Sizing A UPS System For Non-Linear Loads

SOLIDSTATE
CONTROLS, INC.

Solidstate Controls Incorporated
875 Dearborn Drive
Columbus, Ohio 43085
Tel : (614) 846-7500
Fax: (614) 885-3990

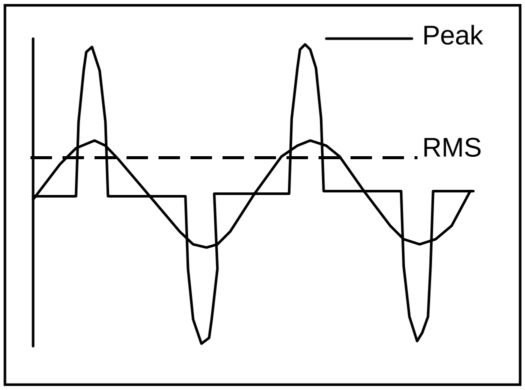
Sizing A UPS System For Non-Linear Loads

Abstract

The safe and efficient control of a critical process such as a recovery boiler system has been made possible by Distributed Control Systems (DCS). These DCS systems often require uninterruptible AC voltage which is provided by static (electronic) inverters.

The insertion of an inverter, which is a limited capacity device between the DCS and the utility power, requires some knowledge of the input power requirements of distributed control system's internal power supplies.

Examination of the current waveform of a modern DCS would reveal a wave shape much like the one shown in **Figure 1**. The current is not sinusoidal and is not continuous. The peak current is much greater than the RMS (root-mean-square) value, often 2.5 times as large. This kind of non-linear current is characteristic of the electronic AC-DC power supplies used in many DCS systems.



Non-Linear Loads
Definition of Crest Factor

$$\text{Crest Factor} = \frac{I_{peak}}{I_{rms}}$$

Crest Factor (CF)

- The ratio of the peak value to it's RMS value
- For a sine wave the Crest Factor is 1.414

Figure 1

Over the past 20 years, AC-DC power supplies have evolved from ferroresonant to series-regulator and finally to switch-mode designs. Table "A" highlights some of the characteristics of the three types of power supplies.

The oldest design, the ferroresonant, uses a large input magnetic regulator. By today's DCS packaging standards, the ferroresonant power supply is big and heavy. There are still some control systems manufacturers that use ferroresonant supplies because of their reliability and low input harmonic current distortion.

The series-regulator design uses an input isolation transformer coupled with a transistorized voltage regulator stage. Poor conversion efficiency and narrow input range have restricted its use.

The third type of power supply, the switch-mode (SMPS) has the advantage of the smallest size and lightest weight because the line frequency magnetics have been eliminated. (Refer to **Figure 2**) The reduction in the input inductive reactance and the insertion of a large capacitor together has produced an extremely compact but extremely non-linear device. Since the SMPS is the dominant power supply in many DCS systems, its input current characteristics must be understood when sizing an inverter.

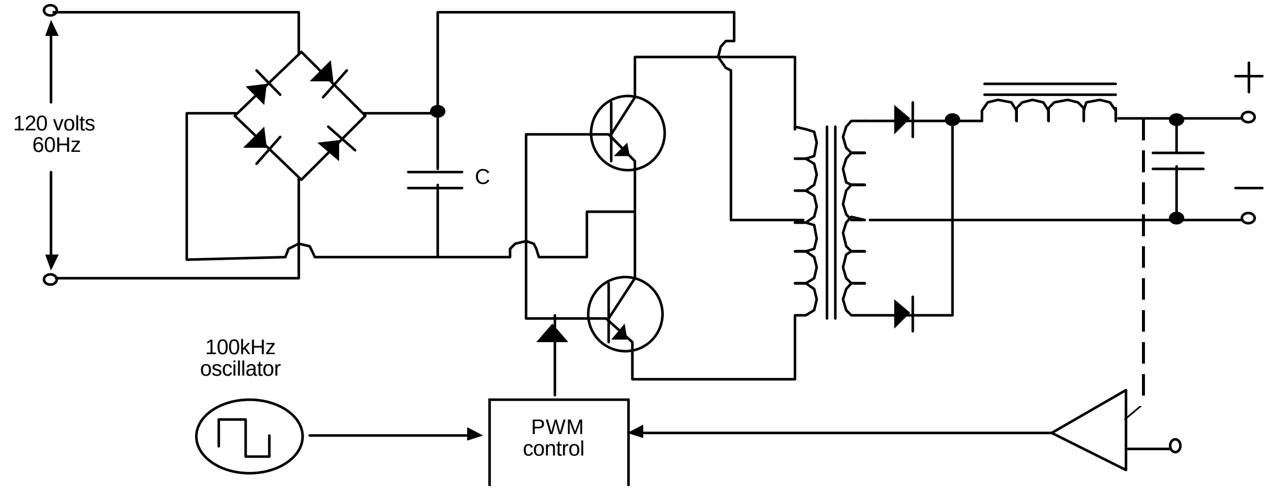


Figure 2 Switch Mode Power Supply (extremely non-Linear)

There are four (4) important factors that must be carefully considered whenever inverters are used with extremely non-linear loads such as switch-mode power supplies (SMPS). These factors are:

1) Crest Factor (Published Vs Actual)

2) Repetitive & Non-Repetitive peak load currents

3) Harmonic Voltage Distortion

4) Inverter Technology

Crest Factor (Published vs Actual)

Many distributed Control System (DCS) manuals make reference to a ratio often called "Crest Factor" which is simply the ratio of the peak current value divided by the root-mean-square (RMS) value. Often in these manuals the user is cautioned to oversize the inverter based on published crest factor data for the various control modules that comprise the DCS system. This approach if not used with caution will invariably lead to oversized inverters.

Suppose we construct a hypothetical distributed control system that will require (20) twenty control modules, with each control module using one switch-mode power supply. Let us further suppose that in our hypothetical system, the power supply is a 200W model as shown in Table "B". (Table "B" is a typical listing of the SMPS input characteristics)

This supply can produce 200 watts of DC output power, has a universal 120/240 V, 50/60 Hz input, and is designed to maintain its DC output voltage for 10 milliseconds with a total loss of AC input. This power hold-up time is supplied from an internal 470 UF or VF electrolytic capacitor (Figure 2 component "C")

Since our DCS system will use twenty (20) of these supplies in its overall control scheme, one might be tempted to multiply the 432 VA input demand times 20 and add "fudge" factors because of the large crest factor (Table "B", column 5B).

Very often inverters are over-sized because their rated crest factor (typically 3.0) is less than published power supply data. Table “B” indicates a power supplies crest factor of 3.4.

The assumption, of course, is that the crest factor of the switch-mode supply is a constant value. Table "C" summarized actual values taken on a 10 kVA ferroresonant inverter with a simulated switch-mode load. The load of 8.43 kVA is very close to our hypothetical load of twenty (20) 200W power supplies. In Table "C", notice that the load crest factor has decreased from 3.4 to 2.3. This reduction in crest factor is a result of a change in the source to load impedance ration (Zs/Zl, see figure 3). An example will clarify the concept:

Suppose that when the original performance data in Table "B" was measured, a 3 kVA transformer with a 5% impedance was used to provide power to a single 200 watt supply.

The source-load impedance ratio in this case would be:

$$Zs/\ ZK\ =.24/.33= 1/138$$

$$\text{Where } Z= E^2 VA$$

If we were to add (5) five more 200w supplies for a total of 6 units, the new ratio would be:

$$Zs/\ ZL = .24/5.5 =1/23$$

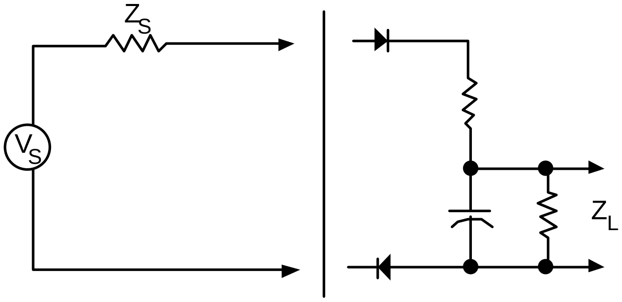


Figure 3 Switch Mode Power Supply

Published power supply data rarely takes this effect into account and thus actual crest factors will be lower.

The reduction in crest factor is a predictable and repeatable result whenever switch-mode power supplies are used with power sources that have inductive reactance in series with the switch-mode power supply. In Table "C", the inverter's output reactance reduced the load crest factor. The reduction in crest factor is accomplished by changing the shape of the switch mode's input current waveform to a wider shape with less amplitude. The area under the current curve tends to remain constant, but the harmonics, particularly the 3rd and 5th, are attenuated.

Measurements performed on 10 & 30 kVA ferroresonant inverters with simulated switch-mode loads (see tables "D" &"E") show that over a load range of 25-100% the load crest factor values ranged from 2.2 to 2.5.

The important point to be emphasized from the data in tables "D" & "E" is that ferroresonant inverters do not need to be oversized because of the high crest factor associated with switch-mode power supplies. Crest factor is dependent on the application and must be used with caution as an inverter sizing criterion.

Again, referring to table "C", the peak current has been reduced from a predicted value of 12.2 x 20 =224 A (Table "B" column 4B) to an actual value of 156A. (Table "C" column 4C) but even these reduced values of peak current can be a problem for some inverter technologies that use linear magnetics.

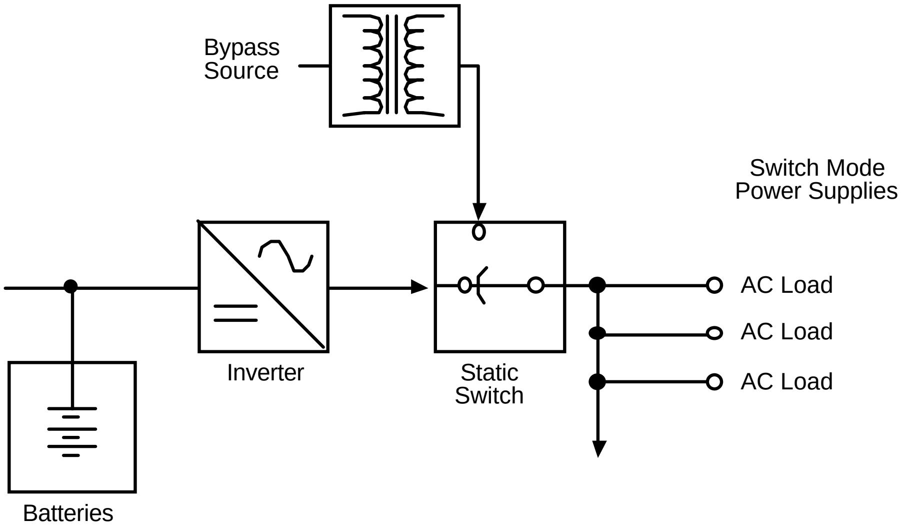


Figure 4

Peak Current Effects

Figure 4 is a simple block diagram of an inverter with a static switch used in critical control applications.

This topology is commonly called an "on-line" system because the inverter normally supplies the critical load. Between the inverter and the critical load is an electronic switch (static) that will transfer the critical load to a fail-over source (static bypass), should the load current demand exceed the inverters rated capacity (or should the inverter fail)

If the static switch is designed for sinusoidal current with a crest factor of 1.414, then a non-sinusoidal current with a crest factor of 2.4 will cause premature load switching to bypass. Static switch transfer sensing for overcurrent is best accomplished with true RMS values rather than peak current values.

For example, if the 10kVA system (Table "C" data) had used a sinusoidal, peak sensing current design the connected loads peak current of 156A (column 4C) would have been 11% over its static switch transfer point, assuming a 120% overload capacity. True RMS sensing rather than peak sensing is a very important feature in a well-designed system to prevent premature static switch operation.

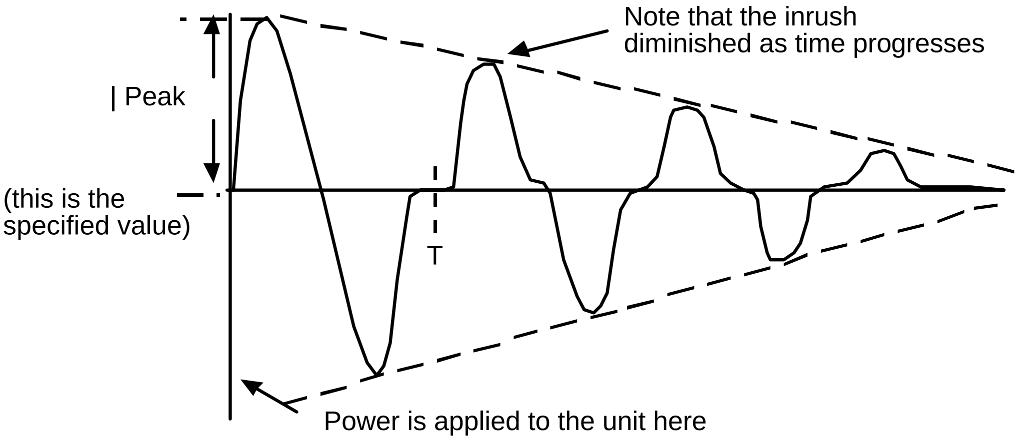


Figure 5 Inrush current that occurs when the power is first applied to a unit. It is measured in peak amperes as shown.

The cold start inrush current (Table "B & C", Columns 6B & 6C) is also important when selecting an inverter system. Unlike their predecessors, switch-mode power supplies are sensitive to the peak voltage of their input supply. Usually the input peak voltage must stay above 140 VAC to prevent a power supply shut down. Figure 5 shows the characteristics wave shape of the input current during the first several cycles of a cold start.

During a cold start the inrush current will cause the static switch (**Figure 3**) to transfer the critical loads to the bypass source. The bypass source circuit must be a "stiff" (i.e. low impedance) design if the peak voltage is to be maintained above 140 VAC (on a 120 VAC RMS design). Since the static switch is in the middle of the bypass circuit its switching devices must be sized to handle the inrush current during an initial power up. A well-designed static switch will have a 1000% rating for one cycle based on the inverter's full load capacity.

Harmonic Distortion

Harmonic distortion of the inverter's output voltage is a possibility whenever high non-linear loads are connected. Not much data exists on this topic because, at this time, no testing standards for inverters exist that address voltage distortion with non-linear loads.

The standards in place today IEEE 944, NEMA PE-1, and IEC 146-2 set limits on inverter harmonic voltage distortion with linear loads only. Inverter voltage distortion performance with linear loads is not a reliable predictor of performance with non-linear loads. The IEEE, NEMA, & IEC inverter performance standards specify that the total harmonic distortion shall not exceed 5% with linear loads. In the current standards, no mention is made of inverter performance with non-linear loads. Perhaps future revisions will address this issue.

The harmonics distortion issue is complex, and we recommend the IEEE-519 document as an excellent tutorial on the subject of power harmonics.

Regarding inverter performance with non-linear loads, Tables "B" & "E" list the test results for a 10 & 30 kVA system. The inverters were tested with both 100% non-linear switch-mode simulation and mixtures of linear and non-linear loads. Voltage distortion was measured at the inverter output terminals. The measurements taken in Tables “D” & “E” show that with non-linear loading, the voltage distortion decreases with load.

Measurements were also taken with mixtures of linear and non-linear loads. The total harmonic distortion is decreased as the percentage of linear loads is increased. What is not shown in the data is the effect of voltage drop in the distribution wiring which will make the voltage distortion increase.

Distributed control systems often have long distances between the inverter and the non-linear load. The voltage drop in the power distribution system will vectorially add with the inverter's output voltage to increase the voltage distortion at the load. It is not uncommon to measure 4% THD at the inverter's output and 8% THD hundreds of feet away at the connection point of the non-linear load. What is important to remember is that the power wiring can affect voltage distortion whenever harmonic currents are flowing.

For the switch-mode supplies shown in Table "C" the harmonics currents, mostly 3rd, 5th, and 7th comprise 23% of the total load current. Conductor sizes need to be increased at least 30% for distance over 50 ft. to minimize the effects of distribution voltage drop. (Keep in mind the requirement of a minimum of 140 VAC peak).

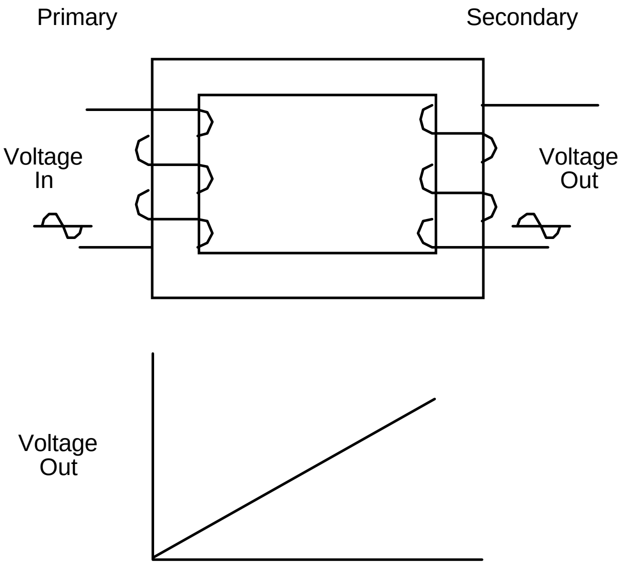
What has not been mentioned is how much current and voltage distortion is too much and how will current and voltage distortion affect the operation of the DCS. The answer to these questions depends not only on the DCS design, but also on the sensitivity of other critical load that may be sharing the inverter's output. In general, devices that have linear magnetics, (including motors) will be sensitive to harmonics. The switch-mode power supplies are not particularly sensitive to the harmonic current since they contain no line frequency magnetics, but they are sensitive to low peak voltages.

If there are distribution transformers in either the static bypass circuit or the inverter output circuit, they must be designed for non-linear currents. Dry type distribution transformers are designed for passing only line frequency currents not harmonic currents. The stray losses, which contribute to the transformer's winding temperature increases as the square of the frequency.

ANSI/IEEE C57.110-1986 addresses the design sizing of K-factor rated transformers. Transformers for use with switch-mode loads must be rated for a minimum of K-13. Using K-factor rated transformers will eliminate overheating, but will do nothing to improve voltage distortion. In fact, most linear transformers will add harmonic distortion to their input voltage waveforms.

Inverter Technology

In the world of industrial inverters two inversion technologies dominate: Ferroresonant and Pulse-Width-Modulation (PWM).



Characteristics of Linear Transfers

- Tight Coupling of flux between primary and secondary windings
- Bi-directional power flow
- High current drawn from primary when the secondary is short-circuited

Figure 6A Linear Transformer

PWM inverters synthesize a sinusoidal output waveform from a constant-height, variable width high frequency pulse stream. The pulse stream is stripped of its high frequency carrier (20-50 kHz) by a low-pass filter and reduced to a 120 VAC level through a linear power transformer.

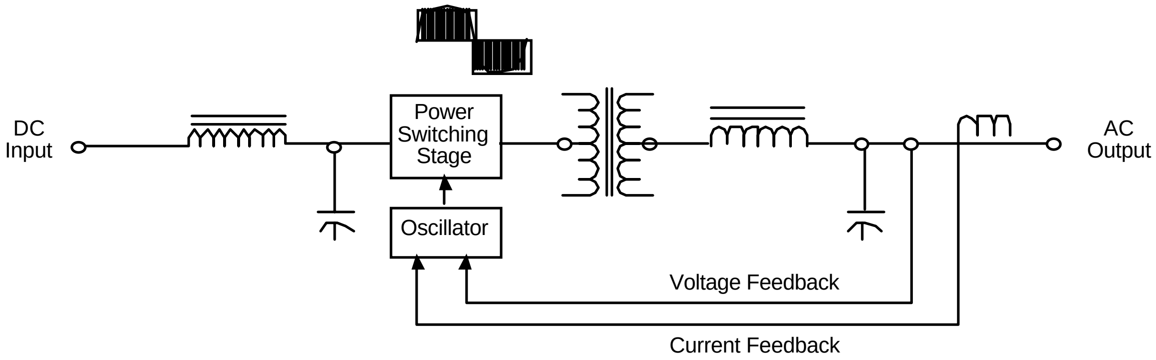
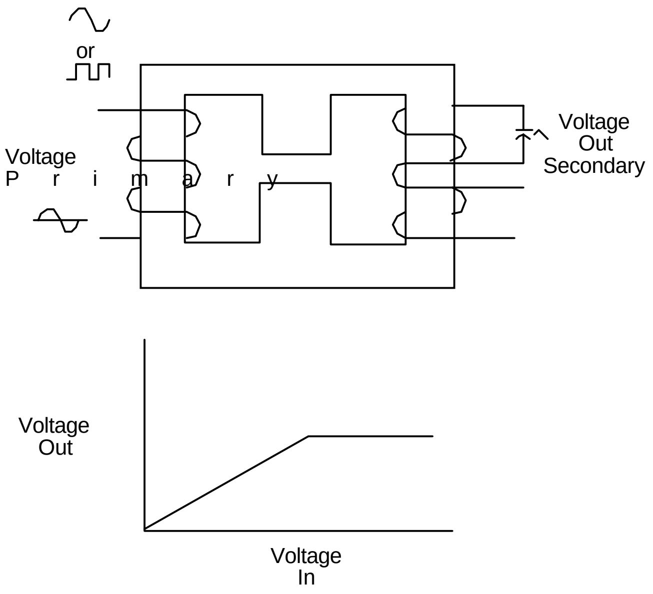


Figure 6B Power Switching at 20-50 kHZ Rate *T1 is a Linear Transformer

The harmonics created by switch-mode power supplies can affect the PWM's linear power transformer adversely by increasing its eddy current losses. Additionally, because of the tight coupling between the input switching bridge and the load, the high peak currents must be carried by the bridge switching transistors. PWM inverters are more sensitive to non-linear currents and often must be oversized for proper operation.

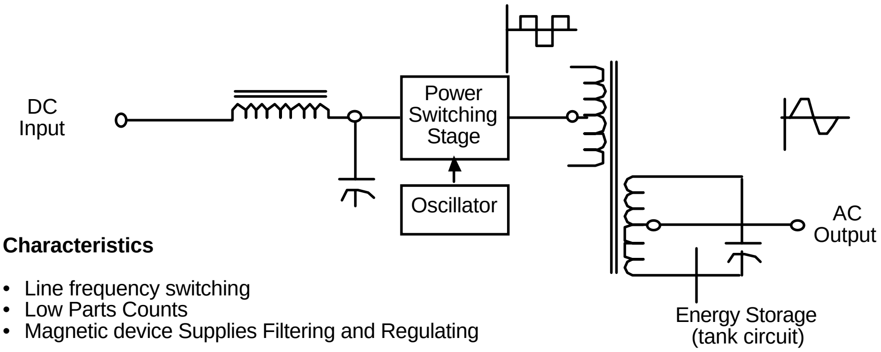


Characteristics of Non-Linear Transfers

- Loose Coupling of flux between primary and secondary windings
- Uni-directional power flow
- Inherent current limiting to 175% upon short circuit at the secondary-windings

Figure 7A Ferroresonant Transformer

In contrast, Ferroresonant inverters do not use linear magnetics. A line frequency square wave developed by the switch bridge is filtered into a sinusoidal wave shape by means of the non-linear actions of a saturated, resonant secondary winding. The peak current demanded by a non-linear load is supplied by the storage energy in the saturated secondary. The load current is not coupled to the switching bridge. The secondary winding also contains harmonic traps tuned to the 3rd and 5th harmonic.



Characteristics

- Line frequency switching
- Low Parts Counts
- Magnetic device Supplies Filtering and Regulating

Figure 7B Ferroresonant Inverter

Ferroresonant inverters are uniquely compatible with switch-mode power supplies and do not have to be oversized to provide proper operation.

Table A

DISTRIBUTED CONTROL SYSTEM (DCS)
AC-DC POWER SUPPLY COMPARISON
120 VAC 1Ø INPUT

AC-DC Supply Design	**1A** Output Capacity	**2A** Efficiency Wo/Wi Watts	**3A** Size Cu. In.	**4A** Weight Lbs.	**5A** Input Range (Volts)	**6A** Input THD (%)	**7A** 3rd	**8A** 5th Harmonic (% of F)	**9A** 7th
FERRO	192	.70	350	32	95-130	15	13	7	2.5
SERIES-R	216	.35	240	14	105-125	27	13	20	12
SMPS	200	.77	148	6	99-132	97	80	52	30

Table B

SWITCH-MODE POWER SUPPLY DATA
(200W CAPACITY)

Power Supply Design	**1B** Input Voltage (AC)	**2B** Steady-Stage Input Amps	**3B** Input VA	**4B** Peak Input Amps	**5B** Crest Factor	**6B** In Rush Input Amps	**7B** Input Power Factor	**8B** 3rd Harmonic % of F.	**9B** 5th
SMPS (QTY 1)	120 V	3.6 A.	432 VA	12.2	3.4	24 A	60	80%	52%

Table C

DCS INPUT DATA MEASURED VALUES ON A
10 kVA FERRORESONANT INVERTER

Non-Linear Load	1C Input Voltage AC	2C Steady-Stage Input Amps	3C Input VA	4C Peak Input Amps	5C Crest Factor	6C In Rush Amps Amps	7C Input Power Factor	8C 3rd Harmonic % of F.	9C 5th
SMPS (QTY 20)	124V	68A	8.4 kVA	156A	2.3	* 460A *Estimated	.74	72%	38%

Table D
10kVA Inverter

LOAD	KW	kVA	P.F.	AMPS	C.F.	V-THD
25% TOTAL LOAD						
100% N-L	1.992	2.841	.70	22.9	2.5	4.6
75% N-L, 25% L	2.247	2.502	.90	20.2	2.3	3.8
50% N-L, 50% L	2.289	2.495	.92	20.1	2.2	3.8
50% TOTAL LOAD						
100% N-L	3.645	5.080	.72	41.1	2.5	5.6
50% N-L, 50% L	4.685	5.013	.93	40.4	2.1	4.6
25% N-L, 75% L	4.956	5.057	.98	40.7	1.8	4.1
75% TOTAL LOAD						
100% N-L	6.981	8.116	.74	65.6	2.3	6.6
75% N-L, 25% L	6.867	7.848	.87	63.4	2.2	5.7
50% N-L, 50% L	6.874	7.360	.93	59.4	2.0	5.2
25% N-L, 75% L	7.401	7.476	.99	60.2	1.6	4.2
100% TOTAL LOAD						
100% N-L	6.238	8.428	.74	67.9	2.3	6.7
75% N-L, 25% L	8.648	9.861	.88	80.0	2.2	6.4
50% N-L, 50% L	9.435	10.180	.93	82.7	2.1	5.7
25% N-L, 75% L	9.758	9.989	.98	81.2	1.9	4.7

Table E
30kVA Inverter

LOAD	KW	KVA	P.F.	AMPS	C.F.	V-THD
25% TOTAL LOAD						
100% N-L	5.163	7.381	.70	58.0	2.5	4.9
75% N-L, 25% L	5.981	7.511	.80	59.7	2.4	4.7
50% N-L, 50% L	7.001	7.774	.90	61.6	2.2	4.2
25% N-L, 75% L	7.449	7.665	.97	60.9	1.9	3.6
50% TOTAL LOAD						
100% N-L	11.070	15.010	.74	118.4	2.3	6.3
75% N-L, 25% L	12.580	14.980	.84	119.2	2.2	6.1
50% N-L, 50% L	13.780	15.030	.92	119.1	2.1	5.5
25% N-L, 75% L	14.720	15.110	.97	119.9	1.9	4.8
75% TOTAL LOAD						
100% N-L	17.110	22.600	.76	178.6	2.2	7.2
75% N-L, 25% L	19.210	22.720	.85	181.2	2.2	6.7
50% N-L, 50% L	20.490	22.380	.92	177.7	2.2	6.0
25% N-L, 75% L	21.940	22.550	.97	179.0	2.0	4.9
100% TOTAL LOAD						
100% N-L	22.890	30.050	.76	240.0	2.3	7.4
75% N-L, 25% L	25.170	29.750	.85	238.3	2.3	6.8
50% N-L, 50% L	27.200	29.760	.91	237.8	2.2	5.7
25% N-L, 75% L	29.220	30.190	.97	242.0	2.2	4.6