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DEVELOPMENT OF SOFTWARE TO IMPROVE A.C. POWER QUALITY ON LARGE SPACECRAFT

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NOMENCLATURE

AC	Alternating current
[A]	Matrix A
$A^{(i)}$	The i^{th} harmonic component of A
ΔA	The change in A
α	Delay angle on a rectifier
c	Real component of a complex Fourier coefficient
C	Capacitance
d	Imaginary component of a complex Fourier coefficient
DC	Direct current
f	Frequency
f(t)	Time varying function
I	Current magnitude
j	$(-1)^{0.5}$
[J]	Jacobian matrix
L	Inductance
ω	Imaginary component of a complex frequency
P	Real power
Q	Reactive volt-ampere
R	Resistance
SCR	Silicon controlled rectifier
THD	Total harmonic distortion
τ	Time constant
T	Period of a sinusoidal waveform
θ	Phase angle
V	Voltage magnitude
V(t)	Voltage in the time domain

1. Introduction

To insure the reliability of a 20 kHz, AC power system on spacecraft, it is essential to analyze its behavior under many adverse operating conditions. Some of these conditions include overloads, short circuits, switching surges, and harmonic distortions. Harmonic distortions can become a serious problem. It can cause malfunctions in equipment that the power system is supplying, and, during extremely distortions such as voltage resonance, it can cause equipment and insulation failures due to the extreme peak voltages.

To address the harmonic distortion issue, work was begun under the 1990 NASA-ASEE Summer Faculty Fellowship Program. Software, originally developed by EPRI, called HARMFLO, a power flow program capable of analyzing harmonic conditions on three phase, balanced, 60 Hz, AC power systems, was modified to analyze single phase, 20 kHz, AC power systems. Since almost all of the equipment used on spacecraft power systems is electrically different from equipment used on terrestrial power systems, it was also necessary to develop mathematical models for the equipment to be used on the spacecraft. The modelling was also started under the same fellowship work period. Details of the modifications and models completed during the 1990 NASA-ASEE Summer Faculty Fellowship Program can be found in a project report [1].

As a continuation of the work to develop a complete package necessary for the full analysis of spacecraft AC power system behavior, development work has continued through NASA Grant NAG3-1254. This report details the work covered by the above mentioned grant.

2. Operation of a Voltage Controlled, Full Wave Rectifier

The voltage controlled, full wave rectifier which is presently designated for use on spacecraft power systems is shown in Figure 1. This is the voltage controlled rectifier that was modelled under this grant. The output voltage waveform produced by the rectifier in Figure 1 is shown in Figure 2.

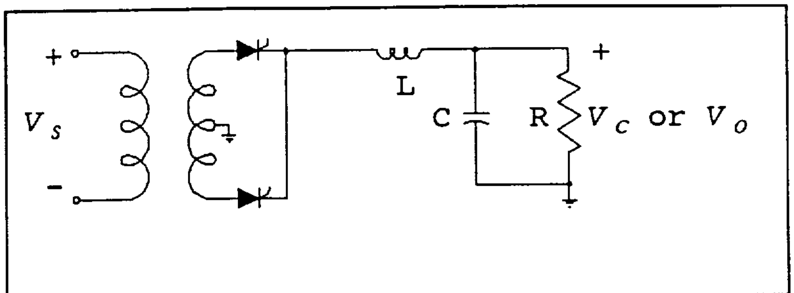

Figure 1 - Voltage Controlled, Full Wave Rectifier

Maximum DC output voltage is achieved when the firing angle, α, (i.e., the electrical angle at which the SCR is gated) is at a minimum. This angle is the point in time when the capacitor voltage, V_C, drops below the magnitude of the input source voltage, V_S. This point is the same operating point that would be obtained if the SCR were replaced by a standard diode (i.e., making it an uncontrolled, full wave rectifier). The output voltage of the rectifier can be controlled to a value lower than the uncontrolled value by delaying the firing angle. The firing angle is defined by

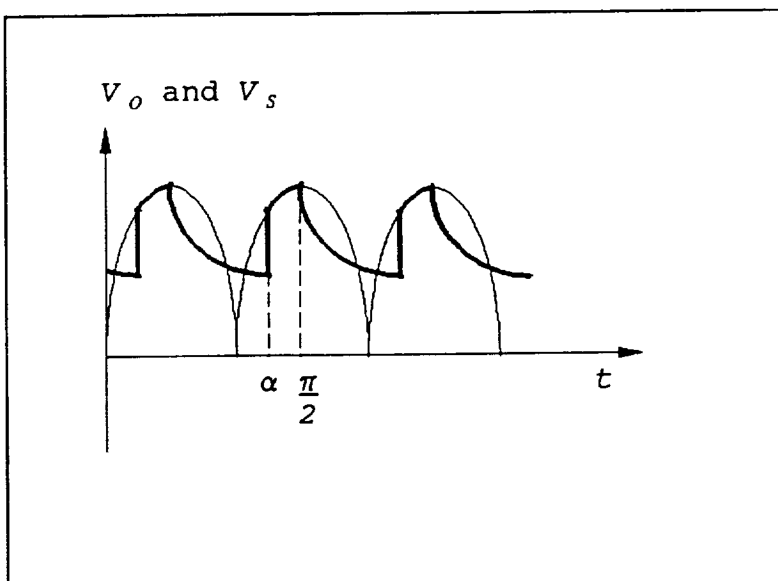

Figure 2 - Output Voltage Waveform of a Voltage Controlled, Full Wave Rectifier

$$\alpha_{min}\ (\textit{the uncontrolled value}) \leq \alpha \leq \frac{\pi}{2} \ .$$

3. Modelling of a Voltage Controlled, Full Wave Rectifier

To model a voltage controlled, full wave rectifier, it is first necessary to determine α. In order to find the value of α that will produce a fixed output voltage, it is essential to understand the role that α plays in determining the output voltage.

The first step is to divide the output waveform into two sections,

$$V(t) = V_p e^{-\frac{(t-\frac{\pi}{2\omega})}{RC}} \quad for \ \frac{\pi}{2\omega} \le t \le \frac{\alpha}{\omega} \, ,$$

and

$$V(t) = V_p \sin(\omega t - \alpha) \quad for \ \frac{\alpha}{\omega} < t \le \frac{2\pi}{\omega} \, .$$

Now, since

$$V_{DC} = \sqrt{\frac{1}{T}\int_0^T V^2(t)\, dt} \, ,$$

the output voltage of the rectifier is found by evaluating

$$V_{DC} = \sqrt{\frac{\omega V_p^2}{2\pi}\left[\int_{\frac{\alpha}{\omega}}^{\frac{\pi}{2\omega}} \sin^2(\omega t - \alpha)\, dt + \int_{\frac{\pi}{2\omega}}^{\frac{\alpha+2\pi}{\omega}} e^{-\frac{2t+\frac{\pi}{\omega}}{RC}}\, dt\right]} \, . \qquad (1)$$

Since $V_s(t)$ is defined by

$$V_s(t) = \sum_{i=0}^{\infty} |V_i| \sin(i\omega t + \theta_i) \, ,$$

this incorporates any harmonic distortion present on the source side of the rectifier in the calculation of the output voltage. With the input waveform known, the peak value of $V_s(t)$, V_p is found by

$$V_p = Max[V_s(t)] \ for \ 0 \le t < \frac{\pi}{2\omega} \, .$$

Once the value for V_p has been determined, the value of α which produces the desired output voltage from the rectifier, V'_o, can be determined by varying the firing angle from a starting value of $\alpha_0 = 0$ by small steps defined by

$$\alpha_{i+1} = \alpha_i + \delta$$

where $\delta = \pi/360$ radians or 0.5 degrees until the value produced by Equation 1 is equal to V'_o. It is important to note that the value of V_p must be determined, due to possible voltage resonance situations, before the above procedure is followed.

With a known value of α, it is now possible to determine the input current waveform from the time of firing to the point of commutation (i.e., $t = \pi/2\omega$). The method for this step is outlined in Section 5 of Reference [1]. It should be noted that the input voltage is approximated by

$$V_s(t) = V_p \sin(\omega t + \alpha_{\min}) \ .$$

Since the development of the input current waveform uses the approximation of a single harmonic (i.e., fundamental only) waveform for the voltage, it is necessary to approximate the input voltage as a single harmonic waveform with a peak value equal to that of the actual $V_s(t)$. Although this is a necessary approximation required to make the determination of the input current reasonable, the error introduced should be small.

With a known input current waveform, it is now possible to determine the Fourier coefficients of the current waveform. The Fourier series, in rectangular form, of a time function is given by

$$f(t) = c_o + \sum_{n=1}^{\infty} c_n \cos(n\omega_o t) + d_n \sin(n\omega_o t)$$

where,

$$c_o = \frac{1}{T_o} \int_{t_1}^{t_1 + T_o} f(t)\, dt, \tag{2}$$

$$c_n = \frac{2}{T_o} \int_{t_1}^{t_1 + T_o} f(t) \cos(n \omega_o t)\, dt \text{ and}, \tag{3}$$

$$d_n = \frac{2}{T_o} \int_{t_1}^{t_1 + T_o} f(t) \sin(n \omega_o t)\, dt. \tag{4}$$

Since the rectifier is the source of the current waveform, the source side bus of the rectifier is the point where the harmonic current injection occurs. The details of this injection and its impact on HARMFLO will be discussed in Section 4 of this report.

Once the values of c_n and d_n have been determined using Equations (2) through (4), they are put in polar form:

$$|I_j^{(n)}| \text{ and } \theta_j^{(n)} \text{ for } 1 \leq n < \infty$$

which are the harmonic coefficients of the injection current at the rectifier's AC bus. At this point they are placed in the appropriate locations in the $[\Delta I]$ vector. $[\Delta I]$ is the updated vector at each iteration in the solution of

$$[\Delta V] = [J][\Delta I]$$

where $[J]$ is the Jacobian matrix.

The harmonic power is allowed to converge with the above procedures incorporated into the algorithm, and the results are the magnitudes and phase angles of the steady-state harmonic voltages at every bus in the system.

4. Test of HARMFLO with a Voltage Controlled, Full Wave Rectifier

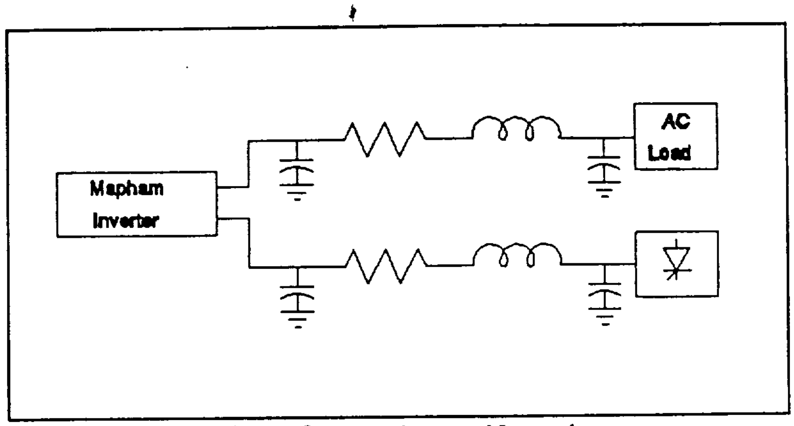

Figure 3 - Test System Network

In order to demonstrate the results of the work described above, the following test system was analyzed using HARMFLO. The test system is shown in Figure 3. The test system consists of an inverter source (i.e., a Mapham inverter) supplying a standard AC load of 40 kW on a radial line from the inverter. The inverter is also supplying a voltage controlled, full wave rectifier on another radial line. The AC load is a 5.0 kVA load running at an 80% lagging power factor. The rectifier is a voltage controlled, full wave rectifier that is set to an output voltage of 89 VDC. The input data for this system is shown in Figure 4. The output from the resulting harmonic power flow using the data in Figure 3 is shown in Appendix A. The results of this test are very encouraging. Since there are no testbed results available at this time which could be used as a benchmark for this modelling, there will have to be tests run when a power system simulator is completed to validate the model for the voltage controlled, full wave rectifier.

One check which offers encouragement is in the power consumed by the rectifier. Since the D.C. voltage is to be controlled, in this sample system, to 89 VDC and the load resistor is 10 Ω, the output power of the rectifier should then be 792 W or 0.792 kW. The last page of the program's output indicates a real power input to the rectifier of the A.C. side of 0.639 kW. Although this is a 20% error, it should be noted that this is well within the 100 W tolerance which the program is designed to maintain.

The author plans to make these tests part of the next proposal which will complete the testing and develop a model for the bi-directional power unit. The author is also working very closely with the NASA proctor of this grant so that the power system simulator which will be constructed will have the features necessary to allow for the testing of the models developed under all of this work.

```
  1
NASA Test System
  2
Test System for Paper #899383 of the IECEC '89 Conference, Vol. 1
  3
  1  Sourc1    08                                          100.00        0.0
 16.0e-6  1.71e-6   2.0e-6   1.8e-6   0.0e-0  2.00e+4  440.0    1.0e+4
  3  Load1    03                              40.0   30.0
  2  Rectf1    19
 75.0     1.0e-6    2.0e-7   1.0e+1
9999
  4
  1   3 0.54   1.75
  1   2 0.54   1.75
  1   0  0.0   -5305.
  3   0  0.0   -5305.
  1   0  0.0   -5305.
  2   0  0.0   -5305.
  3   0 160.0  120.0                              1
  1   0  0.0   649.09                             1
9999
  5
  9 590 080 1   000          3
 15
```

Figure 4 - HARMFLO Input Data for Test System

5. Conclusions and Recommendations

This report for NASA Grant NAG3-1254 documents the work done which successfully completes the grant according to schedule. The results of this work are that (1) the harmonic power now has a model of a single phase, voltage controlled, full wave rectifier; and (2) HARMFLO has been ported to the SUN workstation platform. The operations of the new model for the voltage controlled, full wave rectifier appears to work very well. Although insufficient test data exists to completely validate the model, the results produced by HARMFLO seem to be reasonable and do not appear to be grossly in error.

Further work must be done to validate the models and locate points which need fine tuning. The major hurdle in this area is an actual test system where various configurations can be connected and measured. This will generate the data necessary to find the strengths and weaknesses of the software so that the confidence level in the models can be increased to a higher level.

LIST OF REFERENCES

LIST OF REFERENCES

[1] Kraft, L. A., "Development of a Single Phase Harmonic Power Flow Program to Study the 20 KHz A.C. Power System for Large Spacecraft," NASA-ASEE 1990 Summer Faculty Fellowship Program, Summer 1990.

APPENDICES

APPENDIX A

```
1NASA Test System                                                              page =     1

 Test System for Paper #899383 of the IECEC '89 Conference, Vol. 1

1NASA Test System                                                              page =     2

 fundamental loadflow bus data  (percent voltage, power)
  bus  name            type  sub-type    p gen     q gen         s     p load    q load   voltage   q shunt
kshunq

    1    Sourc1          0         8      0.00      0.00      0.00      0.00      0.00    100.00      0.00
    0

 Lr:  0.160D-04 H,  Cr:  0.171D-05 F,  Cs:  0.200D-05 F,  Ll:  0.180D-05 H,  Lm:  0.000D+00 H,  fsw:  0.200D+05
Hz
 Vbase:  0.440D+03 V,  and Sbase:  0.100D+05 W

    3     Load1          0         3      0.00      0.00      0.00     40.00     30.00      0.00      0.00
    0
    2    Rectf1          1         9      0.00      0.00      0.00      0.00      0.00      0.00      0.00
    0

 Vc:  0.890D+02 V, Cr:  0.100D-05 F, Lr:  0.200D-06 H, Rr:  0.100D+02 Ohms.

 end of code 3 bus data
```

```
 line and transformer data  (percent impedance, charging)
 from      to
  bus     bus          r1          x1    charging          r0          x0         tap   t-type    z-type
h-only

    1       3      0.5400      1.7500        0.00      0.0000      0.0000       0.000        0         0
    0
    1       2      0.5400      1.7500        0.00      0.0000      0.0000       0.000        0         0
    0
    1       0      0.0000  -5305.0000        0.00      0.0000      0.0000       0.000        0         0
    0
 *** message code     2 ***
 assumed shunt connection type = 1

    3       0      0.0000  -5305.0000        0.00      0.0000      0.0000       0.000        0         0
    0
 *** message code     2 ***
 assumed shunt connection type = 1

    1       0      0.0000  -5305.0000        0.00      0.0000      0.0000       0.000        0         0
    0
 *** message code     2 ***
 assumed shunt connection type = 1

    2       0      0.0000  -5305.0000        0.00      0.0000      0.0000       0.000        0         0
    0
 *** message code     2 ***
 assumed shunt connection type = 1

    3       0    160.0000    120.0000        0.00      0.0000      0.0000       0.000        0         0
    1
 *** message code     2 ***
 assumed shunt connection type = 1

    1       0      0.0000    649.0900        0.00      0.0000      0.0000       0.000        0         0
    1
 *** message code     2 ***
 assumed shunt connection type = 1

 end of code 4 line and transformer data
```

```
1NASA Test System                                                          page =     4

 solution options

 option number     1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19
 20

 option value      0    9    5   90    0   80    1    0    0    0    0    0    0    0    0    0    0    0
0    0

 Root used is: -.81003D+04 + J 0.19543D+06

 ****
 Total Harmonic Distortion (THD) of Current for the Inverter at Bus:  1 is   0.57%
 ****

 end of starting estimates

1NASA Test System                                                          page =     5

 fundamental loadflow iteration summary

              absolute real power mismatch     absolute reactive power mismatch
                                      worst                                  worst
 iteration          average     worst   bus            average     worst      bus

         0            23.96     40.00     3              15.00     28.11        3
         1             0.16      0.31     3               0.14      0.28        3
         2             0.00      0.00     3               0.00      0.00        3
```

```
1NASA Test System                                                                          page =     6

 fundamental loadflow output  (percent voltage, power)
 from                                                                                   to
  bus   name          voltage   angle        pg         qg         pl         ql   q shunt  bus   name
 p          q        tap


    1    Sourc1      100.00    0.00     48.06      22.92       0.00       0.00      0.00
                                                                                          3      Load1
40.13      28.57
                                                                                          2     Rectf1
7.92      -1.87
                                                                                       neut   z shunt
0.00      -1.89
                                                                                       neut   z shunt
0.00      -1.89

    2    Rectf1       99.99   -0.09      0.00       0.00       7.92       0.00      0.00
                                                                                          1     Sourc1
-7.92       1.88
                                                                                       neut   z shunt
0.00      -1.88

    3     Load1       99.28   -0.32      0.00       0.00      40.00      30.00      0.00
                                                                                          1     Sourc1
-40.00     -28.14
                                                                                       neut   z shunt
0.00      -1.86

 total real power loss =       0.13

 ************************************************************
 *      SINGLE PHASE, VOLTAGE CONTROLLED RECTIFIER          *
 * MINIMUM FIRING ANGLE AND MAXIMUM VOLTAGE INFORMATION *
 ************************************************************


*** For a rectifier at bus    2 the commutation angle is:  94.1 degrees
***                             the firing angle is: 13.7016 degrees
   Uncontrolled DC output voltage is :    0.9128D+02 volts

 *** Rectifier voltage at bus   2 is   89.9 V which is the desired value.  Firing angle fixed at 26.95 degrees
```

harmonic loadflow iteration summary

iteration	quantity	harmonic	absolute real mismatch average	absolute real mismatch worst	absolute real mismatch worst bus	absolute imaginary mismatch average	absolute imaginary mismatch worst	absolute imaginary mismatch worst bus	voltampere mismatch average	voltampere mismatch worst	voltampere mismatch worst bus
0	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0
	current	2	0.64	1.92	3	0.97	2.51	3			
	current	3	2.56	4.10	2	2.89	5.51	2			
	current	4	0.21	0.62	3	1.00	1.12	1			
	current	5	2.52	5.72	2	3.48	6.36	2			
1	power		0.00	0.00	2	0.00	0.00	2	0.00	0.00	0
	current	2	0.00	0.00	1	0.00	0.00	3			
	current	3	4.78	8.58	2	4.10	6.37	1			
	current	4	0.00	0.00	1	0.00	0.00	3			
	current	5	9.77	16.74	1	5.49	13.18	2			
2	power		0.00	0.00	2	0.00	0.00	3	0.00	0.00	0
	current	2	0.00	0.00	3	0.00	0.00	3			
	current	3	1.83	2.59	3	0.55	0.85	2			
	current	4	0.00	0.00	2	0.00	0.00	2			
	current	5	15.22	18.22	2	18.88	24.41	1			
3	power		0.00	0.00	2	0.00	0.00	2	0.00	0.00	0
	current	2	0.00	0.00	3	0.00	0.00	2			
	current	3	0.06	0.08	1	0.25	0.37	3			
	current	4	0.00	0.00	2	0.00	0.00	2			
	current	5	92.62	141.14	1	111.26	169.97	1			
4	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0

harmonic loadflow iteration summary

iteration	quantity	harmonic	absolute real mismatch average	absolute real mismatch worst	absolute real mismatch worst bus	absolute imaginary mismatch average	absolute imaginary mismatch worst	absolute imaginary mismatch worst bus	voltampere mismatch average	voltampere mismatch worst	voltampere mismatch worst bus
	current	2	0.00	0.00	3	0.00	0.00	1			
	current	3	0.00	0.00	3	0.00	0.00	3			
	current	4	0.00	0.00	2	0.00	0.00	2			
	current	5	27.15	39.83	1	276.83	411.96	1			
5	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0
	current	2	0.00	0.00	2	0.00	0.00	1			
	current	3	0.00	0.00	3	0.00	0.00	3			
	current	4	0.00	0.00	2	0.00	0.00	2			
	current	5	22.82	32.39	1	133.03	201.76	1			
6	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0
	current	2	0.00	0.00	3	0.00	0.00	2			
	current	3	0.00	0.00	1	0.00	0.00	1			
	current	4	0.00	0.00	2	0.00	0.00	2			
	current	5	6.31	8.71	1	27.85	36.59	1			
7	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0
	current	2	0.00	0.00	3	0.00	0.00	3			
	current	3	0.00	0.00	1	0.00	0.00	1			
	current	4	0.00	0.00	1	0.00	0.00	1			

harmonic loadflow iteration summary

			absolute real mismatch			absolute imaginary mismatch			voltampere mismatch		
iteration	quantity	harmonic	average	worst	worst bus	average	worst	worst bus	average	worst	worst bus
	current	5	1.83	3.16	2	9.67	13.05	1			
8	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0
	current	2	0.00	0.00	3	0.00	0.00	1			
	current	3	0.00	0.00	2	0.00	0.00	3			
	current	4	0.00	0.00	1	0.00	0.00	3			
	current	5	1.44	1.93	1	0.99	1.38	1			
9	power		0.00	0.00	3	0.00	0.00	3	0.00	0.00	0
	current	2	0.00	0.00	1	0.00	0.00	3			
	current	3	0.00	0.00	1	0.00	0.00	2			
	current	4	0.00	0.00	1	0.00	0.00	1			
	current	5	0.05	0.08	1	0.09	0.12	1			
10	power		0.00	0.00	2	0.00	0.00	2	0.00	0.00	0
	current	2	0.00	0.00	3	0.00	0.00	1			
	current	3	0.00	0.00	2	0.00	0.00	1			
	current	4	0.00	0.00	2	0.00	0.00	1			
	current	5	0.00	0.00	1	0.00	0.00	1			

fundamental loadflow output (percent voltage, power)

from bus / p	name / q	voltage / tap	angle	pg	qg	pl	ql	q shunt	to bus	name
1	Sourc1	100.00	0.00	48.06	22.92	0.00	0.00	0.00		
40.13	28.57								3	Load1
7.92	-1.87								2	Rectf1
0.00	-1.89								neut	z shunt
0.00	-1.89								neut	z shunt
2	Rectf1	99.99	-0.09	0.00	0.00	7.92	0.00	0.00		
-7.92	1.88								1	Sourc1
0.00	-1.88								neut	z shunt
3	Load1	99.28	-0.32	0.00	0.00	40.00	30.00	0.00		
-40.00	-28.14								1	Sourc1
0.00	-1.86								neut	z shunt

real power loss for this harmonic = 0.13

harmonic loadflow output for harmonic number 2, frequency = 120 hz. (percent voltage, current, power)

from bus tap	name	voltage magnitude	voltage angle	to bus	name	p	q	current magnitude	current angle
1	Sourc1	0.0000	-98.05						
				3	Load1	0.000000	0.000000	0.000002	-150.92
				2	Rectf1	0.000000	0.000000	0.000001	20.52
				neut	z shunt	0.000000	0.000000	0.000000	-8.05
				neut	z shunt	0.000000	0.000000	0.000000	-8.05
				neut	z shunt	0.000000	0.000000	0.000000	171.95
2	Rectf1	0.0000	-97.95						
				1	Sourc1	0.000000	0.000000	0.000001	-159.48
				neut	z shunt	0.000000	0.000000	0.000000	-7.95
3	Load1	0.0000	-98.35						
				1	Sourc1	0.000000	0.000000	0.000002	29.08
				neut	z shunt	0.000000	0.000000	0.000000	-8.35
				neut	z shunt	0.000000	0.000000	0.000002	-154.66

real power loss for this harmonic = 0.00

1NASA Test System page = 12

harmonic loadflow output for harmonic number 3, frequency = 180 hz. (percent voltage, current, power)

from bus	name	voltage magnitude	voltage angle	to bus	name	p	q	current magnitude	current angle
tap									
1	Sourc1	28.7309	-32.99						
				3	Load1	0.836406	1.437627	5.789011	-92.80
				2	Rectf1	-1.767185	-1.018877	7.099909	117.04
				neut	z shunt	0.000000	-0.466803	1.624743	57.01
				neut	z shunt	0.000000	-0.466803	1.624743	57.01
				neut	z shunt	0.000000	0.423908	1.475444	-122.99
2	Rectf1	28.9519	-32.39						
				1	Sourc1	1.769907	1.045342	7.099909	-62.96
				neut	z shunt	0.000000	-0.474012	1.637240	57.61
3	Load1	28.4527	-33.25						
				1	Sourc1	-0.834596	-1.420033	5.789011	87.20
				neut	z shunt	0.000000	-0.457809	1.609014	56.75
				neut	z shunt	0.834596	1.877841	7.222345	-99.29

real power loss for this harmonic = -0.83

harmonic loadflow output for harmonic number 4, frequency = 240 hz. (percent voltage, current, power)

from bus	name	voltage magnitude	voltage angle	to bus	name	p	q	current magnitude	current angle
tap									
1	Sourc1	0.0000	-131.51						
				3	Load1	0.000000	0.000000	0.000001	167.42
				2	Rectf1	0.000000	0.000000	0.000001	25.74
				neut	z shunt	0.000000	0.000000	0.000001	-41.51
				neut	z shunt	0.000000	0.000000	0.000001	-41.51
				neut	z shunt	0.000000	0.000000	0.000000	138.49
2	Rectf1	0.0000	-131.07						
				1	Sourc1	0.000000	0.000000	0.000001	-154.26
				neut	z shunt	0.000000	0.000000	0.000001	-41.07
3	Load1	0.0000	-131.72						
				1	Sourc1	0.000000	0.000000	0.000001	-12.58
				neut	z shunt	0.000000	0.000000	0.000001	-41.72
				neut	z shunt	0.000000	0.000000	0.000001	156.71

real power loss for this harmonic = 0.00