	42.6	63.2	11270.3	88.7	88.1	88.3	88.1	48.6	47.7	48.1
5034	42.7	125.2	22423.9	93.0	89.1	89.2	89.0	91.2	89.8	90.7
5029	42.6	188.7	33667.3	94.5	90.4	90.5	90.1	135.2	132.8	133.4
5030	42.6	251.8	44953.0	94.8	92.1	92.2	91.7	179.8	176.8	177.0
5030	42.6	314.7	56125.1	94.8	94.0	94.1	93.5	224.9	220.4	221.2
5524	46.8	28.7	5672.4	77.9	96.1	96.3	96.2	25.8	25.3	25.9
5531	46.9	57.4	11229.6	87.3	96.5	96.6	96.5	44.9	44.2	44.5
5534	46.9	114.0	22462.2	92.3	97.3	97.4	97.1	84.0	82.8	83.9
5527	46.8	172.1	33723.8	93.7	98.5	98.6	98.3	124.2	122.4	123.3
5528	46.9	228.4	44827.4	94.6	100.0	100.1	99.8	163.4	161.1	162.3
5524	46.8	286.1	56081.8	94.7	101.9	101.9	101.6	204.5	201.1	202.9
6026	51.1	26.4	5608.3	75.9	104.5	104.9	104.7	24.4	24.2	24.2
6032	51.1	52.6	11231.6	85.4	104.8	105.0	104.8	42.2	41.5	42.4
6031	51.1	105.2	22495.3	91.3	105.6	105.6	105.5	78.2	77.1	78.1
6033	51.1	157.9	33731.7	93.4	106.7	106.8	106.6	114.2	112.9	114.1
6031	51.1	209.8	44859.5	94.1	108.2	108.2	107.9	150.8	148.8	150.1
6032	51.1	262.1	56130.4	94.7	109.9	109.9	109.6	187.5	185.2	186.7

Table 1. Short-duration testing of Delphi series machine with 325 Vdc link (cont.)

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
6523	55.3	24.0	5644.1	75.8	111.3	111.6	111.4	23.5	23.1	23.5
6526	55.3	48.9	11293.7	84.7	112.3	112.8	112.5	40.2	39.4	40.0
6529	55.3	97.0	22483.4	90.3	113.8	114.0	113.7	73.3	72.3	73.2
6526	55.3	145.5	33702.1	92.5	114.8	115.0	114.7	106.7	105.7	106.6
6527	55.3	193.4	44838.0	93.5	116.2	116.3	116.0	140.2	138.7	139.8
6527	55.3	242.0	56044.2	94.2	117.7	117.7	117.5	174.2	172.5	173.9
7019	59.5	22.7	5670.2	71.6	119.3	119.6	119.3	25.7	25.2	25.7
7021	59.5	45.3	11318.6	82.9	118.9	119.4	119.1	41.0	40.5	40.8
7019	59.5	90.4	22360.4	89.1	118.7	119.0	118.6	72.0	71.1	71.8
7023	59.5	134.6	33532.4	91.9	118.4	118.6	118.3	103.7	102.8	103.4
7025	59.5	179.9	44867.8	93.3	118.1	118.2	117.9	136.3	135.2	136.3
7025	59.5	224.2	55946.9	94.0	117.8	117.9	117.5	169.4	167.5	168.9
7515	63.7	21.2	5620.2	68.3	121.1	121.6	121.3	44.7	44.0	44.2
7517	63.7	41.5	11089.0	80.3	120.2	120.6	120.1	56.8	55.8	56.2
7516	63.7	84.4	22425.9	88.3	119.0	119.5	119.1	83.2	82.6	82.8
7511	63.7	125.4	33538.9	91.4	118.6	118.8	118.5	111.3	110.0	110.9
7512	63.7	167.9	44786.8	92.7	118.1	118.2	118.0	141.3	140.0	141.2
7507	63.6	209.9	55890.0	93.5	117.8	117.8	117.5	172.0	170.6	171.9
8020	68.0	19.3	5564.0	65.9	122.1	122.7	122.0	68.0	66.5	67.8
8019	68.0	39.5	11239.8	78.7	121.1	121.6	121.1	77.2	76.6	77.3
8019	68.0	78.9	22450.5	87.0	119.7	120.2	119.7	99.4	98.6	99.2
8017	67.9	117.8	33515.3	90.1	118.9	119.4	119.0	123.9	123.2	123.1
8014	67.9	157.3	44778.1	91.7	118.3	118.6	118.1	151.2	149.6	150.6
8011	67.9	197.1	55970.5	92.8	117.8	118.0	117.6	179.4	177.9	178.9
8512	72.1	18.5	5568.9	62.7	122.3	122.9	122.3	89.1	88.5	89.3
8512	72.1	37.7	11280.7	77.2	121.5	122.0	121.3	96.6	95.7	96.5
8516	72.2	74.3	22575.4	86.8	120.1	120.5	120.0	115.2	114.6	115.4
8514	72.2	111.2	33578.7	89.3	119.2	119.5	119.0	137.3	136.3	137.1
8515	72.2	147.8	44629.2	90.7	118.6	118.9	118.4	161.6	160.3	161.4
8510	72.1	185.1	55890.8	91.9	118.1	118.3	117.9	187.4	186.3	187.1
9038	76.6	17.5	5661.6	58.8	122.2	122.7	122.5	125.4	124.7	125.2
9034	76.6	35.0	11204.1	73.7	121.2	121.9	121.6	129.6	129.0	129.4
9038	76.6	70.2	22396.8	83.9	120.3	120.7	120.5	143.3	142.8	143.4
9031	76.5	105.1	33654.1	88.3	119.4	119.8	119.2	161.3	160.4	161.2
9042	76.6	140.5	44997.3	90.0	118.9	119.3	118.9	181.1	180.2	180.8
9042	76.6	174.9	56062.1	90.8	118.4	118.8	118.1	203.8	202.3	203.3

Table 1. Short-duration testing of Delphi series machine with 325 Vdc link (cont.)

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
9534	80.8	16.9	5577.2	55.3	122.5	123.3	122.7	137.8	136.9	137.8
9533	80.8	33.2	11218.2	71.5	121.8	122.4	121.9	141.4	140.7	141.6
9532	80.8	66.2	22448.2	82.8	120.7	121.3	120.7	154.0	153.2	154.3
9530	80.8	99.5	33679.6	87.2	119.8	120.2	119.7	170.1	169.4	170.1
9526	80.7	132.6	44839.0	89.6	119.0	119.3	118.9	188.6	187.8	188.5
9528	80.7	165.3	56040.2	90.5	118.4	118.6	118.2	210.1	209.2	210.0
10011	84.8	16.0	5701.7	52.8	122.6	123.3	122.4	151.2	150.0	151.5
10022	84.9	31.6	11333.5	69.0	121.8	122.6	122.2	155.9	155.0	154.9
10021	84.9	62.6	22346.1	80.6	121.0	121.6	120.6	167.4	166.1	167.8
10020	84.9	94.8	33604.4	85.1	119.7	120.3	119.6	183.0	181.7	182.5
10020	84.9	126.4	44844.7	88.2	119.1	119.2	118.8	199.7	199.1	200.1
10015	84.9	157.1	55905.1	89.3	118.2	118.4	117.9	220.3	219.5	220.2
10521	89.2	15.5	5675.8	51.7	122.5	123.2	122.5	162.9	162.3	163.2
10525	89.2	29.8	11238.2	67.1	122.0	122.6	122.0	166.7	166.1	166.8
10527	89.2	59.8	22516.0	78.9	120.7	121.2	120.5	178.2	177.4	178.3
10528	89.2	89.9	33532.4	84.1	119.8	120.3	119.6	191.6	190.7	191.8
10521	89.2	119.7	44694.6	86.9	118.9	119.1	118.6	208.2	207.7	208.6
10520	89.2	149.9	55937.6	88.6	118.1	118.4	118.0	227.1	226.5	226.9
11021	93.4	14.6	5608.3	49.5	122.1	122.8	122.1	171.8	171.1	171.9
11022	93.4	28.6	11198.7	65.8	121.6	122.2	121.6	175.1	174.3	175.0
11024	93.4	57.4	22361.3	78.2	120.4	120.9	120.4	185.0	184.3	185.0
11021	93.4	85.6	33608.3	83.7	119.5	119.9	119.4	198.4	197.8	198.5
11022	93.4	114.5	44809.1	86.5	118.6	119.1	118.5	214.5	213.8	214.3
11024	93.4	142.8	55968.7	88.0	118.0	118.3	117.8	232.8	232.0	232.7
11517	97.6	13.6	5534.4	45.7	122.3	122.9	122.2	180.5	179.8	180.6
11520	97.6	27.3	11193.0	62.8	121.5	122.1	121.5	184.3	183.7	184.3
11519	97.6	54.8	22473.0	76.0	120.6	121.2	120.6	193.7	193.2	193.7
11518	97.6	81.6	33506.1	81.8	119.7	120.0	119.5	206.5	206.1	206.6
11518	97.6	109.1	44763.2	85.1	118.8	119.2	118.7	221.7	221.1	221.6
11516	97.6	137.0	55993.1	87.2	117.9	118.3	117.7	239.3	238.4	238.9
12033	102.0	13.3	5624.5	43.6	122.0	122.5	122.0	189.2	188.9	189.3
12032	102.0	26.6	11445.0	61.2	121.6	122.2	121.6	191.9	191.5	192.1
12033	102.0	52.6	22560.3	73.8	120.6	121.1	120.5	202.2	201.7	202.3
12033	102.0	78.7	33644.9	79.9	119.5	120.0	119.4	214.7	214.0	214.6
12031	102.0	105.1	44876.6	84.0	118.7	119.1	118.6	228.7	228.1	228.7
12037	102.0	130.3	55767.6	86.1	117.8	118.1	117.7	245.1	244.6	245.0

Table 2. Short-duration testing of Delphi series machine with 200 Vdc link

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (kW)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
521	4.4	59.8	1110.2	93.0	8.9	8.9	8.9	44.6	45.0	44.4
515	4.4	119.7	2183.5	93.1	9.2	9.2	9.2	86.1	86.1	85.6
514	4.4	238.8	4350.2	90.0	9.8	9.9	9.8	169.4	169.6	168.5
516	4.4	359.1	6564.8	85.6	10.7	10.7	10.7	254.8	254.8	253.3
518	4.4	476.9	8790.0	80.2	11.8	11.8	11.8	342.2	341.5	339.5
518	4.4	592.8	10883.4	73.4	13.1	13.0	13.0	429.0	425.9	427.2
1010	8.6	59.3	2152.1	93.1	17.9	17.9	17.9	43.4	43.3	42.9
1012	8.6	118.7	4281.9	94.5	18.2	18.2	18.2	83.9	84.0	83.1
1015	8.6	238.4	8595.0	93.5	19.0	19.1	19.0	166.5	166.5	165.1
1011	8.6	357.8	12859.1	90.9	20.2	20.2	20.1	251.0	250.8	248.6
1011	8.6	477.1	17147.2	87.1	21.7	21.7	21.7	338.7	337.8	335.1
1011	8.6	594.1	21330.0	83.2	23.3	23.2	23.3	427.1	425.7	426.4
1507	12.8	59.8	3209.9	92.7	26.8	26.8	26.8	43.6	43.2	42.8
1511	12.8	119.2	6393.5	94.8	27.1	27.2	27.1	84.0	83.6	82.7
1506	12.8	238.7	12751.0	94.3	28.2	28.3	28.1	166.1	165.3	163.7
1507	12.8	358.3	19147.3	92.7	29.7	29.8	29.7	249.9	248.8	246.9
1506	12.8	478.2	25536.4	90.3	31.5	31.6	31.4	337.4	335.4	332.8
1508	12.8	594.7	31790.9	87.8	33.6	33.5	33.6	424.1	422.6	421.9
2002	17.0	59.8	4255.8	91.8	35.8	35.8	35.7	43.7	43.1	43.0
2003	17.0	119.5	8494.8	94.0	36.2	36.3	36.2	84.5	83.5	83.3
2000	17.0	239.0	16963.5	94.0	37.6	37.7	37.5	167.0	164.9	164.1
2002	17.0	357.7	25448.8	92.9	39.4	39.5	39.2	251.0	248.8	247.7
2004	17.0	476.8	33964.2	91.3	41.6	41.6	41.5	337.9	335.3	333.5
2003	17.0	595.9	42410.6	89.2	44.2	44.2	44.2	426.1	425.7	424.3
2498	21.2	59.8	5315.0	91.2	44.7	44.7	44.6	44.1	43.3	43.2
2499	21.2	119.7	10613.3	94.0	45.2	45.3	45.1	84.8	83.4	83.6
2498	21.2	238.8	21193.7	94.5	46.7	46.8	46.6	166.8	165.0	164.7
2501	21.2	358.1	31799.7	93.7	48.8	48.8	48.7	251.0	248.6	248.0
2499	21.2	477.8	42350.2	92.4	51.5	51.4	51.2	338.0	334.6	333.7
2499	21.2	596.1	52865.4	91.4	54.3	54.3	54.3	422.5	421.2	419.7
2998	25.4	52.5	5612.5	89.6	53.5	53.6	53.5	39.5	38.8	38.9
2996	25.4	105.0	11165.0	92.9	54.0	54.1	54.0	74.9	74.2	74.3
2995	25.4	209.8	22311.7	94.5	55.4	55.4	55.3	146.7	145.4	145.3
2995	25.4	314.2	33405.3	94.1	57.3	57.4	57.2	219.8	217.7	217.6
2997	25.4	419.4	44607.1	93.4	59.8	59.8	59.6	294.9	292.5	292.1
2997	25.4	524.3	55676.5	92.2	62.8	62.8	62.6	372.1	368.9	367.8

Table 2. Short-duration testing of Delphi series machine with 200 Vdc link (cont.)

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
3495	29.6	45.2	5616.3	88.1	62.1	62.1	62.1	34.5	34.0	34.2
3492	29.6	90.3	11174.8	92.1	62.7	62.7	62.6	65.1	64.2	64.5
3501	29.7	179.7	22337.4	94.5	63.9	64.0	63.8	126.0	125.2	124.9
3498	29.6	269.6	33474.7	94.6	65.6	65.7	65.5	188.3	186.8	186.5
3503	29.7	359.4	44677.6	94.4	67.8	67.8	67.6	251.7	249.8	249.0
3500	29.7	449.8	55814.3	93.7	70.3	70.3	70.1	317.1	314.0	313.2
3989	33.8	39.0	5557.8	85.5	70.8	71.0	70.8	31.3	30.4	30.3
3991	33.8	78.7	11118.8	91.2	71.3	71.4	71.2	57.7	56.5	57.0
3994	33.8	157.5	22334.0	94.1	72.2	72.5	72.2	111.3	111.0	109.4
3991	33.8	235.8	33399.0	94.7	72.4	72.4	72.2	165.9	164.0	164.9
3993	33.8	314.1	44538.4	94.7	71.9	72.1	71.7	224.5	221.7	221.2
3994	33.9	393.8	55787.5	94.1	71.4	71.7	71.3	286.3	284.7	282.2
4500	38.1	35.3	5613.1	83.5	74.6	74.8	74.6	47.6	47.1	47.3
4506	38.2	69.6	11200.3	90.3	73.8	74.0	73.7	70.0	68.9	69.3
4509	38.2	140.0	22439.4	94.3	73.0	73.1	72.9	116.1	115.4	115.6
4511	38.2	209.8	33628.0	95.0	72.5	72.5	72.3	166.4	165.2	165.7
4506	38.2	279.4	44704.6	94.9	72.0	72.1	71.8	219.9	218.0	218.4
4505	38.2	348.9	55813.2	94.3	71.6	71.6	71.3	277.6	274.9	275.4
4987	42.3	32.5	5567.9	79.8	75.6	75.9	75.6	84.1	83.1	83.5
4993	42.3	62.9	11158.5	88.1	74.7	75.1	74.8	100.0	98.8	98.6
5002	42.4	125.8	22394.0	92.8	73.5	73.7	73.4	137.3	136.1	136.7
4997	42.4	188.9	33539.7	94.1	72.8	73.0	72.7	179.7	178.2	178.8
4996	42.3	251.6	44638.9	94.4	72.1	72.2	72.0	227.2	225.7	225.9
4991	42.3	314.4	55713.6	94.1	71.6	71.8	71.4	279.7	276.9	277.0
5502	46.6	28.6	5560.2	76.6	75.9	76.4	76.0	119.4	118.2	118.7
5500	46.6	57.3	11165.6	86.4	75.4	75.6	75.3	129.8	129.0	129.5
5502	46.6	114.8	22403.0	91.5	74.0	74.2	73.9	161.0	159.6	160.0
5505	46.7	170.9	33452.9	93.1	73.2	73.3	73.1	196.9	195.3	196.1
5503	46.6	229.0	44714.4	93.7	72.3	72.6	72.2	239.8	237.7	238.1
5500	46.6	285.6	55770.8	93.6	71.8	71.8	71.4	287.0	284.6	285.1
5998	50.8	26.5	5661.0	73.2	76.3	76.6	76.3	148.7	147.9	148.1
5998	50.8	52.4	11148.3	83.4	75.5	75.9	75.6	158.5	157.5	157.6
6002	50.9	104.8	22318.8	90.2	74.3	74.6	74.3	183.4	182.1	182.3
6001	50.9	157.7	33500.9	92.0	73.3	73.6	73.2	215.2	213.8	214.0
6003	50.9	209.2	44663.8	93.0	72.6	72.7	72.3	252.4	250.8	251.2
6001	50.9	261.7	55755.6	93.1	71.9	72.1	71.6	295.0	292.7	293.3

Table 2. Short-duration testing of Delphi series machine with 200 Vdc link (cont.)

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
6496	55.1	23.8	5608.8	69.2	76.4	76.8	76.4	174.1	172.9	173.4
6496	55.1	48.7	11289.1	81.6	75.6	76.0	75.6	182.5	181.2	181.7
6499	55.1	97.1	22421.1	88.4	74.5	74.9	74.4	203.8	202.4	203.0
6498	55.1	145.3	33475.0	90.6	73.5	73.9	73.4	231.9	230.3	230.7
6497	55.1	194.1	44722.4	91.9	72.7	73.0	72.5	265.6	263.7	264.1
6498	55.1	242.0	55809.5	92.3	71.9	72.1	71.6	304.9	302.6	303.0
6990	59.2	22.2	5603.4	66.6	76.5	77.0	76.6	195.6	194.2	194.7
6992	59.3	45.2	11217.7	78.3	75.8	76.2	75.8	203.3	202.0	202.6
6993	59.3	89.9	22260.5	86.5	74.7	75.1	74.6	222.2	220.7	221.3
6990	59.2	134.9	33455.2	89.4	73.8	74.1	73.6	247.5	245.8	246.3
6993	59.3	180.0	44645.8	90.6	72.9	73.1	72.6	278.2	276.4	276.8
6990	59.2	224.3	55724.0	91.4	72.1	72.3	71.8	314.1	311.9	312.4
7491	63.5	21.4	5613.3	62.2	76.5	77.0	76.6	213.6	212.2	212.8
7489	63.5	42.1	11191.8	75.9	75.8	76.3	75.9	220.4	218.9	219.4
7489	63.5	84.1	22337.7	84.8	74.8	75.2	74.7	237.1	235.5	236.2
7488	63.5	126.3	33503.3	88.4	73.8	74.2	73.7	259.8	258.1	258.5
7487	63.5	167.6	44627.7	90.0	73.0	73.3	72.7	287.8	285.8	286.4
7488	63.5	209.6	55715.2	90.7	72.0	72.2	71.7	322.1	319.9	320.3
7989	67.7	20.1	5628.2	59.2	76.8	77.3	76.8	227.6	226.2	226.8
7989	67.7	39.7	11265.2	73.8	75.8	76.4	75.8	234.4	232.8	233.5
7993	67.7	78.8	22367.9	83.1	74.9	75.2	74.7	249.7	248.4	248.9
7983	67.7	118.4	33544.2	86.8	74.0	74.3	73.7	270.7	269.1	269.8
7983	67.7	157.6	44581.6	89.1	73.0	73.3	72.8	296.6	294.6	295.1
7984	67.7	196.8	55757.3	89.8	72.0	72.2	71.6	329.5	327.4	328.0
8495	72.0	18.6	5685.0	55.8	76.6	77.2	76.6	242.1	240.7	241.3
8499	72.0	37.1	11140.0	70.7	75.9	76.5	75.9	247.7	246.3	246.7
8500	72.0	74.4	22428.8	81.5	75.0	75.5	74.9	262.4	260.8	261.3
8495	72.0	110.7	33410.0	85.7	74.0	74.4	73.8	282.0	280.2	280.9
8499	72.0	148.3	44629.4	87.7	73.1	73.5	72.8	306.7	304.7	305.3
8499	72.0	185.1	55816.6	89.2	72.0	72.1	71.5	337.7	335.3	336.0
8997	76.3	17.7	5601.8	51.7	76.4	76.9	76.6	256.7	255.3	255.8
9001	76.3	35.2	11247.0	68.0	75.9	76.6	76.0	261.3	259.9	260.5
9004	76.3	69.7	22277.2	80.1	74.9	75.4	74.9	274.6	273.1	273.6
8997	76.2	105.3	33564.4	85.0	73.8	74.4	73.6	293.4	291.8	292.1
9003	76.3	140.0	44741.4	87.1	72.9	73.1	72.6	317.0	315.1	315.4
9008	76.3	174.7	55877.5	88.0	72.0	72.4	71.7	345.4	343.2	343.6

Table 2. Short-duration testing of Delphi series machine with 200 Vdc link (cont.)

Rotor speed (rpm)	Speed (MPH)	Measured torque (Nm)	Mech. power (W)	Machine effic. (%)	Vrms A	Vrms B	Vrms C	Irms A	Irms B	Irms C
9485	80.4	17.3	5681.1	48.7	76.3	76.8	76.2	268.3	267.0	267.6
9491	80.4	33.8	11459.2	66.4	75.9	76.5	75.9	272.5	270.9	271.4
9489	80.4	67.3	22390.8	78.5	75.0	75.4	74.8	284.5	283.0	283.5
9493	80.5	99.6	33480.4	82.9	73.9	74.4	73.7	301.6	299.8	300.3
9491	80.4	132.9	44650.5	85.5	72.8	73.1	72.5	324.5	322.7	323.0
9490	80.4	166.3	55770.5	86.5	72.0	72.2	71.6	351.5	349.4	349.7
10003	84.8	15.6	5710.1	46.7	76.5	77.1	76.4	280.6	279.2	279.7
10003	84.8	32.2	11329.9	62.6	76.0	76.6	75.9	284.7	283.1	283.5
10004	84.8	62.8	22391.7	75.9	74.9	75.3	74.7	296.6	295.1	295.4
10006	84.8	94.4	33549.2	81.4	73.8	74.1	73.4	313.0	311.3	311.9
10008	84.8	125.4	44537.8	84.3	72.9	73.1	72.5	333.0	331.2	331.6
10008	84.8	157.1	55825.3	86.8	72.0	72.2	71.6	356.9	355.1	355.4
10490	88.9	15.5	5704.2	43.5	76.6	77.1	76.5	291.0	289.7	290.0
10498	89.0	30.2	11200.7	60.3	76.1	76.6	75.9	294.4	292.9	293.3
10495	88.9	60.3	22320.2	73.7	74.8	75.3	74.7	306.0	304.5	304.9
10496	89.0	90.3	33476.9	80.4	73.8	74.3	73.6	320.6	318.9	319.3
10501	89.0	119.1	44480.6	83.2	72.8	73.1	72.4	339.6	337.8	338.1
10498	89.0	149.7	55820.3	85.3	72.1	72.3	71.6	363.1	361.1	361.5
10974	93.0	14.1	5519.8	40.6	76.5	77.1	76.5	302.4	301.2	301.3
10978	93.0	28.9	11307.9	58.5	76.0	76.5	75.9	304.9	303.7	303.9
10990	93.1	57.1	22190.8	72.2	74.8	75.3	74.6	315.3	313.8	314.1
10990	93.1	85.6	33419.4	78.8	74.0	74.4	73.8	328.8	327.2	327.4
10990	93.1	114.4	44634.1	82.1	72.9	73.1	72.5	347.3	345.6	345.8
10992	93.2	142.5	55706.5	84.0	71.8	72.0	71.3	370.9	369.0	369.1
11505	97.5	13.7	5647.3	39.2	76.4	77.0	76.3	307.1	305.8	306.1
11514	97.6	27.3	11271.1	55.7	75.8	76.3	75.7	310.6	309.3	309.5
11516	97.6	54.7	22428.8	70.5	74.8	75.3	74.7	319.8	318.6	318.6
11521	97.6	82.4	33758.4	77.8	73.8	74.1	73.5	333.4	332.2	332.3
11526	97.7	109.8	44835.0	80.7	72.7	73.0	72.4	352.1	350.5	350.4
11524	97.7	136.6	55948.2	83.5	71.7	71.9	71.4	373.8	372.1	372.0
11990	101.6	12.9	5590.5	36.2	76.5	77.0	76.4	311.9	310.7	310.9
11995	101.7	26.5	11377.7	53.2	75.6	76.1	75.4	315.2	314.1	314.2
11998	101.7	52.9	22538.4	68.3	74.8	75.2	74.6	324.2	323.0	323.1
11999	101.7	78.6	33615.6	76.1	73.8	74.1	73.5	337.6	336.3	336.3
12005	101.7	104.9	44759.5	80.4	72.4	72.7	72.1	355.3	353.7	353.8
11991	101.6	131.0	55814.7	84.7	68.4	68.7	68.1	381.1	379.3	379.4

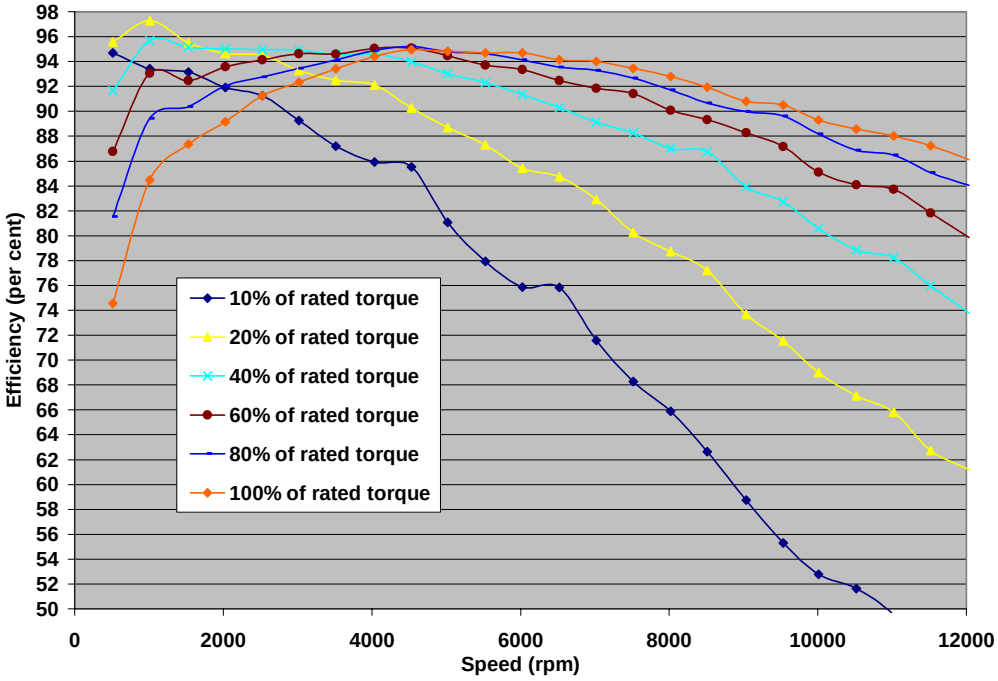

Fig. 2. Efficiency vs. load and speed with 325 Vdc link.

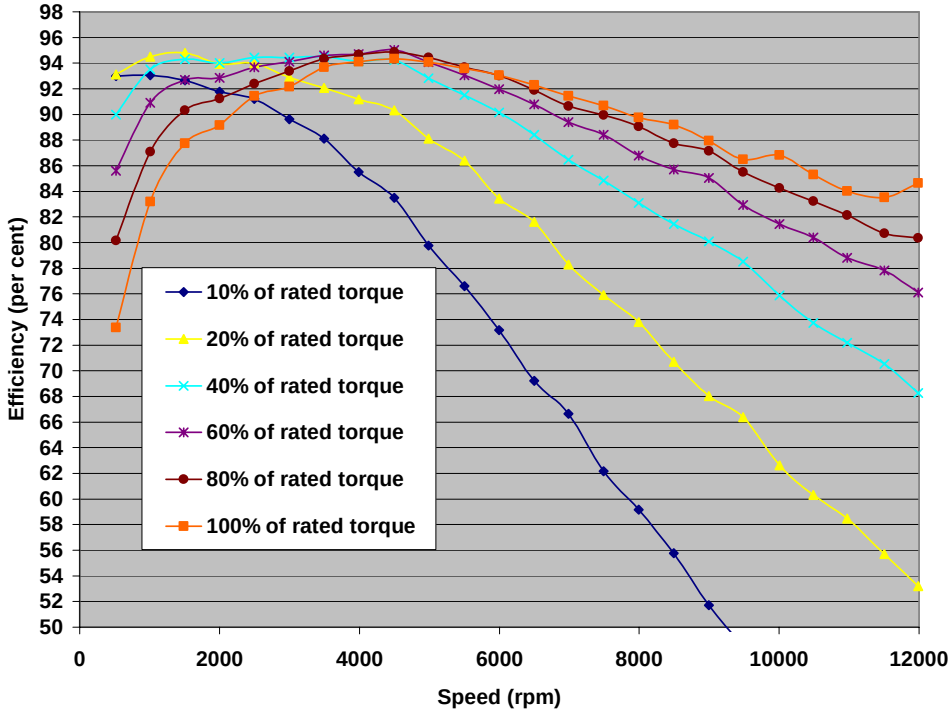

Fig. 3. Efficiency vs. load and speed with 200 Vdc link.

Continuous power tests were run at approximately 2630 rpm (22 mph) and 10,625 rpm (90 mph). The inlet coolant temperature was maintained at 70ºC during the continuous power tests. The machine was operated at 31.5 kW to compensate for the estimated efficiency of the final drive, 95%. Figure 4 shows a plot of the stator temperature vs. time during the continuous power test results for the machine. The stator temperature stabilized at 171ºC after 33.5 minutes of testing at 22 mph. The stator temperature was approximately 124ºC after 20.5 minutes of testing at 90 mph.

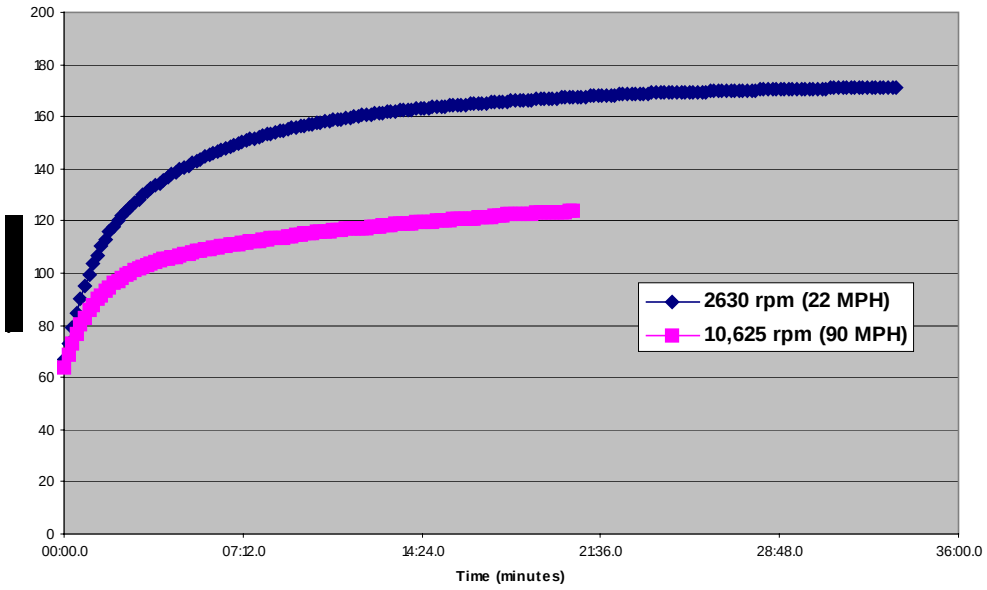

Fig. 4. Continuous power test.

The test data were measured and collected using a Yokogawa PZ4000 power meter and other dynamometer cell instrumentation.

4. SUMMARY OF FINDINGS

The deliverable series machine produced continuous and peak mechanical power from 3000 to 12,000 rpm with the minimal dc link voltage, 200 Vdc. The machine developed at least 596 Nm from approximately 500 to 2500 rpm during the tests with the minimal dc link voltage. The machine demonstrated efficiencies of ≥ 93% from 2997 to 6003 rpm with mechanical loads ≥ 30kW, and from 3500 to 6001 rpm with mechanical power levels ≥ 55kW with the minimal dc link voltage. The machine has slightly higher efficiencies when operated with a dc link voltage of 325 Vdc compared with 200 Vdc. At mechanical power levels of ≥ 55kW, the machine demonstrated efficiencies of ≥ 93% from 3511 to 7507 rpm and ≥ 90% from 2496 to 9528 rpm with a dc link voltage of 325 Vdc.

Table 3 lists speed ranges where the machine efficiency was greater than or equal to 93% and 90% with dc link voltages of 325 and 200 Vdc. From 3000 to 12,000 rpm, the machine is

operating at ≥ the continuous power level at 60% of rated torque and at ≥ the peak power levels at 100% of rated torque.

The deliverable series machine has a volume of 9.5 l and a mass of 38.9 Kg. The machine met the volume goal of 11 l, but had a mass of 3.9 Kg more than the 35 Kg goal. The specific power density goal is 1.57 kW/Kg and the deliverable series machine had a specific power density of 1.41 kW/Kg.

Table 3. Machine efficiency performance

Percent of rated torque (%)	dc link voltage (Vdc)	Efficiency ≥ 93% speed (rpm) range		Efficiency ≥ 90% speed (rpm) range	
		From	To	From	To
10	325	516	1532	325	2525
20	325	518	3023	518	4535
40	325	1034	5034	514	6529
60	325	2020	6033	1032	8017
80	325	3015	7025	1502	9042
100	325	3511	7507	2496	9528
10	200	521	1010	521	2498
20	200	515	2499	515	4506
40	200	1015	4509	514	6002
60	200	2501	5505	1011	6500
80	200	2997	6003	1506	7487
100	200	3500	6001	2499	7488

DISTRIBUTION

Internal

1. D. J. Adams
2. C. W. Ayers
3. C. L. Coomer
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6. L. D. Marlino
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8. S. C. Nelson

9–10. Laboratory Records

External

11. S. A. Rogers, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.
12. E. J. Wall, U.S. Department of Energy, EE-2G/Forrestal Building, 1000 Independence Avenue, S.W., Washington, D.C. 20585.