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Test And Evaluation Of DC Power Supplies In High-Frequency AC Microgrids

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Abstract: A 600Hz single phase High Frequency AC microgrid has been proposed to integrate the renewable source and load. In order to test the functions and evaluation the performance of DC power supply in this new 600Hz system, two types of DC power supply, the linear rectifier power supply and switch mode DC power supply, were tested and evaluated in this paper. The test method and experiment results of line regulation and/or load regulation, dynamic characteristics, heat, noise, inputs power factor, efficiency, input harmonics of DC power supply are provided. The analysis and explanation are given. Both types of DC power supply can not only function successfully when directly connected to a 600 Hz AC source, but can have superior performance and higher efficiency operating in a 600Hz than 60Hz system.

Keywords: Distributed generation, Microgrids, DC power supply

I. INTRODUCTION

Distributed generation (DG) has been considered as a promising alternative for the coordinated and flexible expansion of the present energy distribution system with reduced cost and improved reliability[1]. Distributed Generation is a small-scale electric power source connected directly to the utility's distribution network or on the customer site of the meter, and it provides electric power at a site closer to customers than the central station generation. The capacity scale of DG typically ranges from 1 KW to 50 MW. DG provides a multitude of services to utilities and consumers, including standby generation, peak shaving capability, base-load generation, or cogeneration. For businesses, DG can reduce peak demand charges, reduce overall energy use, ensure greater power quality and reliability, and reduce emissions. For large utilities and power producers, DG can augment overall system reliability, avoid large investments in transmission system upgrades, reduce transmission losses, closely match capacity increases to demand growth, and open markets in remote or environmentally constrained areas. Given continued technological and technical advances, Distributed Generation can provide economic and environmental benefits well into the 21st century[2].

Various technologies are available for DG, including turbine generators, internal combustion engine/ generators, micro-turbines, photovoltaic/solar panels, wind turbines, and fuel cells. These small modular generation technologies interconnected to distribution systems can form a new type of power system, the microgrid[1]. The microgrid concept is a big step towards solving the controllability problems of distributed resources. In a microgrid, a cluster of loads and microsources operate as a single controllable system to provide power and heat in their local area. Power electronic converters are very important for the Microgrid. Most of microsources must be power electronic based to provide required flexibility to insure operation as a single aggregated system. In order to optimize system structure, a high-frequency AC link[4,5]has been used as the power electronic interface to achieve better utilization of the microgrid[3]. Single-phase 600 Hz high-frequency AC (HFAC) microgrids are considered to be used to combine the renewable sources with the loads and the grid in this project.

In high frequency AC microgrid systems, DC power supplies should function normally when plugged into a power socket. The questions to be addressed in this paper is, "Can the present-day DC power supplies now manage to function properly with frequencies over 60 Hz?" "How about the performance of these devices when operating under different frequencies?"

In this paper two types of DC power supplies, the linear rectifier power supply and the switched mode DC power supply, are tested and evaluated in this paper. The configuration and specification of two types of DC power supply are provided in Section II. In Section III, the line regulation and/or load regulation, dynamic characteristics, heat, noise, input power factor, efficiency, input harmonics of linear rectifier power supply in 600Hz HFAC system are tested and explained. The experiment tests of static performance and dynamic characteristic of switch mode DC power supply system are evaluated in Section IV. Final conclusions are presented in Section V.

II. THE TWO TYPES OF DC POWER SUPPLY

There are mainly two types of DC power supply commonly used in the home. The first version is a linear rectifier power supply and the other type is the switched mode DC power supply. Two commercial DC power supplies have been tested. One was a YAMAHA 525AV4309 linear rectifier power supply for audio amplifier, which will be called TYPE I in this paper. The other is a Compaq PPP014S switched mode DC power supply for laptop computers. Compaq PPP014S will be called TYPE Ⅱ. The rated input and output is shown in Table 1.

Table 1. Rated Input and Output

DC Power Supply		INPUT		OUTPUT	
		Voltage	Current	Voltage	Current
I	YAMAHA 525AV4309	120 V	0.18 A	14 V	800 mA
Ⅱ	Compaq PPP014s	100~240 V	2.4 A	18.5 V	4.9 A

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The configuration of a TYPE Ⅰ power supply is shown in Fig. 1.

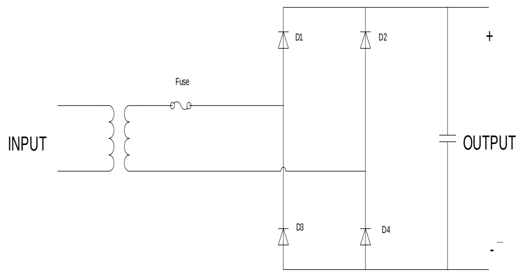

Fig 1. Topology of TYPE I DC power supply.

The diodes D1, D2, D3 and D4 used in the TYPE Ⅰ supply were 1N5407. The simplified topology of TYPE Ⅱ is illustrated in Fig. 2 and the model of power electronics device used are listed in Table 2. Diodes D1, D2, D3, D4 is an integrated bridge rectifier GBU608. D5 is in reality four parallel diodes.

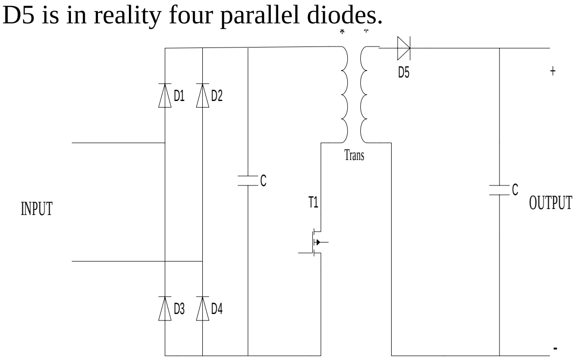

Fig 2. Simplified Topology of TYPE Ⅱ DC power supply.

Table 2 Device used in TYPE Ⅱ DC power supply

Device	Model
D1,D2,D3,D4	GBU608
T1	11N60C3
D5	STPS20H100CT

In addition to the desired 600 Hz, the power supplies were also tested operating at three other frequencies, 50 Hz, 60 Hz and 400 Hz. The values of 50 and 60 Hz, are commonly used as the base frequency of power systems while 400 Hz is usually employed in aircraft. The frequency variable AC power source used in the test was Pacific 345-ASX. The list of test equipment is:

Multimeters: Fluke 8050A
Fluke 79III
Power Analyzer: Voltech PM300
Thermometer: Lutron TM-909
Osclloscope: Agilent 54624A
Sound Level Meter: Simpson 886

III. TEST RESULTS OF LINEAR RECTIFIER POWER SUPPLY

(1) Load Regulation

The load characteristics of TYPE I is as presented in Fig. 3. The abscissa is the ratio of the actual DC output current to the rated DC output current in percentage. The ordinate is the DC output voltage in Volts. The test results at different frequencies are shown in points of different color as in the legend. The trend lines of the characteristics at the four frequencies are of different colors, which is also illustrated in the legend. All similar figures in the report will use the same color designation.

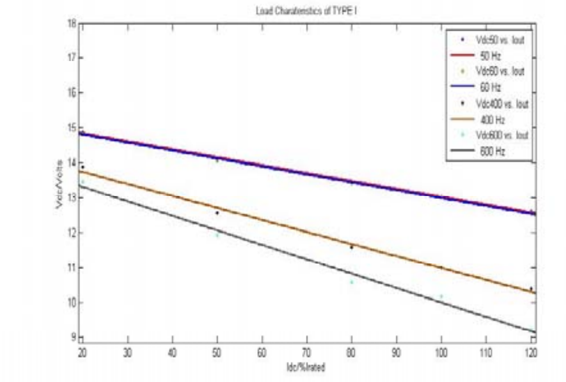

Fig 3. Load Characteristics of TYPE Ⅰ DC power supply.

The load regulation is calculated by the following equation:

$$\text{Load Regulation}=\frac{(V_{out}-V_{out\_rated})}{V_{out\_rated}}\times 100\% \quad (1)$$

In (1), V_{out} is the actual DC output voltage and V_{out_rated} is the output voltage at rated current under certain input frequency. The load regulation of a TYPE Ⅰ power supply is shown in Table 3.

Table 3. Load Regulation of TYPE Ⅰ

	Load Regulation				
Frequency	20%Ir	50%Ir	80%Ir	100%Ir	120%Ir
50 Hz	14.19%	8.28%	3.35%	0.00%	-3.27%
60 Hz	14.17%	8.10%	3.28%	0.00%	-3.46%
400 Hz	26.18%	14.20%	5.49%	0.00%	-5.55%
600 Hz	32.48%	17.39%	4.10%	0.00%	-9.29%

From Fig. 3, it can be seen that the output voltage of a TYPE I supply reduces substantially as the input frequency goes up. The output voltage at rated output current under 600 Hz is nearly 3 volts less than the output under 50 Hz. The load regulation also becomes poorer as the input frequency increase. However, the load of DC power supply, which is YAMAHA audio amplifier still functions very well at 400Hz and 600Hz.

(2) Analysis of Voltage Reduction of the Linear Power Supply

To explain the reason of the reduction of the output voltage, the transformer of TYPE I DC power supply is tested separately. The results are shown in Table 4. From Table 4, when the secondary side current is set to a value near rated current, the secondary voltage does not drop substantially. Therefore, the output voltage drop of TYPE I mainly suffer from the increase of forward voltage of the diodes. In addition to the

Table 4. Test of transformer of TYPE I

Freq/Hz	Vpri/V	Ipri/mA	Ppri/w	Vsec/V	Isec/A	P.F.pri	Psec/w	Efficiency
50	109.99	150.88	13.412	11.23	0.9	0.808	10.107	75.36%
60	110.02	124.36	12.951	11.28	0.9	0.948	10.152	78.39%
400	109.95	109.61	11.732	11.13	0.9	0.973	10.017	85.38%
600	109.98	108.94	11.397	10.87	0.9	0.951	9.783	85.84%

conclusion above, the power factor and efficiency of the transformer are much better at 400 and 600 Hz.

(3) Dynamics Characteristics

The dynamics characteristics of the TYPE I power supply when the input voltage is 110 volts and the output current is at its rated value (800 mA) are shown in Fig4~ Fig.7. Channel 1 is the input AC voltage that is reduced to 1/200 of its real value. Channel 2 is the output DC voltage that is reduced to 1/50 of the real value.

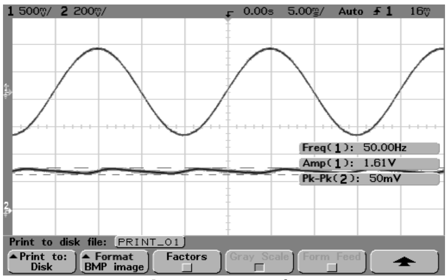

Fig 4.Dynamics characteristics of TYPE I at 50 Hz.

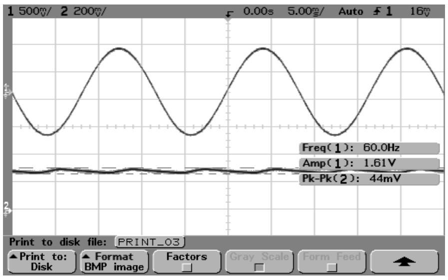

Fig 5.Dynamics characteristics of TYPE I at 60 Hz.

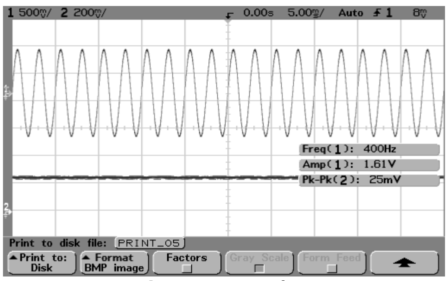

Fig 6. Dynamics characteristics of TYPE I at 400 Hz.

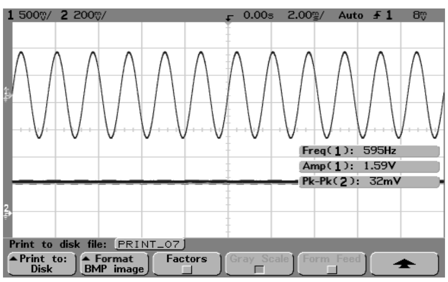

Fig 7. Dynamic characteristics of TYPE I at 600 Hz.

It can be concluded that the ripple of the output voltage decreases with a high input frequency. When operating at 400 Hz, the ripple was found to be the smallest.

(4) Heat

The heat of the power supplies is measured by the temperature degree in this test. The temperature becomes stable after 30 minutes. Figure 8 shows the temperature of TYPE I's diodes:

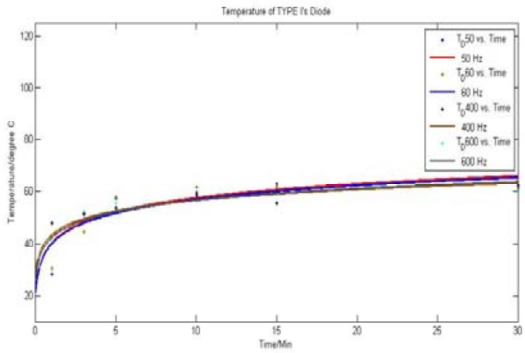

Fig 8. Temperature of TYPE I's diodes in degrees C.

Figures 9 and 10 show the temperature of transformer's windings and core, respectively:

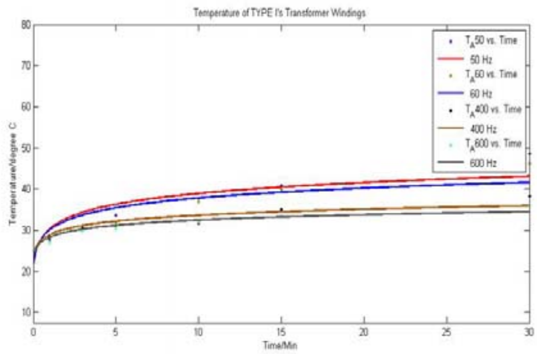

Fig 9. Temperature of TYPE I's transformer windings.

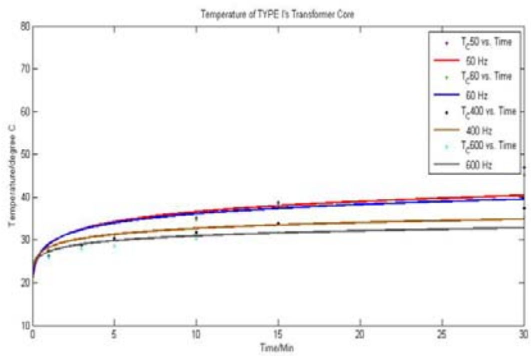

Fig 10. Temperature of TYPE I's Transformer Core.

The figure is interpreted similarly as explained in Section III (1). The different colored represent the test results at different frequencies. In Fig. 8, the temperature of the diodes is slightly higher as the input frequency goes up. In contrast, the temperature of both the windings and the core of the transformer reduces when the frequency increase. This is because that the core is less saturated when the frequency is higher, as a result the losses is less. It can be expected that when designing a transformer that will be used under 600 Hz, the volume of the core can be substantially reduced.

(5) Noise

The sound level is tested when the DC power supply on and off. For the small DC power supply tested, there is no detectable difference when the power supply is turned on.

(6) Input Power Factor

When the output voltage is set to 110 V and the output current varied, the power factor is similar when the power supply operates under different frequencies. The power factor also increases as the load current becomes larger. The test results are shown below in Table 5. I_{out_r} means rated output current.

Table 5. Power Factor of TYPE I at Rated Input Voltage

Freq./Hz	Input Power Factor				
	20% Iout_r	50% Iout_r	80% Iout_r	100% Iout_r	120% Iout_r
50	0.404	0.596	0.700	0.743	0.774
60	0.650	0.748	0.786	0.804	0.818
400	0.795	0.804	0.809	0.810	0.810
600	0.793	0.798	0.796	0.791	0.785

(7) Efficiency

Table 6 is the results of the efficiency calculation at rated output current.

Table 6. Efficiency of TYPE I at Rated Current.

Freq./Hz	Eff
50	66.26%
60	68.64%
400	73.34%
600	73.01%

The efficiency increases as the input frequency goes up except that the efficiency at 600 Hz is somewhat lower than that at 400 Hz. From Table 4, the efficiency of the transformer is higher at 600 Hz; the abnormal decrease is the result of the increase of the losses of the power diode.

(8). Input Harmonics

The total harmonic distortion at rated output current is test and listed in Table 7.

Table 7. THD at Rated Output Current.

Freq./Hz	THD
50	0.313%
60	0.166%
400	0.495%
600	0.272%

The harmonics varies a lot during the test, and does not show a clear trend. This may come from the AC source.

IV. Test Results of Switched Mode DC Power Supply

(1). Line Regulation

Due to the limit of the voltage output of the frequency variable AC power supply (Pacific 345-ASX). The range between 90 and 135 Volts is used for the input voltage in the line regulation test.

The power supply is tested when the output current is set to the rated value (4.5 A) and the input voltage varies over the range stated above. The line characteristics are plotted below in Fig. 11. Similar to the figure before, test results and trend lines at different frequencies is represented by different color points and lines as stated in the legend. The abscissa is the input AC voltage and the ordinate is the DC output voltage.

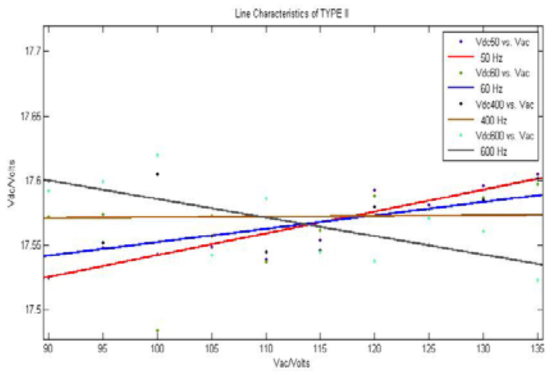

Fig 11. Line characteristics of TYPE II DC power supply.

By using (2), the line regulation can be calculated. V_{out_rated} is the output voltage when the input is 110 V. The results of the calculation are listed in Table 8.

$$\text{Line Regulation} = \frac{(V_{out} - V_{out\_rated})}{V_{out\_rated}} \times 100\% \quad (2)$$

Table 8 Line Regulation of TYPE II.

Freq./Hz		50	60	400	600
Line Regulation	90 V	-0.08%	0.02%	0.31%	0.03%
	135 V	0.38%	0.34%	0.32%	-0.36%

Because of the existence of the closed loop control of TYPE II, the line regulation is very good and does not change as the input frequency varies.

(2). Load Regulation

TYPE II's load characteristics are shown below in Fig. 12, the figure can be interpreted in the same manner.

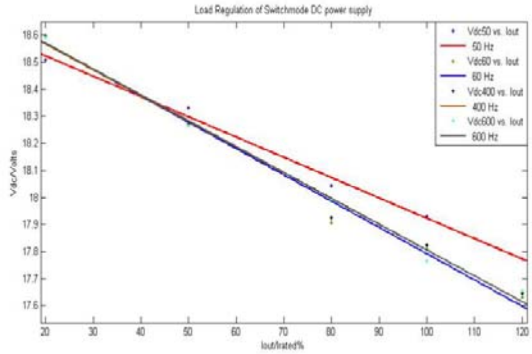

Fig 12. Load characteristics of TYPE II DC power supply.

Using (1), the load regulation can again be calculated. The results are listed in Table 9.

Table 9. Load regulation of TYPE II.

	Load Regulation				
Frequency	20%Ir	50%Ir	80%Ir	100%Ir	120%Ir
50 Hz	3.22%	2.23%	0.61%	0.00%	-0.89%
60 Hz	4.42%	2.59%	0.54%	0.00%	-1.01%
400 Hz	4.35%	2.49%	0.57%	0.00%	-1.00%
600 Hz	4.66%	2.81%	1.28%	0.00%	-0.62%

The load regulation is much better than that of TYPE I. This result is clearly because of the closed loop controller employed.

(3). Dynamic Characteristics

The same as in the test of TYPE I, the dynamics characteristics of TYPE II when the input voltage is 110 volts and the output current is at its rated value (4.9 A) are shown in Figures 13 to 16. Channel 1 is the input AC voltage that is reduced to 1/200 of its real value. Channel 2 is the output DC voltage that is reduced to 1/50 of the real value.

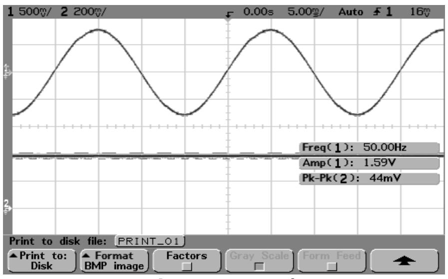

Fig 13. Dynamics characteristics of TYPE II at 50 Hz.

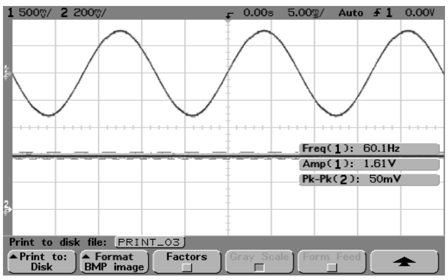

Fig 14. Dynamics characteristics of TYPE II at 60 Hz.

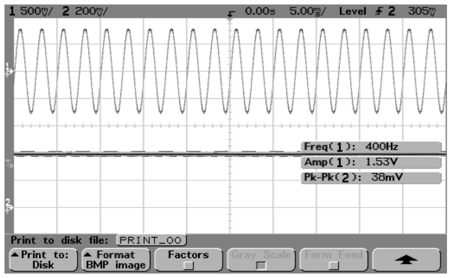

Fig 15. Dynamics characteristics of TYPE II at 400 Hz.

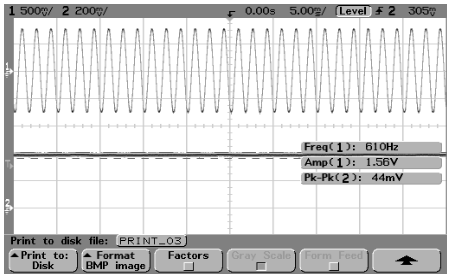

Fig 16. Dynamics characteristics of TYPE II at 600 Hz.

From Fig. 13 to Fig. 16, it can be concluded that the ripple of the output voltage for TYPE II is almost the same level when the frequency varies.

(4). Heat

As can be seen from the configuration of TYPE II (Fig. 2), the working frequency of the right part (including T1, D5 and the high frequency transformer) does not change when the input frequency varies. Therefore, the test of temperature only tests the power supply with a focus on the bridge rectifier. Figure 17 shows the results.

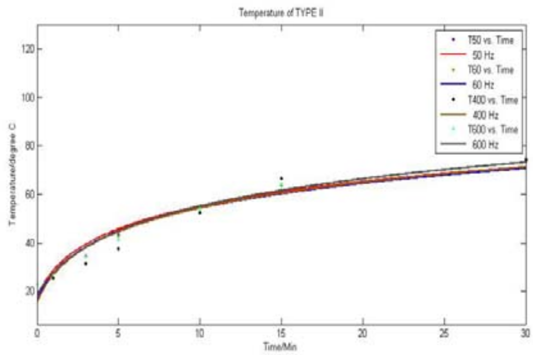

Fig 17. Temperature of TYPE II DC power supply.

Similar to the diodes of TYPE I, the temperature of the bridge rectifier is slightly higher when the frequency is higher. But the difference is not very evident.

(5). Noise

The same as in the test of TYPE I, the sound level is tested when the DC power supply on and off. There is no detectable difference in sound level when the power supply is turned on for any of the frequencies.

(6). Input Power Factor

When the output voltage is set to 110 V and the output current varied, the power factor is higher when operating at 400 Hz and 600 Hz. The power factor also increases as the load current becomes larger. The test results are shown below in Table 10. The quantity I_{out_r} represents rated output current.

Table 10. Power factor of TYPE II.

Freq./Hz	Input Power Factor				
	20% Iout_r	50% Iout_r	80% Iout_r	100% Iout_r	120% Iout_r
50	0.429	0.504	0.547	0.56	0.577
60	0.422	0.49	0.534	0.546	0.563
400	0.467	0.549	0.584	0.594	0.608
600	0.448	0.564	0.605	0.617	0.631

(7). Efficiency

The efficiency of TYPE II is listed in Table 11 below:

Table 11. Efficiency of TYPE II

Freq./Hz	Eff
50	84.94%
60	84.83%
400	83.78%
600	84.40%

The efficiency at 50 and 60 Hz is slightly higher which is because the efficiency of the rectifier at low frequency is a little higher.

(8). Input Harmonics

The total harmonic distortion of TYPE II at rated output current is test and listed in Table 12.

Table 12. THD at rated output current.

Freq./Hz	THD
50	0.703%
60	0.787%
400	0.936%
600	1.179%

The THD clearly increases when the input frequency becomes higher. However, this effect may due to the AC source itself.

V. Conclusion

In 600Hz High Frequency AC microgrid system, two typical kinds of DC power supply, linear rectifier power supply and switch mode DC power supply, were tested and evaluated. The experiments results of line regulation and/or load regulation, dynamic characteristics, heat, noise, input power factor, efficiency, input harmonics of the DC power supply were given. Both types of DC power supply can operate successfully when directly connected to a 600 Hz AC source. Moreover it is shown that they have superior performance and higher efficiency in a 600Hz than 60 Hz system.

For TYPE I- linear rectifier power supply, due to the increase in the forward voltage of diodes, the output voltage of TYPE I drops substantially. The load regulation suffers, also as a result. However, the converter still works satisfactorily even at 600 Hz. The ripple of the output voltage is decreased with the use of a high input frequency. The diodes in the power supplies generate more heat and their losses are larger at the higher frequencies. The heat of transformer reduces when the input frequency becomes higher which also means that the volume of the transformer can be reduced if it is designed to work at 600 Hz rather than 60 Hz. The power factor TYPE I is similar when the input frequency varies. The efficiency of TYPE I is higher at higher input frequency. It is suggested that the efficiency and load regulation of linear rectifier power supply will be further improved with high frequency power diodes, the price of which is almost the same as the price of 60Hz power diodes.

For TYPE II-switched mode DC power supply, similar line regulation and load regulation is obtained at different input frequencies because of the closed loop controller. The ripple of the output voltage is almost the same level at all different input frequencies. The power factor of TYPE II goes up as the input frequency increase. The efficiency of TYPE II is similar at different frequencies. This result suggests that the performance of switched mode DC power supply are will not change with a input frequency increase, and that the power factor will be higher at high frequency.

Acknowledgment

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