Radial Flux

LABORATORIES

Technical Paper

G102-20 Multi Pole Generator

Introduction

This paper examines the voltage regulation, torque & efficiency of the RFL G102-20 generator, using the results of testing conducted on 2 Feb 2010.

The G102-20 was designed using Finite Element Analysis (FEA) with a nominal rated output of 20 Kw at 186 RPM, giving an input torque of 1,100 Nm and an efficiency of 96%.

The test results of 2 Feb show that the G102-20 has an efficiency of 96.6% at an output of 21.390 Kw, 0.6% higher than its design specifications.

Test Results

Testing was conducted on 2 Feb 2010 to assist analysis of the voltage regulation, torque & efficiency characteristics of the RFL G102-20 (20kw).

To reflect design parameters the test was undertaken at a fixed rpm of 185. Thes results show and output of 21.390 Kw giving an efficiency of 96.6%, a 0.6% increase on design specifications.

The generator was then taken to a 232% overload of 46.76 Kw at a torque of 2,631 Nm. At this load the efficiency was 92.0%. once again exceeding design parameters.

Voltage Regulation of RFL Design

In a salient pole PM AC. generator (surface mounted magnets), the direct-axis synchronous reactance (*Xd)* and the quadrature-axis synchronous reactance (*Xq)*, are approximately equal [3]. The effect of this is that the reactance increases the voltage drop under load, giving an unacceptable voltage regulation under load.

In typical PM AC generators with buried magnets, *Xq* is greater than *Xd*. If the *Xq/Xd* ratio is large enough the generator can achieve zero or even negative voltage regulation at a specific load. [3]

Testing shows that the RFL design exhibits similar characteristic to those found in buried magnet type design, with a *Xq/Xd* ratio of aprox. 2.76.

The RFL generartor exhibits excellent RMS voltage regulation. This effect is called inverse salience [1,2]. The RMS voltage drop from no-load to full load (21 Kw) was 4.4%, or +- 2.2 %. This is fluctuation is well within the Australian standards of +- 5% RMS for line transmitted electricity.

This level of voltage regulation was only maintained up to the rated loads of 20 Kw. Once the generator was placed into overload the voltage regulating effects started to diminish as the load increased.

Torque efficiency:

Analysis was then undertaken to determine an explanation for the unusual torque load readings observed when the generator was in overload, over 21 Kw.

To establish the torque being used to produce output power and consumed internally to overcome losses, the no load torque had to be removed. The assumption is that the torque used to overcome the friction, winding & Iron loss will remain constant if the generator rpm is held constant over the load range. Table 2.1 Shows the Nm/Amp calculated after the removal of the no load torque figures. The Nm/Amp was plotted and the resulting graph (Fig. 9) shows a line trending down. Due to the constraints of the test rig (max power of the drive motor is 45kw) the upper limits of this attribute of the generator was not able to be determined..

The results show (table 1) that Nm/Amp remains fairly constant from 19.8 up to 29.4 Amps. As the load current increases from 29.4 to 143 Amps the Nm/Amp reduces to 18.139. This is an 8.4% drop in torque to produce the output power of 46.19kw. Further analysis was undertaken for a typical surface mounted PM AC generator with a constant Nm/Amp over the same output range (table 2.2). A comparison between the RFL and this generator was then undertaken (Table 2.1 and 2.2) looking at efficiency, losses & torque. It can be seen that the efficiency is 92.0% from the test generator at 46.19kw and only 83.3% for the comparison generator. This is an improvement of 8.7%.

An analysis of the losses of the two generators shows that losses for the RFL generator are 4,620 watts and the comparison generator are 9,274 watts this is 4,654 watts less or around 50% less losses. This results in the RFL generator having a requirement for 240 Nm less input torque for the same output power.

To determine the source of these significant improvements possible drivers were analysed starting with measuring the variation of flux within the air-gap. Flux variation in the air gap would evidence itself in an increase in output voltage with load. Additionally it would also show as increased iron losses, due to higher flux in the lamination iron.

The voltage, although increasing slightly at lower loads due to the inverse salient pole effect, did not show the levels of variation needed to account for the effect. The losses were also less than expected, this provides evidence that there is no increase in Iron losses.

The magnetic drag effect was then analysed Magnetic drag is where the magnetic flux is moved off centre as the load increases. In a normal PM generator (where the magnets are in the direct axis) this effect can cause demagnetization at the edges of the magnets and a drop in performance. In the RFL generator the magnets are in the quadrature axis and embedded between iron pole pieces. The magnetic centre can move without effecting the magnets. The magnetic centre can move up to 20 Electrical Deg and still not cause the demagnetization of the magnets, or a drop in performance.

If this effect is due to magnetic drag, then this should show up as a change in the phase voltage waveform under load. An oscilloscope was used and the waveforms observed under load conditions. The Phase waveforms observed are shown in Fig. 5 (No-load wave forms) and Fig. 6 (21 Kw waveforms) Fig. 7 (42 Kw waveform). The wave forms measured were the phase “A” wave form and the Phase “A” to “B” wave forms. As the windings are connected in star the Phase “A” to “B” is a summation of phase “A” and “B” at 120 Degrees. It can be observed that the Phase ”A” waveform under load distorts to one side, this is clear evidence of the magnetic flux moving off centre.

To determine the impact of the movement of magnetic flux on the performance of the generator analysis of the IXq current flow was undertaken. With the magnet flux on centre the IXq current has the effect of increasing the voltage output. As the flux moves off centre under heavy load, the maximum IXq current flows when the winding has passed the permanent magnet centre.

The effect of the movement of flux is to provide a boost of torque for the rotor in the direction of rotation. The test results highlight this is by a reduction in the driving torque required. The extra torque of 240 Nm is coming from the current flowing in the quadrature axis IXq. These results explain why the attributes of excellent voltage regulation fall away when the generator moves into overload levels of output at the same time as torque efficiency is improved.

This torque efficiency is the same effect observed in switched reluctance motors, where the iron in Xq axis of the rotor is used to deliver the torque to drive the motor. This effect causes eddy currents to flow in the rotor iron, but as the RFL design uses laminations in the rotor the eddy currents are very low.

Conclusion:

There are two effects being highlighted by the testing and the analysis undertaken.

The first is excellent voltage regulation from no load to full load. The voltage regulation is 1.94% at 11.5 Kw and a very good 5.24% at 24.5 Kw. This is due to the Xq/Xd ration being high (2.763), causing an inverse salience effect. [1, 2]

The second effect, torque efficiency, only becomes evident when the generator is in overload mode (17.0 Kw to 42 Kw). As the load current increases beyond 50 Amps the flux is dragged off centre and the inductive current IXq no longer helps to increase the voltage but starts to act as a driving force to assist the input driving force. This is reflected by a drop in the Nm torque required to produce a given output, and shows in a drop in the Nm/Amps ratio. The voltage regulation effect drops off as the torque efficiency increases The RFL design has both very good voltage regulation and exceptional overload efficiency, this along with large savings in weight and cost mean that design using the RFL principal will give much higher power to weight and higher efficiency. The RFL design works as a PM unit with a switched reluctance effect evident at high loads. This delivers exceptional overload performance. It also gives an exceptional torque to weigh ratio, in excess of 30Nm / kg for high torque applications. This is 1.5 better than any other designs currently being used.

References

[1] T.J.E. Miller *Brushless Permanent Magnet and Reluctance Drives.* Oxford Publications, 1989.

[2] B.J. Chalmers, “Performance of interior type permanent-magnet alternator,” *IEE-Proc. On elect. Power Applications*, Vol. 141, No. 4, July 1994, pp.186-190

[3] T.F. Chan, Lie-Ton Yan and L.L. Lai, *Analysis and Performance of a Three-phase A.C. Generator with Inset Permanent –magnet Rotor* Conference on Advances in Power System Control, Operation and Management (APSCOM 2000) October 2000, Hong Kong.

Appendix

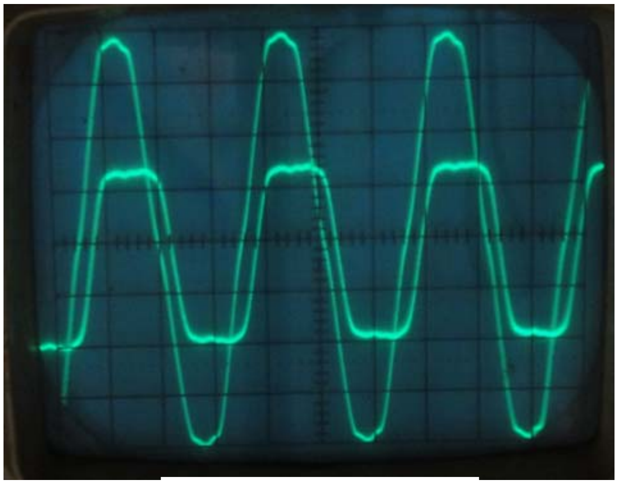


Fig. 5
No Load Waveform

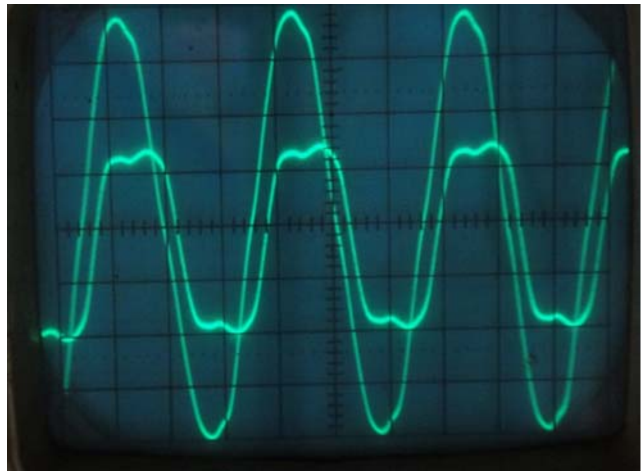


Fig. 6
20 Kw Waveform

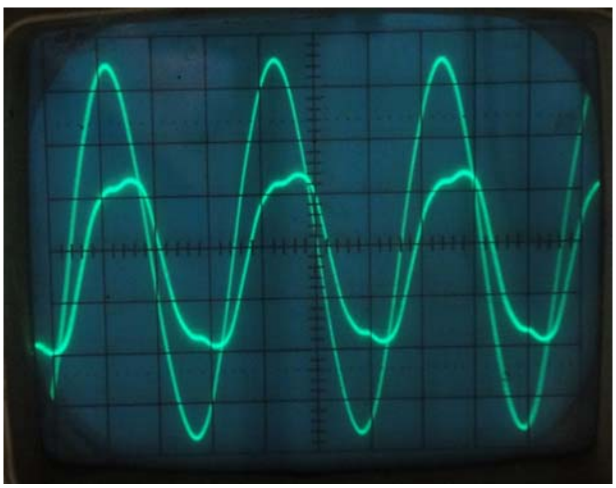


Fig. 7
40 Kw Waveform

Table 1

G102 185 RPM

GMI G102 20 Kw Generator Constant Speed test

Date =	02/02/10	Cold Wind Res =	0.12	Ohms
Amb Air =	25.0 Deg C	Test Rig Bearing loss Nm =	10	Nm
Test By =	Paul Lillington	*Current Error corr =	0.988	(VMS test)
				(Report 09.30287)

Read No		Run Time (min)	Power Out (Watts)	Amps	Volts	Freq	Force N	Corr Power Out (Watts)	Corr Amps	Torque Nm	RPM	Power In (Watts)	Loss (Watts)	Measured Efficiency
1		0.00	0.00	0.00	227.00	74.05	37.40	0.00	0.00	27.40	185.13	531.18	531.18	0.0%
2		3.00	3,913.00	10.05	225.50	74.02	234.20	3866.04	9.93	224.20	185.05	4,344.64	478.59	89.0%
3		6.00	7,835.00	20.09	225.30	74.42	431.70	7740.98	19.85	421.70	186.05	8,216.03	475.05	94.2%
4		9.00	11,471.00	29.76	222.60	74.04	620.20	11333.35	29.40	610.20	185.10	11,827.89	494.54	95.8%
5		12.00	18,167.00	47.86	219.00	74.01	968.30	17949.00	47.29	958.30	185.03	18,567.80	618.81	96.7%
6		15.00	21,390.00	56.94	216.90	73.93	1140.30	21133.32	56.26	1130.30	184.83	21,876.76	743.44	96.6%
7		18.00	24,360.00	65.31	215.10	74.02	1294.20	24067.68	64.53	1284.20	185.05	24,885.73	818.05	96.7%
8		21.00	27,270.00	73.93	213.00	74.06	1453.80	26942.76	73.04	1443.80	185.15	27,993.64	1050.88	96.2%
9		24.00	30,030.00	82.35	210.60	74.01	1605.10	29669.64	81.36	1595.10	185.03	30,906.30	1236.66	96.0%
10		27.00	34,980.00	98.18	205.60	74.00	1880.10	34560.24	97.00	1870.10	185.00	36,229.74	1669.50	95.4%
11		30.00	37,200.00	105.81	202.90	74.00	2008.10	36753.60	104.54	1998.10	185.00	38,709.50	1955.90	94.9%
12		33.00	39,300.00	113.20	200.20	74.04	2125.20	38828.40	111.84	2115.20	185.10	41,000.25	2171.85	94.7%
13		36.00	41,130.00	120.24	197.45	74.02	2236.20	40636.44	118.80	2226.20	185.05	43,140.17	2503.73	94.2%
14		39.00	42,640.00	126.00	193.95	73.79	2334.80	42128.32	124.49	2324.80	184.48	44,910.90	2782.58	93.8%
15		42.00	45,630.00	138.93	189.60	74.11	2554.10	45082.44	137.26	2544.10	185.28	49,360.51	4278.07	92.4%
16		45.00	46,760.00	144.74	186.51	74.05	2631.40	46198.88	143.00	2621.40	185.13	50,819.10	4620.22	92.0%

= Rated Output

7% Voltage drop under load + - 3.5% Regulation

*Values adjusted down to reflect the results of the NATA calibration of the current sensing resistors

Table 2.1

GMI 20 Kw GENERATOR TEST RESULTS (From dyno test)

Read No	Corr Power Out (Watts)	Corr Amps	Torque Nm	Nm/Amp	RPM	Power In (Watts)	Loss (Watts)	Measured Efficiency
1	0.00	0.00	27.40		185.13	531.18	531.18	0.0%
2	3,866.04	9.93	224.20	19.8199	185.05	4,344.64	478.59	89.0%
3	7,740.98	19.85	421.70	19.8651	186.05	8,216.03	475.05	94.2%
4	11,333.35	29.40	610.20	19.8212	185.10	11,827.89	494.54	95.8%
5	17,949.00	47.29	958.30	19.6867	185.03	18,567.80	618.81	96.7%
6	21,133.32	56.26	1130.30	19.6048	184.83	21,876.76	743.44	96.6%
7	24,067.68	64.53	1284.20	19.4773	185.05	24,885.73	818.05	96.7%
8	26,942.76	73.04	1443.80	19.3914	185.15	27,993.64	1050.88	96.2%
9	29,669.64	81.36	1595.10	19.2683	185.03	30,906.30	1236.66	96.0%
10	34,560.24	97.00	1870.10	18.9965	185.00	36,229.74	1669.50	95.4%
11	36,753.60	104.54	1998.10	18.8511	185.00	38,709.50	1955.90	94.9%
12	38,828.40	111.84	2115.20	18.6675	185.10	41,000.25	2171.85	94.7%
13	40,636.44	118.80	2226.20	18.5089	185.05	43,140.17	2503.73	94.2%
14	42,128.32	124.49	2324.80	18.4548	184.48	44,910.90	2782.58	93.8%
15	45,082.44	137.26	2544.10	18.3349	185.28	49,360.51	4278.07	92.4%
16	46,198.88	143.00	2621.40	18.1395	185.13	50,819.10	4620.22	92.0%

Table 2.2

Typical Surface mounted PM 20 Kw AC GENERATOR (Constant Nm/Amp)

Read	Constant Nm/Amp Efficiency	Nm for Constant Nm/Amp	Loss (Watts)	Power In For Constant Nm/Amp
1				
2	89.0%	224.20	478.59	4,344.64
3	94.4%	420.80	457.59	8,198.57
4	95.8%	610.16	493.82	11,827.17
5	96.0%	964.60	740.85	18,689.85
6	95.6%	1,142.40	977.72	22,111.04
7	95.1%	1,306.31	1,246.43	25,314.11
8	94.2%	1,475.10	1,657.83	28,600.59
9	93.4%	1,639.99	2,106.34	31,775.98
10	91.5%	1,949.97	3,216.82	37,777.06
11	90.4%	2,099.38	3,918.03	40,671.63
12	89.3%	2,244.09	4,670.25	43,498.65
13	88.0%	2,381.95	5,521.93	46,158.37
14	87.4%	2,494.74	6,065.57	48,193.89
15	84.6%	2,747.94	8,232.96	53,315.40
16	83.3%	2,861.71	9,278.96	55,477.84

Fig. 8

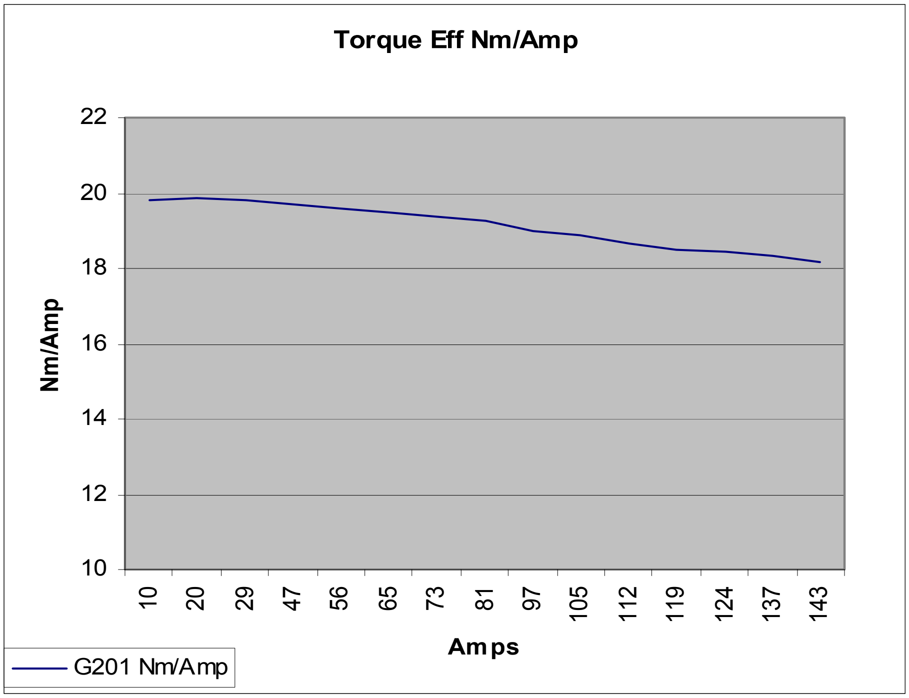
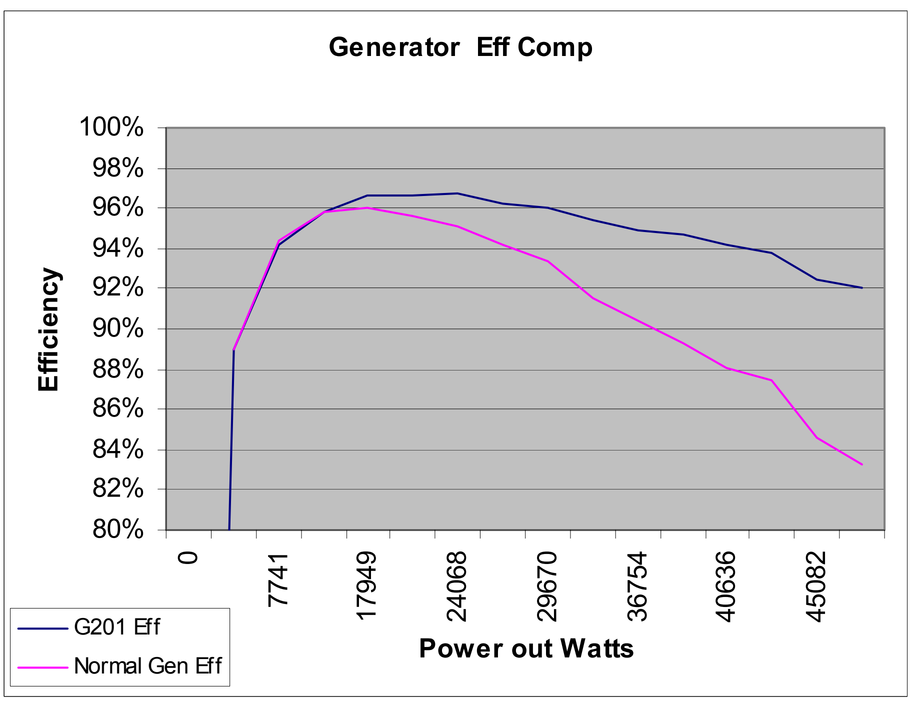

Torque Eff Nm/Amp
22
20
18
16
14
12
10
Nm/Amp
10
20
29
47
56
65
73
81
97
105
112
119
124
137
143
Amps
G201 Nm/Amp

Fig. 9


Generator Eff Comp
100%
98%
96%
94%
92%
90%
88%
86%
84%
82%
80%
Efficiency
0
7741
17949
24068
29670
36754
40636
45082
Power out Watts
G201 Eff
Normal Gen Eff