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INVESTIGATION OF A FAMILY OF POWER CONDITIONERS INTEGRATED INTO A UTILITY GRID

Phase II

Report Period Covering January 1—December 31, 1981

By
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1. EXECUTIVE SUMMARY

This report deals with Category II, "intermediate size", power conditioners for solar photovoltaic (SPV) arrays in the range 30 kW to 600 kW. These systems interface with three-phase utility distributions at low voltage, below 1000 V; 480 V was selected as the nominal design value, but our results are equally applicable to converters at 208 V, 240 V and 660 V distributions.

Our main conclusion is that a family of designs based on the programmed-wave voltage-sourced dc-to-ac converter will best serve the needs of the application. The designs are modular in nature, with a three-phase six-pulse bridge as the basic power circuit building block. Two bridge designs, at 30 kW and 150 kW rating, are needed to cover the range. Power levels from 30 to 90 kW are accommodated by using one, two or three 30 kW bridges in six-pulse, 12-pulse and 18-pulse combinations. The 100 kW to 600 kW range is met by using one, two, three or four 150 kW bridges in six-pulse, 12-pulse, 18-pulse and again 12-pulse combinations.

State-of-the-art baseline designs use impulse-commutated thyristor bridges with front-end dc-to-dc converters in designs very similar to Westinghouse Aerospace Electrical Division's AVI-623. They cannot meet cost goals, by quite a margin, or efficiency goals, though they are much closer to the latter than the former.

Advanced concept designs use gate turn-off devices (GTOs) for the lower power range. These nearly meet the long range efficiency goals, but fail to meet long range cost goals. The higher power units are still thyristor based. Sufficiently large GTOs are not yet available at a reasonable price, nor are they expected to be for quite some time. When large GTOs do enter the marketplace, they can be substituted for thyristors in the 100 kW to 600 kW range with some cost and efficiency gains; however, the thyristor designs meet both long range cost and efficiency goals.

In both power ranges, the advanced designs dispense with a dc-to-dc converter and use a multi-pattern programmed-wave approach as opposed to the fixed pattern, regulated dc link approach of the baseline designs. This technique, by avoiding processing the power twice, is largely responsible for the cost and efficiency gains observed.

The conclusions are not constrained by the choice of building blocks; they would still be valid for other choices, 40 kW or 50 kW lower power base, for example, in conjunction with, perhaps, 200 kW higher power base. The final choice of base ratings will depend on the markets perceived at various power levels within the overall Category II range. This study assumed equally high sales volumes at all powers. However, the general patterns of costs and efficiences observed, and the benefits gained by the advanced designs, will hold true regardless of the actual family organization.

2. DC AND AC INTERFACES

2.1 DC Interface

There is no reason to change the dc interface specification from that established for residential (Category I) power conditioners except possibly in one respect, absolute voltage level. These applications will permit voltages higher than the 300 V limit imposed on the residential system. Whether a higher voltage should be used or not depends on system economics; this study compares designs for the 150 V to 250 V range with those for the 300 V to 500 V range. Slight converter cost and efficiency benefits accrue for the higher dc voltage range in the baseline designs. More significant benefits attach to its use in the advanced designs, and hence we recommend its adoption for Category II unless SPV array economics prohibit such a course. The basic electrical specifications are thus:

DC voltage range: 300 V to 500 V
Permissible current ripple: 5% peak

Array grounded; preferably at nominal center tap, but one pole grounded acceptable. Preferred fault protection is again an array shorting switch permitting subsequent isolation of array and converter via a dc contactor. The difficulties associated with fault detection, discussed in the previous report on residential power conditioning*, remain for these systems.

2.2 AC Interface

These systems will interface with three-phase ac distributions at 208 V, 240 V, 440 V - 480 V or, rarely, 660 V. The same ANSI standard for voltage range, ANSI C84.1, applies as for the residential systems*. Designing for utilization voltage Range B imposes a +6%/-12% tolerance at the interface.

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* Investigation of a Family of Power Conditioners Integrated into a Utility Grid, Phase I Report, Contract DE-AC02-79ET29359, Prepared by Westinghouse Electric Corporation. Pages 21, 26, 30-31.

Existing harmonic levels are similar to those previously reported, and the same current injection specification - 5% total rms, 3% any individual component - was used in the designs.

Transient voltage exposure is very similar; however, because of the lower impedances of these circuits as compared to residential feeders, transient energies tend to be higher. Because the absolute magnitudes of transient voltages are almost independent of system voltage, as shown in Table 2.1, per unit stresses decline as the distribution voltage increases. The conceptual designs, baseline and advanced, will withstand Category A surges from Table 2.1.

Table 2.1

Recommended Surge Voltages and Currents Deemed to Represent the Environment

Location Category	Comparable to IEC SC28A Category	Impulse Waveform	Impulse Maximum* Amplitude	Type of Specimen or Load Circuit	Energy Deposited in a 500 V Suppressor (Joules)
A. Outdoor and Service Entrance	IV	1.2 x 50 μs	10 kV o.c.	High Impedance	--
		8 x 20 μs	10 kA s.c.	Low Impedance	150
B. Major Feeders and Short Branch Circuits	III	1.2 x 50 μs	6 kV o.c.	High Impedance	--
		8 x 20 μs	3 kA s.c.	Low Impedance	40
		0.5 μs - 100 kHz	6 kV o.c.	High Impedance	--
			500 A s.c.	Low Impedance	2
C. Long Branch Circuits and Outlets	II	0.5 μs - 100 kHz	6 kV o.c.	High Impedance	--
			200 A s.c.	Low Impedance	0.8

*o.c.: open-circuit voltage

s.c.: short-circuit current

A major factor in the interfacing of three-phase systems is unbalance , discussed in detail in the next section of this report. The magnitude of unbalance observed on three-phase distributions varies widely with location and loading, but because of its effect on induction and synchronous machines, it is rarely higher than a few percent by the classical definition:

$$\text{Per unit unbalance} = \frac{|\text{Maximum or minimum line voltage} - \text{Average line voltage}|}{\text{Average line voltage}}$$

ANSI C84.1 is currently being revised to stipulate a maximum unbalance of 5%. This is the value for which our designs were executed.

The three-phase distributions that Category II power conditioners must interface may be grounded or ungrounded. Grounded circuits are found whenever four-wire distribution is the norm, i.e., when the neutral is available it is usually grounded. Three-wire distributions, when no neutral connection is provided, are often ungrounded. Thus the power conditioning equipment, to be universally applicable, should successfully interface with grounded or ungrounded three-or four-wire distributions. This it can only do, if it is grounded on the dc side, by having an isolation transformer (or isolation transformers) and making a three-wire (or six-wire) connection.

3. THREE-PHASE AC SYSTEM UNBALANCE

3.1 Analyzing Unbalanced Systems

Although unbalance is almost always defined by the equation given in Section 2.2, analysis of the behavior of unbalanced systems is best approached by the use of symmetrical components. This technique is based on the fact that any set of three phasors can be substituted by the vector summation of three sets of linearly independent phasors. These sets are called the symmetrical components of a three-phase system, and are defined as follows:

The positive sequence set:

Phase A: $A \cos (\omega t) + B \sin (\omega t)$ or A_1

Phase B: $A \cos (\omega t - \frac{2\pi}{3}) + B \sin (\omega t - \frac{2\pi}{3})$ or $a^2 A_1$

Phase C: $A \cos (\omega t - \frac{4\pi}{3}) + B \sin (\omega t - \frac{4\pi}{3})$ or $a^1 A_1$

where a is the vector operator $e^{j2\pi/3}$.

The negative sequence set:

Phase A: $A' \cos (\omega t) + B' \sin (\omega t)$ or A_2

Phase B: $A' \cos (\omega t - \frac{4\pi}{3}) + B' \sin (\omega t - \frac{4\pi}{3})$ or $a\ A_2$

Phase C: $A' \cos (\omega t - \frac{8\pi}{3}) + B' \sin (\omega t - \frac{8\pi}{3}) = A \cos (\omega t - \frac{2\pi}{3}) + B' \sin (\omega t - \frac{2\pi}{3})$

or $a^2 A_2$

The zero sequence set:

Phase A: A'' cos (ωt) + B'' sin (ωt) or A_o

Phase B: A'' cos (ωt) + B'' sin (ωt) or A_o

Phase C: A'' cos (ωt) + B'' sin (ωt) or A_o

Any three phasors can then be expressed, with any reference, by the vector sums

$$A = A_o + A_1 + A_2$$

$$B = A_o + a^2 A_1 + aA_2$$

$$C = A_o + aA_1 + a^2 A_2$$

or, given phasors A, B and C, the vector sums

$$A_1 = \frac{1}{3} (A + aB + a^2 C)$$

$$A_2 = \frac{1}{3} (A + a^2 B + aC)$$

and $$A_o = \frac{1}{3} (A + B + C)$$

give the symmetrical components.

Using these elements, any unbalanced three-phase system may be treated on a single-phase basis using superposition of these three linearly independent components. However, since for any three-wire connection the sum (A + B + C) must be zero, only the positive and negative sequence components need be considered; the zero sequence component, A_o, is necessarily zero.

A set of distribution voltages may be unbalanced because of two primary causes. The most obvious is unbalanced load - asymmetric loading on the three phases will clearly cause asymmetric voltage drops in their finite, non-zero impedances, and result in voltage unbalance. Not quite so obvious, but an almost equally important cause, is the unbalance of line impedances created by long untransposed transmission or distribution lines. Since these lines cannot form a geometrically symmetrical set with respect to each other and earth, their impedances will not be identical over lengthy paths unless they are regularly transposed (physically). In the case of untransposed sets, these unbalanced impedances will create voltage unbalance even with balanced loading.

It should be noted that in a four-wire system it is possible, insofar as the phase voltages (line-to-neutral voltages) are concerned to have magnitude unbalance without phase angle unbalance and vice-versa (i.e., it is possible for A, B and C to have different magnitudes but retain a progressive angular displacement of $-2\pi/3$ radians, or to have equal magnitudes but progressive phase displacements differing from each other and from $-2\pi/3$ radians). In a three-wire system, these conditions are not possible. Because A + B + C must equal zero, amplitude and phase angle unbalances are inevitably concurrent. Thus, if the cosine constituents of A, B and C in a three-wire system are balanced, so must be the sine constituents and vice-versa. By extension, if the real powers are balanced, so must be the reactive powers (and vice-versa) and real power unbalance is always accomplished by reactive power unbalance (and vice-versa) provided either the voltages or the currents are balanced. These relationships are fundamental to three-wire three-phase systems.

Although other types of load can be adversely affected, the major deleterious effects of unbalanced voltages are on induction and synchronous machines. The only useful, positive-torque-producing excitation for such machines is the positive sequence voltage set. The existence of a negative sequence set causes, of course, negative sequence currents to flow in the machines. These currents cause additional heating to an extent greater than their magnitude would suggest. This is because they produce braking torque in the machines, which must be overcome by increased positive sequence currents increasing the total positive torque (in induction machines, the slip increases). It is largely on the basis of "acceptable" machine derating that the 5% maximum unbalance stipulation is to be included in ANSI C84.1.

With regard to power conditioning interface, an unbalanced voltage set raises multiple considerations. The simplest situation is that in which the converter is a balanced three-phase generator producing only positive sequence fundamental voltage (some harmonics are negative sequence in any inverter system). Then in addition to the positive sequence currents which must flow to create the power transfer desired, negative sequence currents will flow. Their magnitude is determined by the negative sequence component of the ac system and the impedance connected between the converter and the system; assuming that impedance to be purely inductive, and to have a value x per unit on the converter's kW base, they cause an increase in the required inverter rating as Table 3.1 shows.

Table 3.1

Per Unit Reactance, x	Inverter Rating Balanced System*	Inverter Rating for 3%	5%	7%	10% Unbalance
.05	1.001	1.698	2.165	2.633	3.338
.1	1.005	1.358	1.596	1.835	2.196
.15	1.011	1.252	1.414	1.578	1.826
.2	1.020	1.205	1.330	1.458	1.651
.25	1.031	1.184	1.288	1.394	1.555
.3	1.044	1.176	1.267	1.359	1.500
.35	1.059	1.178	1.258	1.341	1.468
.4	1.077	1.185	1.259	1.335	1.452
.45	1.097	1.197	1.266	1.337	1.447
.5	1.118	1.213	1.278	1.346	1.450
.55	1.141	1.232	1.294	1.359	1.459
.6	1.166	1.253	1.314	1.376	1.473
.65	1.193	1.277	1.336	1.396	1.491
.7	1.221	1.303	1.360	1.420	1.513
.75	1.250	1.331	1.387	1.445	1.537
.8	1.281	1.360	1.415	1.473	1.563
.85	1.312	1.391	1.445	1.502	1.592
.9	1.345	1.423	1.477	1.533	1.622
.95	1.379	1.456	1.509	1.565	1.654
1	1.414	1.490	1.543	1.599	1.687

*On kW base, is > 1 because of increased voltage required to get torque angle necessary to produce power transfer.

These figures are calculated from the equations given in Appendix A for the case with the converter in balanced operation.

Were it not for harmonic and control stability considerations, the optimum x for a balanced system would be zero p.u.; harmonic requirements force x for a 12-pulse converter to be 0.3 p.u, rating $\geq$ 1.044 p.u. With unbalances of 3, 5, 7 and 10% the corresponding minimum required inverter ratings are 1.176 p.u. (x = 0.3 p.u.), 1.258 p.u. (x = 0.35 p.u.), 1.335 p.u. (x = 0.4 p.u) and 1.447 p.u. (x = .45 p.u.). The nominal values of Table 3.1 can be condensed into the following approximate expressions:

Maximum p.u. required inverter voltage,

$$E_{max} = (1 + .007328 \times U) \sqrt{1 + x^2}$$

Maximum p.u. required inverter current,

$$I_{max} = 1 + \frac{.0116\ U}{X}$$

$$\text{p.u. inverter rating} = E_{max}\ I_{max}$$

where U is the percentage unbalance.

The penalty for 5% unbalance is clearly not inconsequential - at a minimum, for a 12-pulse converter, the converter is required to have 20% higher rating and a tie reactance of 0.35 p.u. rather than 0.3 p.u. However, the rating penalty declines as x is increased; for a programmed-wave converter requiring, say, 0.6 p.u. tie reactance to meet harmonic specifications, 5% unbalance means a 12.7% increase in required rating, and if the tie reactance is 1 p.u., then only 9.1% increase in rating is needed.

If the converter is unbalanced, and the rating penalty accepted, the harmonic spectrum from the converter remains as it is for the balanced case. However, if attempts are made to reduce converter rating penalties by unbalancing converter operation, this is no longer the case. Additional harmonic injection will occur because of the presence of zero sequence harmonics in the individual pole (single phase) voltages of the converter.

To elaborate, the output voltage of a simple single-phase inverter and the individual pole voltages (phase voltages) of a three-phase bridge contain all odd order harmonics. Those whereof the orders are integer multiples of three (i.e., the third, ninth, etc.) form zero sequence sets in any balanced three-phase arrangement (the three-phase bridge being the simplest example) and hence do not appear in the three-wire voltages of such an arrangement. If the converter operation is unbalanced to produce unbalanced fundamental components, these harmonics will be injected into the ac system as mixed positive and negative sequence sets. Expressing the situation less elegantly, suppose three simple single phase converters are individually tied to the system, through reactances, and operated as a balanced set. Then their third-harmonic voltages will be equal in magnitude and all in phase (zero sequence!) and hence the third-harmonic currents flowing in the reactances will be equal in magnitude and all in phase and thus will not flow in the ac system (they cannot, for the only sets of currents that can flow in a three-wire system are those which independently sum to zero) but will circulate around the "delta" connection of the three converters. Now suppose that converter A voltage is increased by 5% and converter B voltage reduced by 5%, to match ac system unbalance. Their third-harmonic voltages are similarly changed, and so are the third-harmonic currents they drive in the tie reactances. The differences in the unbalanced-converter created third-harmonic currents cannot circulate the delta and must flow in the ac system - 10% in the B line, 5% in each of the A and C lines in the example given.

The upshot is that any modulation policy for harmonic suppression must address the zero sequence harmonics of the balanced three-phase converter's individual voltages if unbalanced converter operation is used; if only balanced operation is used, it need not do so.

Now the converter rating penalty (due to unbalance alone, independent of x) independent operation of three single phase converters is (100 + u)/(100-u) or 1.1 for 5% unbalance. However, we take a construction penalty for having three independent single-phase units as opposed to a three-phase unit, and the reduction of rating penalty achieved decreases sharply as x increases - from $\sim$ 10% gain for x = 0.3 to $\sim$ 2.5% gain for x = 0.6. Coupled with the harmonic injection implications of unbalanced, three single-phase converter operation, there is a strong probability that balanced operation of a three-phase converter is better as regards cost and losses; it is certainly simpler from a control viewpoint.

The same arguments apply when unbalanced operation of a three-phase converter (e.g., three-phase six-pulse bridge or combination thereof) is contemplated. However, benefits, if any, are even less in that case because the three converter phases are not then independent - the phase voltage magnitudes are inviolately identical, only their progressive phase displacements can be changed. Whereas the assessment for three independent single-phase converters is straightforward, that for the unbalanced three-phase converter case must be based on the symmetrical components of two unbalanced ac sources - the system and the converter. Appendix A shows how to deal with this case; here it suffices to say that there is even less incentive to adopt unbalanced operation of a three-phase converter than exists for the use of three independent single-phase converters.

All the designs described in this report use balanced operation of three-phase converters. Although there is a chance that the use of three independent single-phase converters would be competitive, we concluded on the basis of the above arguments (and some rudimentary numerical expressions) that it would not offer significant cost or efficiency advantages. It would involve additional harmonic problems and, perhaps worst of all, would introduce control interaction problems (between the three independent converter controls) that are ill-defined but potentially serious if ac system impedance is not negligible.

4. CONVERTER TECHNOLOGY - BASELINE SELECTION

There are only three valid considerations for selecting a power conditioning approach to a given application and specification - cost, efficiency and reliability. Performance is not an issue - if the converter/system designer knows his business, any converter technology which will perform the basic function(s) required - in the case dc-to-ac conversion - can be made to meet the performance specifications. Differences in intrinsic converter behavior which affect the inherent suitability of different converter types for different applications will be reflected in converter system cost, converter system efficiency and converter system reliability. Hence we will not discuss performance aspects in this section except as they make such impacts, and all converter systems considered are assumed to be designed to meet the application performance requirements and specifications.

The list of possible candidate converter technologies is almost endless, but can be logically subdivided into a limited number of types. The first subdivision lies between direct or straightforward approaches and so-called "high technology" approaches.

The former approaches the application by simply inverting the array dc to 60 Hz ac of appropriate quality and using a 60 Hz isolating transformer. The latter seek to save cost (and in some instances, very optimistically, losses) by isolating at some higher frequency. To do so they must invoke double conversion at best - dc to high frequency, high frequency to 60 Hz; often, since the ac-to-ac conversion function is difficult to realize, they use triple conversion, introducing a high frequency to "dc" stage and finally inverting the "dc" to 60 Hz ac. The "dc" is placed in quotation marks because it is usually made pulsating (waveshaped) to avoid the harmonic control problems at the ac interface which attend the use of simple dc-to-ac conversion.

It is not necessary to conduct detailed cost and loss comparisons to reject any and all such approaches vis-a-vis a straightforward approach. Proponents aver that they are "replacing copper and steel with silicon", which must save money, if not immediately, then in the long run. It is not difficult to uncover the fallacy in this argument.

Point one: The dc to high-frequency ac conversion stage of such an approach must of necessity possess all the properties needed of a dc to 60 Hz converter; with an appropriate modulation policy, it, together with a 60 Hz isolation transformer and the same harmonic control ac interface as the high technology candidate uses, could totally fulfill the application requirements. Hence the comparison is immediately reduced to a 60 Hz isolation transformer versus a high-frequency isolation transformer and either an ac-to-ac converter (high frequency to 60 Hz) or an ac-to-dc converter followed by a dc-to-ac converter. Thus the argument is seen to hinge on the contention that this converter, or converters, in conjunction with a high-frequency isolation transformer, is or will be substantially cheaper than a 60 Hz isolation transformer.

Point two: Even in the simplest converter system implemented for any application, the simple current-sourced ac-to-dc/dc-to-ac converter, the cost of converter and controls exceeds the cost of the appropriate 60 Hz isolation transformer used in conjunction with it. In manufacturing costs, the ratio is at least two to one, possibly five to one or more. Hence at present _there is no hope of a high technology approach being cost competitive._

Point three: It is well-known that the cost of power conditioning equipment in the power range under study is not, today, governed by the cost of the semiconductor devices used therein. It would make very little difference to the price of most motor drives, UPS systems and the like _if the power semiconductors were free._ Hence the argument that reduced silicon device costs will make a high technology approach competitive is totally invalid.

Point four: Isolation transformer costs do not by any means reduce linearly in size and cost with increasing frequency. It can be seen that for a given power level, there is an optimum frequency which minimizes the transformer size, and that this frequency steadily decreases with increasing power rating. In part, this situation is brought about by thermal restrictions - the transformer must have sufficient surface area to transfer its conductor and core losses to its coolant (normally ambient air in the power ratings under study) with acceptable temperature rise. Other contributory factors are magnetic material characteristics, the increase of conductor ac losses with frequency due to skin and proximity effects, and the effects of high frequency on insulation systems, for example, the reduction in corona threshold.

When these considerations are applied, the optimum frequency for transformers in the 30 kVA to 600 kVA range considered is found to be far below the 10 kHz to 50 kHz usually predicated for high technology - in the range from a few hundred to a few thousand Hz. The mimimum cost transformer is about one-third the cost of a 60 Hz transformer, at best. Hence the comparison reduces to that between two-thirds the cost of a 60 Hz transformer and the assembly labor and auxiliary components (heat sinks, snubbers, gate or base drive and control and supporting hardware) costs for the ac-to-ac conversion function.

At a minimum, the present ratio for these costs is one to three with simple converters made in hundreds per year. High technology approaches certainly cannot reach parity for volumes of a few thousand per year, since the costs compared are subject to the same inflationary pressures in both cases. It is conceivable that parity might be achieved for volumes of hundreds of thousands per year, but by no means certain.

If the cost picture does not force a decision to reject, for the present and near future, high technology approaches, the addition of efficiency considerations should. Let us begin by postulating a dc-to-ac converter in which power device conduction losses (including gate or base drive losses) are about 1.5% (which is fairly typical) and allow associated switching loss at 60 Hz switching of 1% of the conduction loss (which is optimistic). Then at 600 Hz, which is about the frequency at which a programmed-wave dc-to-60 Hz ac converter would run, switching loss would be 10% of conduction loss and converter efficiency would be 98.35%. At 6 kHz, switching loss would equal conduction loss; at 25 kHz, which is in the frequency range where most high technology proponents propose to operate, switching loss would be about four times conduction loss and converter efficiency would drop to 92.5%. It is clear that the resulting source cost penalty would make the high technology approach noncompetitive - at $0.70 per watt in a 100 kW unit, the converter loss penalty for the example cited would be $4095, or = $41/kW equivalent capital cost - about 30% of the long term cost goal of $145/kW. Since the 60 Hz transformer does not represent anywhere near 30% of the cost of a straightforward approach - its cost is less than half that - there is no hope for a high technology approach to become cost competitive overall by eliminating the 60 Hz transformer.

It may be argued that this is not necessarily the case, since eliminating the 60 Hz transformer eliminates its losses, thus achieving a compensating efficiency credit. This is not so! The 60 Hz transformer is itself quite efficient - 98% or better at full load. A high efficiency transformer replacing it will not have losses less than 40% of the 60 Hz transformer loss, and the losses of the ac-to-ac conversion will in any case certainly approach, if not exceed, those of the dc-to-60 Hz converter. Thus at best the overall "transformation and isolation" losses will be about equal. More likely these losses in the high technology approach will exceed those for the 60 Hz transformer, adding further to the loss penalty suffered by the more sophisticated system. In simple terms, one cannot process the power throughput twice (dc-to-high-frequency ac, ac-to-ac) and even less so thrice (dc-to-high efficiency ac-to-dc-to-60 Hz) and expect to achieve the same efficiency as is achieved when the power is processed once only.

Some proposed high technology approaches seek to improve their competitive position by using a single quadrant (in the V-I plane) dc-to-high-frequency conversion stage. Such a stage should have one-half of the cost of a two quadrant (dc side) dc-to-high-frequency stage, and hence be capital cost competitive with straightforward approaches. Also, since its switching and conduction losses are also only one-half those for the two quadrant version, it will not suffer quite so much in efficiency and may be overall cost competitive. However, at best such an approach may achieve slight capital cost advantage and overall economic parity, at the expense of technical problems, which significantly reduce its applicability.

First, the single quadrant converter operated to waveshape (modulate) its high-frequency output may be plagued by the classical dc-to-dc converter closed-loop control instability for duty cycles less than one-half if it is a buck converter, greater than one-half if it is a boost converter. Second, and perhaps more significant, the overall system has only unidirectional energy flow capability. Hence it can only operate safely in the appropriate two quadrants at the 60 Hz ac terminals. However, the ac-to-ac conversion stage or dc-to-ac conversion stage used for this interface will inevitably be capable of energy flow reversal if the 60 Hz system undergoes a transient which forces it into one of the forbidden quadrants. Since the conversion system upstream of that stage is single quadrant and has no capability for energy flow reversal, a potentially catastrophic fault will result. Since utility system transients which will do this are not infrequent, the reliability of such an equipment is open to serious question.

A further disadvantage of the "dc-to-modulated high-frequency to 60 Hz ac" approach is that it cannot be implemented on a true three-phase basis - three single-phase units must be used to meet three-phase applications. This imposes an economic penalty on the order of 15-20% in capital cost, and also an extra loss penalty.

We have concluded that the high technology approaches do not look promising; in the forms in which they can match straightforward approach capabilities, they cannot achieve capital cost parity and suffer substantial loss penalties. In the forms in which they can possibly achieve capital cost advantage, they still suffer sufficient loss penalty to make their overall economic situation no better than par and have application problems of a potentially serious nature. Thus we restrict the study to straightforward approaches, the five in question being:

1. Simple current-sourced source (line) commutated inverter with power factor correction and harmonic filtering (CSC).

2. The same with a front-end dc-to-dc converter used to limit the amount of power factor correction needed (DCSC).

3. Fixed-pattern programmed-wave voltage-sourced self-commutated converter with front-end dc-to-dc converter (FPPW).

4. Multi-pattern programmed-wave voltage-sourced self-commutated converter (MPPW).

5. Natural or uniform sampling pulse-width-modulated voltage-sourced self-commutated converter, PWM, with or without a front-end dc-to-dc converter.

Self-commutated current-sourced converters are not considered economically competitive because of the costs, losses and technical difficulties associated with the implementation of impulse commutating circuits in such converters. Advanced switching devices do not help such systems because commutation therein is not a function of device properties - it is governed by ac source reactance.

Candidate technology 5, PWM, can be eliminated from consideration. To achieve the same performance as candidate 4, MPPW, it requires a higher switching rate ($\sim$10 times higher) and hence has slightly higher capital cost and significantly higher losses.

Candidate technology 2, DCSC, also quickly falls by the wayside. Using a dc-to-dc converter ahead of a current-sourced line-commutated converter does not reduce the power factor correction needed by a sufficient margin to pay for itself, and introduces significant additional losses.

It does not reduce power factor correction needs much because:

(a) The harmonic filters needed supply a high proportion of the worst case leading VAR requirement for the converter, and they cannot be eliminated by the dc-to-dc converter.

(b) The need for adequate commutation margin makes the converter run at a relatively bad "best case" power factor, and the dc-to-dc converter cannot change this situation.

Hence we very rapidly reduce the candidate technologies to three - CSC, FPPW and MPPW. Of these, only the first two can be considered for the baseline. Because the multi-pattern programmed-wave converters need substantial control investigation and development prior to being implemented in optimized designs, they are not considered as baseline candidates.

Now there is no doubt that the converter section of CSC is less expensive and more efficient than that of an FPPW system. It uses only thyristors, gate drives and controls and does not have a dc-to-dc converter. The voltage sourced approach must use advanced devices (GTOs or transistors) or impulse commutating circuits in conjunction with fast switching thyristors, which in any case cost more than the thyristors in the CSC. However, the dc and ac interface costs are substantially less for FPPW than for CSC. The latter uses an inductor and capacitor at the dc interface, the former just a capacitor and its dc interface costs may be less than one-quarter of those for a CSC. At the ac interface, FPPW can interface via a relatively small (0.3 per unit or so) reactor. A CSC needs leading VAR supply, which may be provided wholly or in part by its harmonic filter, some means of controlling the VAR as converter loading and operating conditions vary, and an intertie reactor. The most reliable VAR control technique uses thyristor controlled shunt reactors, and for a three-phase system the thyristors and controls so used are equivalent to another complete converter.

Thus, the cost advantage that a CSC system might seem to have on the basis of converter costs alone is dissipated by the much greater interfacing costs it incurs. At best, it will achieve capital cost parity with a FPPW system; since efficiencies for the two approaches are not significantly different (though tending to favor CSC if thyristors are used in FPPW, tending to favor FPPW if transistors or GTOs are used therein), overall approximate parity is evident. Thus other criteria must be sought for making the choice. Reliability is also roughly equivalent, in the power range under study where one switching device can easily fulfill a converter switch position's needs, so it cannot be used. The only natural avenue comes from an examination of ac interface behavior.

As noted above, FPPW needs only a simple reactor intertie, or at worst a T (series L-shunt C- series L) filter. A CSC needs multiple shunt tuned filters for harmonic control and perhaps additonal shunt capacitance for leading VAR supply. Two considerations now can be invoked. First, the CSC needs tuned filters. Because of component tolerance, the factory test procedure will be complex and time consuming. Moreover, component temperature and aging coefficients may cause system harmonic performance to degrade, possibly beyond specification limits, after some period of operation. Second, the CSC interface introduces multiple resonances in the ac distribtion system. These can exacerbate voltage transient conditions, create a medium for undesirable interactions between multiple converter systems and the CSC's interfacing filters (and possibly, in consequence, its converter) may be subject to damage from other harmonic generators connected to the utility system. The FPPW system does not suffer any of these problems.

The CSC's ac interface problems can be solved by either of two approaches. Designs can be effected which make the filters insensitive to component value variations and tolerances, and which adequately damp all resonances introduced and are inherently protected against other harmonic generators. Alternatively, site-specific design can be used, as it is, for example, in the application of HVDC transmission and static VAR generators. Unfortunately, in our Category II power range, either of these approaches will so impact the cost of a CSC system as to make it non-competitive with an FPPW system.

We conclude, then, that the appropriate choice for the baseline designs is FPPW, a family of converters using voltage-sourced self-commutated fixed-pattern programmed-wave dc-to-ac converters with front-end dc-to-dc converters for dc link voltage (and hence converter ac output voltage) control.

5. CATEGORY II FAMILY

Having established the technology choice, there remains the problem of structuring a family of power conditioning units to cover the range under study, 30 kW to 500 kW. The "basic building block" will, of course, be a three-phase six-pulse bridge voltage-sourced self-commutated dc-to-ac converter. Thus the simplest family would be one unit - a 500 kW bridge. Obviously, such a choice would yield exorbitant costs and very low efficiencies at the low power end of the range. The other extreme would be to build custom designed and sized units for each and every application, and hence power level. The resulting low volume for any individual unit would make it impossible to meet cost goals at any power level.

Now bridges can be combined into systems with higher pulse numbers. Two six-pulse bridges can be used to form a twelve-pulse system, three to form an eighteen-pulse system and so on. Such combinations afford improved harmonic performance, and hence can further reduce ac interface costs. Thus it makes sense to explore the possibilities of a family in which units comprise some number of basic building blocks. The lowest power rating will have just one such block. Suppose we make the basic bridge rating 30 kW; then the following family would develop:

30 kW - 1	bridge,	6-pulse		
60 kW - 2	bridges,	12-pulse		
90 kW - 3	"	, 18- "	or 12 pulse and 6-pulse	
120 kW - 4	"	, 24- "	or 12- "	
150 kW - 5		, 24- "	or 12- "	and 6-pulse
180 kW - 6	"	, 18- "		
210 kW - 7	"	, 18- "	and 6-pulse	
240 kW - 8	"	, 24- "	or 12- "	
270 kW - 9	"	, 18-pulse		
300 kW -10	"	, 18- "	and 6-pulse	
330 kW -11	"	, 18- "	and 12- "	
360 kW -12	"	, 24- "	, 18-pulse or 12-pulse	
390 kW -13	"	, 24, 18 or 12 pulse and 6- "		

420 kW	-14	bridges,	12-pulse
450 kW	-15	"	, 18- "
480 kW	-16	"	, 24 or 12-pulse
510 kW	-17	"	, 24 or 12- "

Obviously, the family has too many members; the "stepsize" of rating is apposite for the low end of the range, far too small for the high end. However, if we choose a larger building block, so that the stepsize becomes appropriate for the high end, it will be too large, and consequent costs will be too high, at the low end.

The inescapable conclusion is that we need two families, or at best two different building blocks, one for the lower power range, one for the higher. If our first choice is still 30 kW rating, then it can reasonably serve the range 30-120 kW using 1, 2, 3 and 4 bridge combinations in 30, 60, 90 and 120 kW units. Then if we create a 150 kW building block, it can serve the upper range in 1, 2, 3 and 4 bridge combinations having 150, 300, 450 and 600 kW ratings.

The family now has only eight members based on only two basic power units; this seems eminently reasonable, and will be used as the baseline design basis.

Note that in the original large family listing we had nowhere predicated a pulse number greater than 24. This because the harmonic benefits gained by higher pulse numbers are at best tenuous, and in any case the added cost of transformer complications would more than outweigh any realizable ac interface cost saving. The revised family never uses more than four bridges, so could never be more than 24-pulse. There are two questions which arise. Should three bridge combinations be 18-pulse or 12-pulse and 6-pulse and should four bridge combinations be 24-pulse or 12-pulse?

The answer to the latter occurs easily. There are no significant benefits at the ac interface for 24 as opposed to 12-pulse operation, and a 24-pulse system incurs transformer cost penalties because of the 15 degree phase shift required (a 12-pulse system needs 30 degrees phase shifts that are provided without penalty by the wye-delta transformation). Hence four bridge combinations should be 12-pulse.

For three bridge combinations, the answer is not so clear; 18-pulse operation incurs a transformer cost penalty because of the 20 degree phase shifts required, and offers no advantage over 12-pulse operation. However, it has significant advantages over 6-pulse operation, since a simple 6-pulse bridge cannot be interfaced with an inductance alone -- it needs the T (L-C-L) filter. A three bridge, 12-pulse and 6-pulse arrangement would be, of course, one-third 6-pulse. To meet the harmonic specifications of this application, this arrangement needs $\sim$ 0.5 per unit tie reactance, whereas a 12-pulse system needs only 0.3 per unit and an 18-pulse system only 0.12 per unit. Given that for other areas (control stability and fault current limiting), we would probably choose to build 0.3 per unit reactance into the bridge, the trade-off is between the extra transformer cost for an 18-pulse system and the extra 0.2 per unit reactance for a 12-pulse and 6-pulse system. The effective transformer rating increment is 0.05 per unit (averaged among these bridges), making the 18-pulse version the better choice.

Thus the family can be described as follows:

Rating	No of Bridges	Pulse Number	ac Interface
30 kW	1	6	L-C-L
60 "	2	12	L
90 "	3	18	L
120 "	4	12	L
150 "	1	6	L-C-L
300 "	2	12	L
450 "	3	18	L
600 "	4	12	L

It would, obviously, not be necessary to program the converter's waves at all for the 2, 3 and 4 bridge numbers of the family. The one bridge numbers, 30 and 150 kW rating, need L-C-L filters if programmed-wave is not used. It might seem that programming the waves to eliminate the fifth and seventh harmonics is indicated for the one bridge family members, but an examination of the trades involved reveals this not to be so. The reduction of ac interface costs is not great, because the pattern which eliminates fifth and seventh harmonics multiplies the eleventh harmonic magnitudes by a factor close to three and drives the tie reactance needed to about 1.5 per unit. The L-C-L filter for a 6-pulse converter uses a total of 1 per unit reactance with $\sim$ 1.25 per unit capacitance, and the net cost reduction is not large. On the other hand, the required converter rating, per unit, for a 6-pulse converter with that filter is 1.2 per unit; the required rating with a supply reactance tie, x per unit, is $\sqrt{1 + x^2}$ which for x = 1.5 is 1.8 per unit and since converter incremental costs would considerably exceed ac interface savings the programmed wave is contraindicated. Somewhat better results can be obtained by programming the wave for minimum total rms current distortion in an inductive tie, rather than eliminating the fifth and seventh harmonic, but the trade still favors the simple 6-pulse approach and it is adopted for the baseline designs.

Finally, we come to the question of the actual switching devices to be used in the baseline designs. GTOs will not be considered - they are, at the time of the study, not usable without extensive circuit development and thus violate our rules defining baseline system. The choice lies between transistors and thyristors with impulse commutating circuits for both the dc-to-ac converters and the front-end dc-to-dc converters.

Now for the 150 kW bridge, there is no choice. For either input dc range considered, 150-250 V or 300-500 V, transistors could not be used without parallel connecting several devices. It is a fact well proven in the marketplace that he who uses many devices to perform a given function will not be competitive,with he who uses but one. The cost of auxiliary components and assembly labor will render a multiple device approach completely noncompetitive, and thus we conclude that transistors not be used for the higher power units with a 150 kW bridge building block.

For the lower power units, 30 kW bridge building block, transistors cannot presently be used for the 300-500 V dc range without parallel connection, and the same conclusion applies. For the 150-250 V dc range, transistors could be used. However, those available with the required voltage (400 V or more) and currents ($\sim$ 150 amperes peak) capability represent the technical upper limit and are extremely expensive. Thus it is unlikely that a design using them would currently be competitive; on that ground, and in the interests of a consistent approach to all the baseline units, we will choose thyristors throughout.

6. BASELINE COST, LOSS, SIZE AND WEIGHT ESTIMATES

6.1 Introduction and Family Organization

As described in Section 5, the baseline designs comprise from one to four three-phase voltage-sourced self-commutated thyristor dc-to-ac converters with dc link voltage control provided by one to four boost dc-to-dc converters. Cost estimates were established by the procedures used for Category I and previously reported*.

An elementary schematic of a converter "pole" is shown in Figure 6.1; three such poles make a bridge. An elementary schematic of a boost converter is shown in Figure 6.2. The configurations for the family are as follows:

30 kW unit: One 30 kW boost converter, one 30 kW bridge, ac interface as shown in Figure 6.3.

60 kW unit: Two 30 kW boost converters, two 30 kW bridges, ac and dc interfaces as shown in Figure 6.4

90 kW unit: Three 30 kW boost converters, three 30 kW bridges, ac and dc interfaces as shown in Figure 6.5.

120 kW unit: Four 30 kW boost converters, four 30 kW bridges, ac and dc interfaces as shown in Figure 6.6.

150 kW unit: As 30 kW except 150 kW rated boost converter, bridge and passive components.

300 kW unit: As 60 kW except 150 kW rated converters and passive components.

450 kW unit: As 90 kW except 150 kW converters, etc.

600 kW unit: As 120 kW except 150 kW converters, etc.

The boost converter commutating circuit, shown in Figure 6.2, is a commonly used "soft" commutating circuit with no great virtues or

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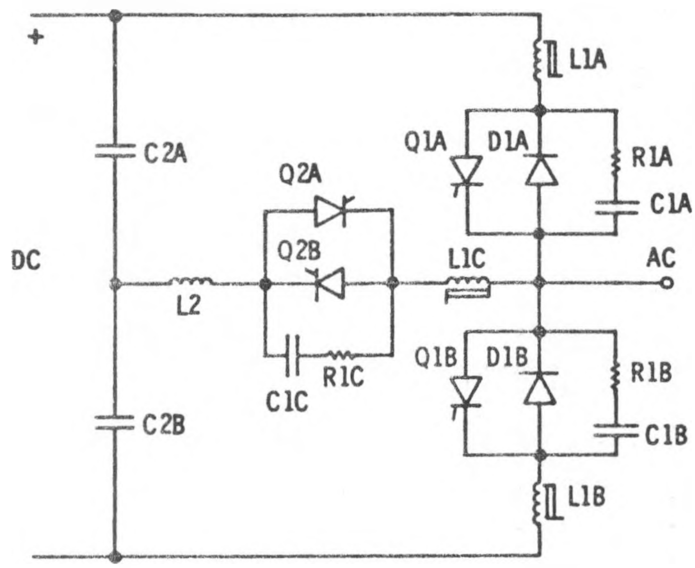
* loc. cit. page 54.

Dwg. 4250812

(a) Split Capacitor Version for Low-Voltage DC



(b) Alternative Commutating Circuit for Higher DC Voltages with Center-Tap Available

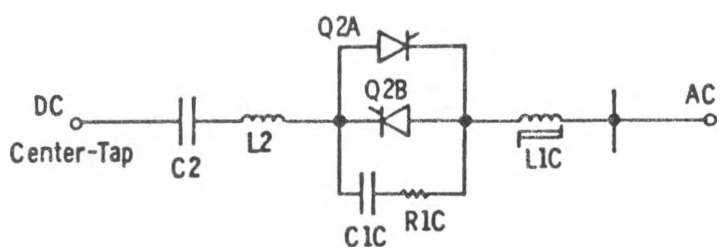


Fig. 6.1—DC to AC converter pole

Dwg. 7752A90

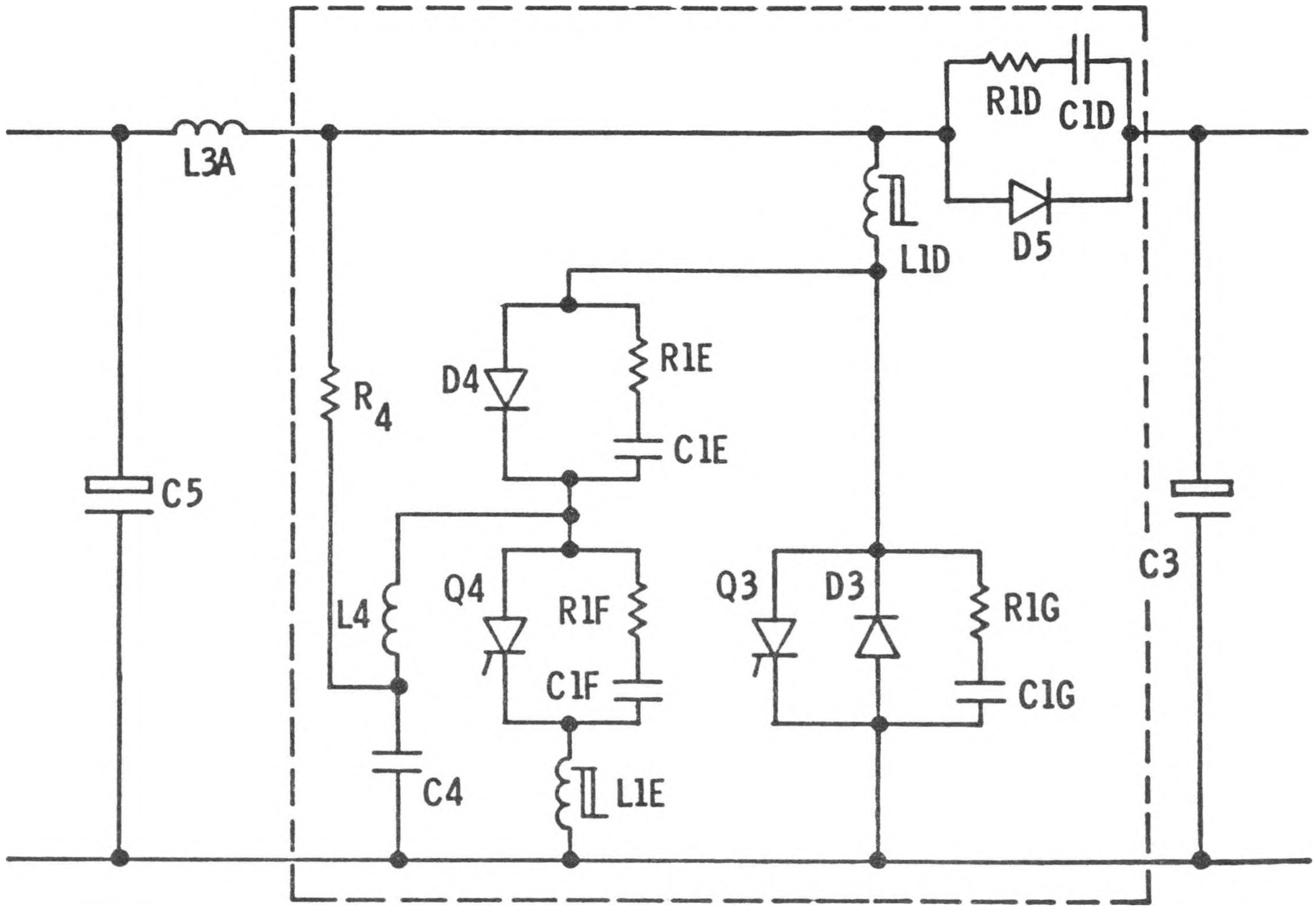


Fig. 6.2 – DC to DC Converter

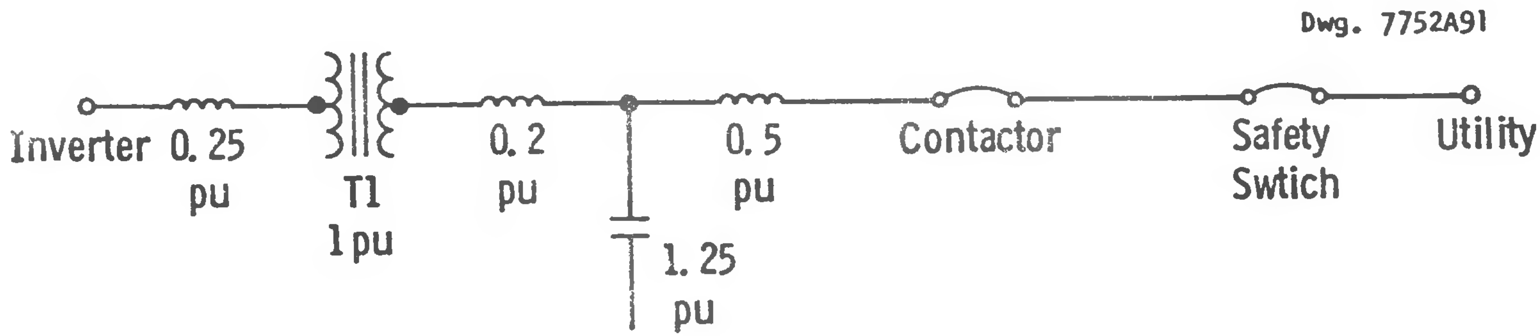


Fig. 6.3—AC interface for 30 and 150 KW units (one line diagram)

Dwg. 7752A89

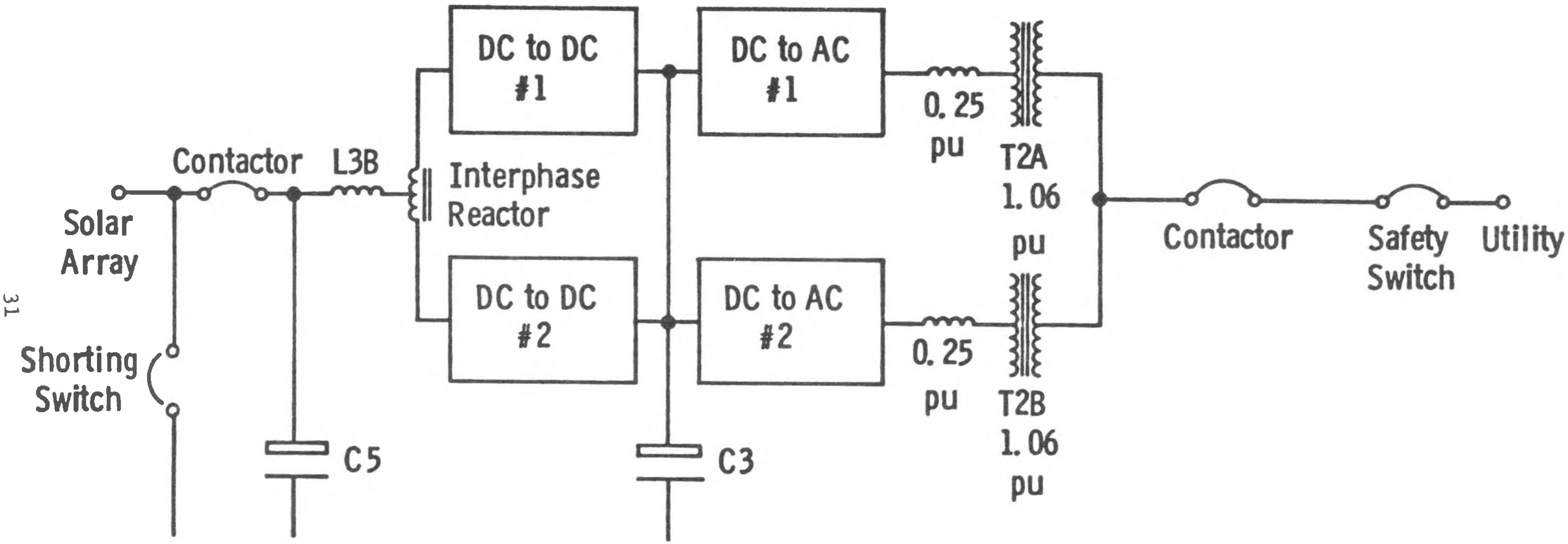


Fig. 6.4—AC and DC interfaces for 60 and 300 KW units (one line diagram)

Dwg. 4250B09

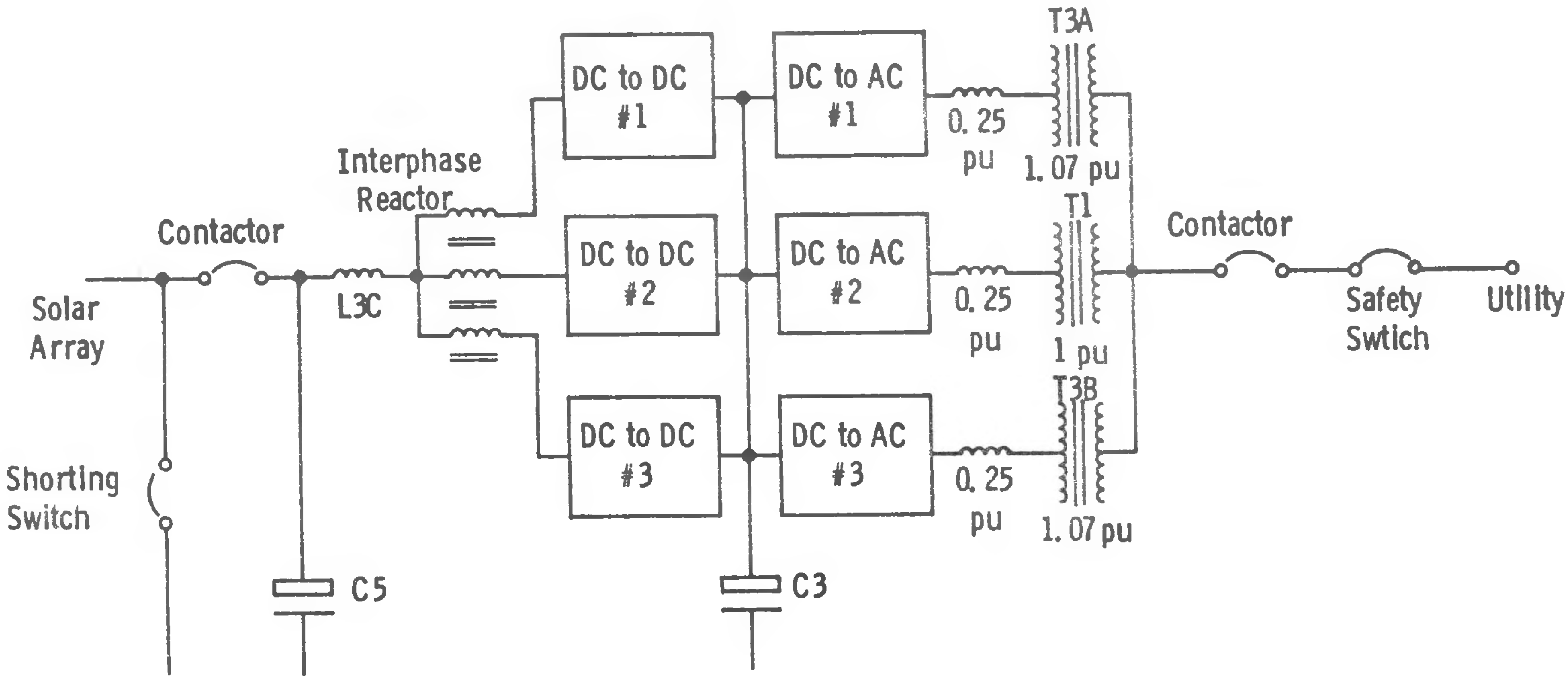


Fig. 6.5—AC and DC interfaces for 90 and 450 KW units (one line diagram)

Dwg. 4250B10

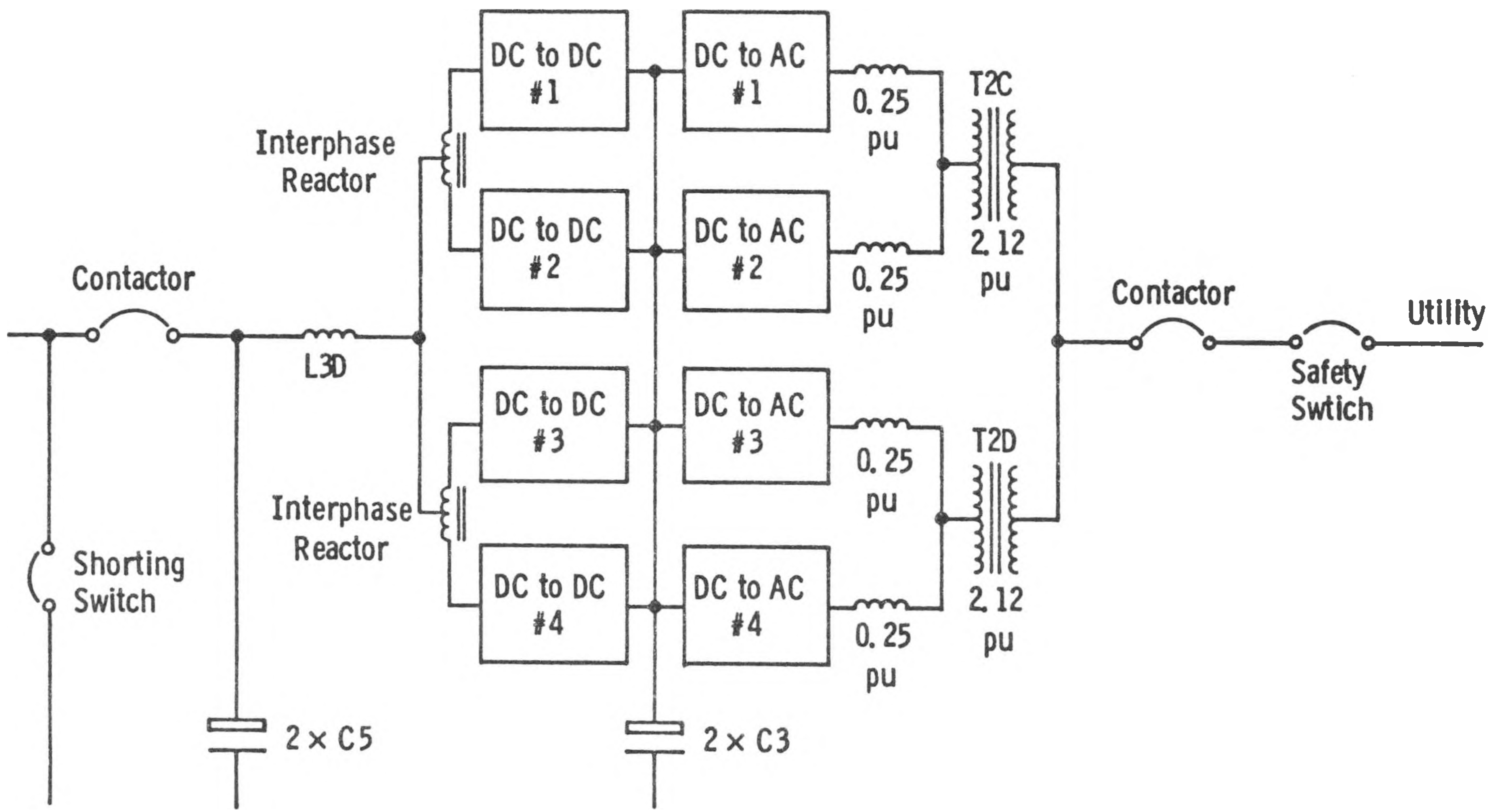


Fig. 6.6—AC and DC interfaces for 120 and 600 KW units (one line diagram)

vices. The dc-to-ac converter commutating circuit shown in Figure 6.1a is one of two versions predicated. For the lower dc voltage range (150-250 V), series capacitors are not needed in the dc link and no "dc center-tap" is available - hence the "ac switched McMurray" configuration shown in Figure 6.1a; Figure 6.1b shows the alternative, which is simply an ac Thévenin equivalent, used for the higher dc voltage range (300-500 V) when series capacitors are needed in the dc link and a dc center-tap is available.

In addition to costing (and making loss, size and weight estimates for) the baseline designs for the two dc source voltage ranges, the original calculations involved two versions of each design - "minimum cost" and "loss penalized". The minimum cost designs used absolute minimum cost magnetic components (transformers, reactors, interphase reactors, etc.). Loss calculations for them showed they had almost no hope of meeting efficiency goals. The loss penalized designs were executed with magnetics cost optimized for a $0.70/watt charge for losses, i.e., the component effective price which was minimized was capital cost plus $0.70 x watts loss. These designs could meet or showed promise of meeting efficiency goals and were not much more expensive (typically ∿ 5%) than the minimum cost designs. Hence we report only the loss penalized designs herein.

6.2 Cost, Size and Weight Estimates

The cost estimate for a 30 kW pole develops as follows, with component designations referencing Figure 6.1:

	Material Cost - $		Assembly Labor - $
	150-250 V	300-500 V	
Q1	$ 50.40	$ 52.45	
D1	20.25	28.75	
Heat Sink	5.13	3.10	
	$ 75.78	$ 84.30	20/20
x2	151.56	168.60	40/40
Q2's	100.80	104.90	
Heat Sink	5.13	3.10	21/21
	$257.49	$276.60	61/61
C1's	20.91	24.90	18/18
R1's	10.14	10.14	18/18
C2	25.16	12.26	12/6
L2	41.55	71.09	8.32/14.22
L1's	5.55	22.23	18/18
	$360.80	$417.22	135.32/135.22
Gate Drives (4)	120.00	120.00	80.00/80.00
	$480.80	$537.22	215.32/215.22

Thus, the 30 kW bridges for 30/60/90/120 kW units, which comprise three poles, have costs of $2088.36 for the 250 V version and $2257.22 for the 500 V version.

The 150 kW pole costs develop as follows:

	Material Cost - $	Assembly Labor - $
	250 V/500 V	
Q1	109/212	
D1	33/21.75	
Heat Sink	15.83/10.12	
	157.83/253.87	40/40
x2	315.66/507.74	80/80
Q2's	100.80/104.90	
Heat Sink	31.66/10.12	20/21
	448.12/622.76	100/101
C1's	21.78/25.92	18/18
R1's	13.92/14.64	18/18
C2	71.98/34.02	12/6
L2	37.52/37.03	7.42/7.40
L1's	44.46/177.87	18/18
	637.78/912.24	173.42/168.40
Gate Drives (4)	120/120	80/80
	757.78/1032.24	253.42/248.40

Thus, the costs of 150 kW bridges for the 150/300/450/600 kW units are $3033.60 for the 250 V version and $3841.92 for the 500 V version. The much larger discrepancy between 250 V and 500 V costs observed here is mainly a consequence of the high thyristor price and high saturable reactor costs for the 500 V version.

Next we deal with ac interface costs. We can draw up the following table for

30/60/90/120 kW units:

	30 kW	60 kW	90 kW	120 kW
Output Transformer(s)	$ 470.60	$ 984.22	$1467.70	$1666.88
Labor for Above	176.87	368.16	549.23	595.66
.25 p.u. Reactor	96.98	193.96	290.94	387.92
Labor for Reactor	52.34	104.68	157.02	209.36
.2 p.u. Reactor	81.53	--	--	--
Labor for Reactor	37.16	--	--	--
.5 p.u. Reactor	165.40	--	--	--
Labor for Reactor	65.16	--	--	--
Filter Capacitor	307.53	--	--	--
Labor for Capacitor	90.00	--	--	--
Total	$1543.57	$1651.02	$2464.89	$2859.82
Contactor	383.00	383.00	646.00	646.00
Labor for Contactor	51.63	51.63	77.93	77.93
Safety Switch (External, Lockable)	83.00	155.00	224.00	224.00
Labor for Safety Switch	59.87	88.67	116.27	116.27

giving total ac interface costs, for both 250 V and 500 V versions, as

	30 kW	60 kW	90 kW	120 kW
AC Interface	$2121.07	$2329.32	$3529.09	$3924.02

The upper power range has an interface costs as follows:

	150 kW	300 kW	450 kW	600 kW
Transformers	$1627.71	$3390.50	$5064.95	$5784.52
Labor	562.57	1170.22	1748.33	1968.22
.25 p.u. Reactor	352.28	650.56	975.84	1301.12
Labor	128.43	256.86	385.29	513.72
.2 p.u. Reactor	277.80	--	--	--
Labor	102.61	--	--	--
.5 p.u. Reactor	552.74	--	--	--
Labor	207.53	--	--	--
Filter Capacitor	1505.52	--	--	--
Labor	432.00	--	--	--
Total	$5722.19	$5468.14	$8174.41	$9567.58
Contactor	$ 646.00	$1905.00	$1905.00	$2766.00
Labor	77.93	217.17	217.17	303.27
Safety Switch	224.00	583.00	989.00	1696.00
Labor	116.27	286.53	448.93	731.73
Total	$6786.39	$8460.37	$11734.51	$15064.58

These totals added to the bridge totals give the cost excluding the dc-to-dc converters and dc interfaces. The sub-totals which develop are tabulated now:

	250 V	500 V
30 kW	$ 4209.43	$ 4378.39
60 kW	6506.04	6843.96
90 kW	9794.17	10301.05
120 kW	12277.46	12953.30
150 kW	9819.99	10628.31
300 kW	14527.57	16144.21
450 kW	20835.31	23260.27
600 kW	27198.98	30432.26

One thing is immediately obvious. The 150 kW design is considerably cheaper than the 120 kW design, indicating that the latter should be dropped from the family; the same factors that make this so for the bridge and ac interface will apply to the dc-to-dc converter and dc interfaces. It is also becoming apparent that the low power units will not meet cost goals.

The dc link capacitance, C3 on all schematics, is identical for all equipments with a given bridge base. Dc-to-dc converter designs were optimized for cost with the trade-off between ripple current allowed and commutating circuit parameters. The converter stage costs develop as follows, component designations referencing Figure 6.2

	30 kW Base		150 kW Base	
	250 V	500 V	250 V	500 V
Q3	$50.40	$52.45	$109.00	$212.0
D3	20.25	28.75	33.00	31.75
Heat Sink	5.13	3.10	15.83	10.12
Labor	20.00	20.00	20.00	20.00
Total	$95.78	$104.30	$177.83	$273.87
D5	$20.25	$ 28.75	$ 33.00	$ 31.75
Heat Sink	5.13	3.10	15.83	10.12
Labor	10.00	10.00	10.00	10.00
Total	$131.16	$146.15	$236.66	$325.74
Q4	$ 50.40	$ 52.45	$109.00	$212.00
D4	20.25	28.75	33.00	31.75
Heat Sink	5.13	3.10	15.83	10.12
Labor	20.00	20.00	20.00	20.00
Total	$226.94	$250.45	$414.49	$599.61
C1's	$ 27.88	$ 33.20	$ 29.04	$ 34.56
Labor	24.00	24.00	24.00	24.00
R1's	13.52	13.52	18.56	19.52
Labor	24.00	24.00	24.00	24.00
L1's	3.70	14.82	29.64	118.58
Labor	12.00	12.00	12.00	12.00
Total	$332.04	$371.99	$551.73	$832.27
C4	$ 17.95	$ 25.42	$ 86.55	$ 45.27
Labor	6.00	6.00	30.00	18.00
L4	37.75	45.89	35.03	35.90
Labor	12.00	12.00	12.00	12.00
R4	19.52	19.52	73.20	73.20
Labor	24.00	24.00	90.00	90.00
Gate Drives (2)	100.00	100.00	100.00	100.00
Total, dc-to-dc converter	$549.26	$604.82	$978.51	$1206.64

The dc capacitor costs are as follows:

	30/60/90 kW 250 V	30/60/90 kW 500 V	150/300/450 kW 250 V and 500 V	600 kW 250 V and 500 V
C5	$ 64.00	$ 76.80	$ 256.00	$ 512.00
Labor	30.00	36.00	120.00	240.00
C3	179.20	179.20	896.00	1792.00
Labor	84.00	84.00	420.00	840.00
Total dc cap. cost	$357.30	$376.00	$1692.00	$3384.00

The costs for dc inductors and interphase reactors are now tabulated:

	250 V	500 V
30 kW Reactor	$128.46	$111.09
Labor	52.77	47.03
	$181.23	$158.12
60 kW Reactor	$108.25	$114.45
Labor	46.05	48.15
Interphase	88.51	88.51
Labor	27.50	27.50
	$270.31	$278.61
90 kW Reactor	$126.32	$138.71
Labor	52.91	56.20
Interphase	107.96	107.96
Labor	47.44	47.44
	$334.63	$350.31
150 kW Reactor	$512.24	$512.71
Labor	180.73	180.87
	$692.97	$693.58
300 kW Reactor	$450.06	$451.19
Labor	160.08	160.43
Interphase	305.27	305.27
Labor	76.50	76.50
	$991.91	$993.39

	250 V	500 V
450 kW Reactor	$612.91	$610.84
Labor	214.33	213.63
Interphase	461.65	461.65
Labor	109.81	109.81
Total	$1398.70	$1395.93
600 kW Reactor	$870.51	$873.00
Labor	300.22	300.99
Interphase (2)	610.54	610.54
Labor	153.00	153.00
Total	$1934.27	$1937.53

The systems also need dc switchgear; 3 poles, 2 for isolation and one for protective shorting of the array, are predicated. Costs are as follows:

	250 V	500 V
30 kW Contactor	$410.00	$320.00
Input	95.33	77.33
Total	$505.33	$397.33
60 kW Contactor	$624.00	$410.00
Labor	151.46	95.33
Total	$775.46	$505.33
90 kW Contactor	$1256.00	$624.00
Labor	304.52	151.46
Total	$1560.53	$775.46
150 kW Contactor	$1728.00	$1256.00
Labor	398.93	304.53
Total	$2126.93	$1560.53
300 kW Contactor	$2660.00	$1728.00
Labor	612.00	398.93
Total	$3272.00	$2126.93
450 kW Contactor	$3968.00	$2660.00
Labor	873.60	612.00
T:tal	$4841.60	$3272.00

600 kW Contactor		$3968.00	$2660.00
Labor		873.60	612.00
	Total	$4841.60	$3272.00

Now these costs, dc-to-dc converter, dc capacitor, dc reactor and interphase transformer and dc contactor can be pulled together to produce "front-end" costs as follows:

	250 V	500 V
30 kW	$1593.02	$1536.27
60 kW	2501.49	2369.58
90 kW	3900.14	3316.23
150 kW	5490.41	5152.75
300 kW	7912.93	7225.60
450 kW	10867.83	9979.85
600 kW	14073.91	13420.09

These are to be combined with the inverter/ac interface costs for total system costs. However, we still need to add control costs, cabinet costs and metering and instrumentation costs.

Control costs are estimated as follows, for both 250 V and 500 V versions:

30 kW Unit:	Material:	$240,	also 150 kW
	Labor:	150	
		$390	
60 kW Unit:	Material:	$400,	also 300 kW
	Labor	250	
		$650	
90 kW Unit:	Material:	$560,	also 450 kW
	Labor:	350	
		$910	
600 kW Unit:	Material:	$720	
	Labor:	450	
		$1170	

Metering and instrumentation costs, including sensors needed for feedback controls are estimated at:

30 kW - \$ 377
60 kW - \$ 606
90 kW - \$ 735
150 kW - \$1131
300 kW - \$1818
450 kW - \$2205
600 kW - \$2592

Cabinet costs, with associated labor for assembly, are below. Equipment sizes and weights are also given:

			W (in)	H (in)	D (in)	Weight (lb)
30 kW - 250 V,	Cabinet	\$387.60	36	72	36	1170.8
	Labor	418.57				
	Total	\$806.17				
30 kW - 500 V,	Cabinet	\$387.60	36	72	36	1114.1
	Labor	410.74				
	Total	\$798.34				
60 kW - 250 V,	Cabinet	\$ 510.40	42	90	36	1581.3
	Labor	777.59				
	Total	\$1287.99				
60 kW - 500 V,	Cabinet	\$ 510.40	42	90	36	1428.1
	Labor	757.95				
	Total	\$1268.35				
90 kW - 250 V,	Cabinet	\$ 697.40	72	84	36	2345.5
	Labor	1165.56				
	Total	\$1862.96				
90 kW - 500 V,	Cabinet	\$ 697.40	72	84	36	2106.2
	Labor	1135.15				
	Total	\$1832.55				
150 kW - 250 V,	Cabinet	\$ 735.90	72	90	36	3633.8
	Labor	653.95				
	Total	\$1389.85				
150 kW - 500 V,	Cabinet	\$ 735.90	72	90	36	3520.9
	Labor	623.23				
	Total	\$1359.13				
300 kW - 250 V,	Cabinet	\$ 962.50	102	90	36	4605.5
	Labor	1082.62				
	Total	\$2045.12				

			W (in)	H (in)	D (in)	Weight (lb)
300 kW - 500 V,	Cabinet	$ 872.30	90	90	36	4159.2
	Labor	1008.19				
	Total	$1970.69				
450 kW - 250 V,	Cabinets	$1472.90	(2) 72	90	36	6610.6
	Labor	1586.25				
	Total	$3059.15				
450 kW - 500 V,	Cabinets	$1382.70	(2) 66	90	36	6135.5
	Labor	1489.53				
	Total	$2872.23				
600 kW - 250 V,	Cabinets	$1834.80	(2) 96	90	36	8504
	Labor	2093.56				
	Total	$3928.36				
600 kW - 500 V,	Cabinets	$1654.40	(2) 84	90	36	7837.5
	Labor	1967.31				
	Total	$3621.71				

The total manufacturing costs can now be tabulated. They are:

	250 V	500 V
30 kW	$ 7375.62	$ 7480.00
60 kW	11551.52	11737.89
90 kW	17202.27	17094.83
150 kW	20678.72	18661.19
300 kW	26953.62	27808.50
450 kW	37877.29	39227.35
600 kW	48963.25	51236.06

Assuming an ICS* ratio of 1.9, the resulting $/kW selling prices (rounded) are as follows:

	250 V	500 V
30 kW	467 $/kW	474 $/kW
60 kW	366 "	372 "
90 kW	363 "	361 "
150 kW	262 "	236 "
300 kW	171 "	176 "
450 kW	160 "	166 "
600 kW	155 "	162 "

* INVENTORY COST STANDARD ratio is the ratio of the selling price to the cost the manufacturer incurs in making the equipment and placing it in inventory prior to shipping to a customer.

It is of some interest to look at a consolidated comparison of the various contributions - inverter and ac interface, front-end and cabinet, metering, etc. The following table shows the breakdown:

250 V Units:

	Inverter, Etc.	Front-End	Cabinet, Etc.
30 kW	267 $/kW	101 $/kW	100 $/kW
60 kW	206 "	79 "	81 "
90 kW	207 "	82 "	74 "
150 kW	124 "	70 "	37 "
300 kW	92 "	50 "	29 "
450 kW	88 "	46 "	26 "
600 kW	86 "	45 "	24 "

500 V Units:

	Inverter, Etc.	Front-End	Cabinet, Etc.
30 kW	277 $/kW	97 $/kW	99 $/kW
60 kW	217 "	75 "	80 "
90 kW	217 "	70 "	73 "
150 kW	135 "	65 "	36 "
300 kW	102 "	46 "	28 "
450 kW	98 "	42 "	25 "
600 kW	96 "	42 "	23 "

A number of conclusions can be drawn from these tabulations. First, obviously, none of the baseline designs meets the cost goal ($140/kW selling price). Second, the higher power units (with the possible exception of the 150 kW) show considerable promise of being able to meet the cost goal with improvements in design and manufacturing methods. Third, the cabinet, metering and instrumentation cost is an extremely important and largely irreducible contributor to the low power units but is not very significant in the higher power range. Fourth, the front-end has slightly higher significance to the higher power units than to the lower power units, and elimination of half its cost would enable 300, 450 and 600 kW units to meet the cost goal.

It seems that it should be possible to design the higher power units to meet the cost goal, comfortably if sufficiently advanced technology is employed. It does not seem likely that the lower power units can do so, but substantial improvements should be possible if:

i) The dc-to-dc converter is eliminated.

ii) Advanced devices are used in the inverter.

iii) The "cabinet, etc" costs are subjected to intense scrutiny and pruned as vigorously as possible.

iv) The ICS ratio is reduced by having a sufficiently well organized and dedicated manufacturing facility.

6.3 Loss Estimates

Detailed loss calculations were carried out for all the units. All individually significant loss producing elements were considered, but it is still likely that the losses of actual equipments would be slightly higher than the numbers presented here because of stray factors the calculations did not (and could not) account. Calculations were done for 0, 20%, 40%, 60%, 80% and 100% loading.

First, ac interface losses which are independent of the dc link voltage.

30 kW Unit:

	% Load					
	0	20	40	60	80	100
.5 p.u. Reactor	76.5 W	84.1 W	106.9 W	145.0 W	198.3 W	266.8 W
Capacitors	75.6	75.6	75.6	75.6	75.6	75.6
.2 p.u. Reactor	37.8	41.6	53.0	72.0	98.5	132.7
Transformer	220.8	243.6	311.9	425.7	585.2	790.1
.25 p.u. Reactor	44.4	48.9	62.4	85.0	116.5	157.1
Total	455.1	493.8	609.8	803.3	1074.1	1422.3

60 kW Unit:

	% Load					
	0	20	40	60	80	100
Transformers	461.2	508.6	650.9	887.9	1219.9	1646.6
.25 p.u. Reactors	88.8	97.8	124.8	170.0	233.0	314.2
Total	550.0	606.4	775.7	1057.9	1452.9	1960.8

90 kW Unit:

	% Load					
	0	20	40	60	80	100
Transformers	689.6	759.7	970.2	1320.9	1812.0	2443.3
.25 p.u. Reactors	133.2	146.7	187.2	255.0	349.5	471.3
Total	822.8	906.4	1157.4	1575.9	2161.5	2914.6

150 kW Units:

	% Load					
	0	20	40	60	80	100
.5 p.u. Reactor	262.2 W	289.0 W	369.5 W	503.7 W	691.5 W	933.0 W
Capacitors	375.2	375.2	375.2	375.2	375.2	375.2
.2 p.u. Reactor	129.7	142.9	182.5	248.6	341.0	459.9
Transformers	765.6	845.1	1083.4	1480.7	2036.9	2752.0
.25 p.u. Reactor	151.0	167.1	215.4	295.8	408.4	553.2
Total	1683.7	1819.3	2226.0	2904.0	3853.0	5073.3

300 kW Units:

	% Load					
	0	20	40	60	80	100
Transformers	1586.0	1752.9	2253.6	3088.1	4256.3	5758.4
.25 p.u. Reactors	303.0	334.2	430.8	591.6	816.8	1106.4
Total	1889.0	2087.1	2684.4	3679.7	5073.1	6864.8

450 kW Units:

	% Load					
	0	20	40	60	80	100
Transformers	2379.6	2625.8	3364.3	4595.1	6318.3	8533.8
.25 p.u. Reactors	453.0	501.3	646.2	887.4	1225.2	1659.6
Total	2832.6	3127.1	4010.5	5482.5	7543.5	10193.4

600 kW Units:

	% Load					
	0	20	40	60	80	100
Transformers	2716.2	3003.6	3865.9	5303.0	7315.0	9901.8
.25 p.u. Reactors	604.0	668.4	861.6	1183.2	1633.6	2212.8
Total	3320.3	3672.0	4727.5	6486.2	8948.6	12114.6

From the above tabulations, it can be seen that ac interface losses are from 2 to 3% of power rating; the transformer losses, which are basically irreducible, are 1-1/2 to 2%.

Next, dc-to-ac converter losses. The loss producing elements are:

Main devices and diodes
Main device snubbers
Commutating devices
Commutating device snubbers
Commutating capacitors
Commutating inductors
Saturable inductors
dc link capacitor

The commutating device and component losses are essentially independent of load, as are snubber losses. Tabulating:

30 kW Bridge - 250 V:

	% Load					
	0	20	40	60	80	100
Main devices	14.4 W	93.0 W	186.0 W	288.0 W	397.2 W	513.0 W
Snubbers and saturable reactors	50.4	50.4	50.4	50.4	50.4	50.4
Commutating devices	28.8	28.8	28.8	28.8	28.8	28.8
Snubbers and saturable reactors	25.2	25.2	25.2	25.2	25.2	25.2
Commutating capacitors and inductors	12.6	12.6	12.6	12.6	12.6	12.6
DC link capacitors	10.5	11.0	12.4	14.8	18.2	22.5
Total	141.9	221.0	315.4	419.8	532.4	652.5

30 kW Bridge - 500 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Devices	7.2	40.2	88.2	146.4	212.4	285.0
(ii)	Snubbers, etc.	151.2	151.2	151.2	151.2	151.2	151.2
(iii)	Comm. devices	7.2	7.2	7.2	7.2	7.2	7.2
(iv)	Snubbers, etc.	75.6	75.6	75.6	75.6	75.6	75.6
(v)	Commutating components	10.8	10.8	10.8	10.8	10.8	10.8
(vi)	DC link capacitors	52.5	53.0	54.4	56.8	60.2	64.5
	Total	304.5	338.0	387.4	448.0	517.4	594.3

150 kW Bridge - 250 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Dev.	72.0 W	394.2 W	799.2 W	1257.6 W	1759.8 W	2299.2 W
(ii)	Snubbers	100.8 at all load levels					
(iii)	Comm. dev.	144.0 " " " "					
(iv)	Snubbers	50.4 " " " "					
(v)	Comm. comp.	26.7 " " " "					
(vi)	DC link caps.	52.5	54.9	62.1	74.1	90.9	112.5
	Total	446.9	771.5	1183.7	1654.1	2173.1	2734.1

150 kV Bridge - 500 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Dev.	28.8	216.6	422.4	639.6	865.8	1099.8
(ii)	Snubbers	302.4 at all load levels					
(iii)	Comm. dev.	57.6 " " " "					
(iv)	Snubbers	151.2 " " " "					
(v)	Comm. comp.	46.5 " " " "					
(vi)	DC link caps.	262.5	264.9	272.1	284.1	300.9	322.5
	Total	849.0	1039.2	1252.2	1481.4	1724.4	1980.0

Finally, the dc-to-dc converter losses. Elements considered are the same, by nomenclature, as for the bridges. Tabulating:

30 kW Bridge - 250 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Dev.	14.4 W	45.5 W	82.7 W	124.0 W	168.6 W	216.0 W
(ii)	Snubbers	50.4	50.4	50.4	50.4	50.4	50.4
(iii)	Comm. dev.	28.8 all loads					
(iv)	Snubbers	25.2 " "					
(v)	Comm. comp.	7.7 " "					
(vi)	DC link caps.	2.4	2.8	3.9	5.9	8.6	12.0
	Total	128.9	160.4	198.7	242.0	289.3	340.1

30 kW - 500 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Dev.	7.2 W	20.8 W	41.0 W	65.8 W	93.9 W	125.2 W
(ii)	Snubbers	151.2	all loads				
(iii)	Comm. dev.	14.4	" "				
(iv)	Snubbers	75.6	" "				
(v)	Comm. comp.	14.4	" "				
(vi)	DC link caps.	9.0	9.3	10.0	11.3	13.1	15.4
	Total	271.8	285.7	306.6	332.7	362.6	396.2

150 kW - 250 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Dev.	108.0	237.0	402.1	590.9	798.7	1022.8
(ii)	Snubbers	100.8	all loads				
(iii)	Comm. dev.	216.0	" "				
(iv)	Snubbers	50.4	" "				
(v)	Comm. comp.	36.0	" "				
(vi)	DC link caps.	12.0	13.9	19.7	29.3	42.8	60.1
	Total	523.2	654.1	825.0	1023.4	1244.7	1486.1

150 kW - 500 V:

		% Load					
		0	20	40	60	80	100
(i)	Main Dev.	36.0	109.2	190.1	276.1	366.1	459.6
(ii)	Snubbers	302.4	all loads				
(iii)	Comm. dev.	72.0	" "				
(iv)	Snubbers	151.2	" "				
(v)	Comm. comp.	62.3	" "				
(vi)	DC link caps.	30.0	31.9	37.7	47.3	60.8	78.1
	Total	653.9	729.0	815.7	911.3	1014.8	1125.6

The following comments are worth noting. For both the dc-to-ac and dc-to-dc converter, snubber losses are very significant, particularly as regards tare (no load) losses. Commutating circuit passive component losses are far less, as are commutating (auxiliary) device losses. This is particularly evident for the 500 V designs. Also, the losses in the dc link capacitors are not completely negligible, and again the 500 V designs are hurt by the necessity to apply voltage sharing resistors to their series-connected electrolytics.

There remain the losses in the dc-to-dc converter reactors and interphase reactors. These tabulate as follows:

	% Load					
	0	20	40	60	80	100
30 kW - 250 V - Reactor	67.6W	72.8W	88.3W	114.2W	150.4W	197.0W
30 kW - 500 V - Reactor	105.3	110.9	127.7	155.8	195.1	245.6
60 kW - 250 V - Reactor	144.4	151.9	174.4	211.8	264.2	331.6
60 kW - 250 V - Interphase	89.0	93.5	107.0	129.5	161.1	201.6
60 kW - 500 V - Reactor	173.2	182.7	211.0	258.3	324.4	409.5
60 kW - 500 V - Interphase	89.0	93.5	107.0	129.5	161.1	201.6
90 kW - 250 V - Reactor	192.2	201.9	231.0	279.5	347.3	434.6
90 kW - 250 V - Interphase	115.4	126.4	159.5	214.5	291.7	390,8
90 kW - 500 V - Reactor	231.7	246.9	292.4	368.2	474.5	611.0
90 kW - 500 V - Reactor	115.4	126.4	159.5	214.5	291.7	390.8
150 kW - 250 V - Reactor	236.3	253.3	304.3	389.3	508.3	661.3
150 kW - 500 V - Reactor	236.5	253.5	304.5	389.6	508.6	661.7
300 kW - 250 V - Reactor	464.8	496.2	590.5	747.7	967.7	1250.6
300 kW - 250 V - Interphase	303.7	319.6	367.4	447.1	558.5	701.9
300 kW - 500 V - Reactor	467.9	499.1	592.6	748.4	966.7	1247.2
300 kW - 500 V - Interphase	303.7	319.6	367.4	447.1	558.5	701.9
450 kW - 250 V - Reactor	648.9	689.8	812.5	1016.9	1303.1	1671.1
450 kW - 250 V - Interphase	320.3	356.6	465.6	647.3	901.5	1228.5
450 kW - 500 V - Reactor	646.7	687.5	809.9	1014.0	1299.6	1666.9
450 kW - 500 V - Interphase	320.3	356.6	465.6	647.3	901.5	1228.5
600 kW - 250 V - Reactor	855.9	910.6	1074.6	1347.9	1730.5	2222.5
600 kW - 250 V - Interphase	607.4	639.2	734.8	894.2	1117.0	1403.8
600 kW - 500 V - Reactor	858.4	913.2	1077.5	1351.3	1734.7	2227.6
600 kW - 500 V - Interphase	607.4	639.2	734.8	894.2	1117.0	1403.9

We can now put together total loss tabulations, by parts and totals; the elements entered are as follows:

(i) ac interface
(ii) dc-to-ac converter
(iii) dc-to-dc converter and dc interface

			% Load					
			0	20	40	60	80	100
30 kW - 250 V	(i)		455.1W	493.8W	609.8W	803.3W	1074.1W	1422.3W
	(ii)		141.9	221.0	315.4	419.8	532.4	652.5
	(iii)		196.5	233.2	287.0	356.2	439.7	537.1
		Total	793.5	948.0	1212.2	1579.3	2046.2	2611.9
30 kW - 500 V	(ii)		304.5	338.0	387.4	448.0	517.4	594.3
	(iii)		377.1	396.6	434.3	488.5	557.4	641.8
		Total	1136.7	1228.4	1431.5	1739.8	2149.2	2658.4
60 kW - 250 V	(i)		550.0	604.4	775.7	1057.9	1452.9	1960.8
	(ii)		283.8	442.0	630.8	839.6	1064.8	1305.0
	(iii)		491.2	566.2	678.8	825.3	1003.9	1213.4
		Total	1325.0	1614.6	2085.3	2722.8	3521.6	4479.2
60 kW - 500 V	(ii)		609.0	676.0	774.8	896.0	1034.8	1188.6
	(iii)		805.8	847.6	931.2	1053.2	1210.7	1403.5
		Total	1964.8	2130.0	2481.7	3007.1	3698.4	4552.9
90 kW - 250 V	(i)		822.8	906.4	1157.4	1575.9	2161.5	2914.6
	(ii)		452.7	663.0	946.2	1259.4	1597.2	1957.5
	(iii)		694.3	809.5	986.6	1220.0	1506.9	1845.7
		Total	1942.8	2378.9	3090.2	4055.3	5265.6	6717.8
90 kW - 500 V	(ii)		913.5	1014.0	1162.2	1344.0	1552.2	1782.9
	(iii)		1162.5	1230.4	1371.7	1580.8	1854.0	2190.4
		Total	2898.8	3150.8	3691.3	4500.7	5567.7	6887.9
150 kW - 250 V	(i)		1683.7	1819.3	2226.0	2904.4	3853.0	5073.3
	(ii)		446.9	771.5	1183.7	1654.1	2173.1	2734.1
	(iii)		759.5	907.4	1129.3	1412.7	1753.0	2147.4
		Total	2890.1	3498.2	4539.0	5971.2	7779.1	9954.8
150 kW - 500 V	(ii)		849.0	1039.2	1252.2	1481.4	1724.4	1980.0
	(iii)		890.4	982.5	1120.2	1300.9	1523.4	1787.3
		Total	3423.1	3841.0	4598.4	5686.7	7100.8	8840.6
300 kW - 250 V	(i)		1889.0	2087.1	2684.4	3679.7	5073.1	6864.8
	(ii)		893.8	1543.0	2367.4	3308.2	4346.2	5468.2
	(iii)		1814.9	2124.0	2607.9	3241.6	4015.6	4924.7
		Total	4597.7	5754.1	7659.7	10229.5	13434.9	17257.7
300 kW - 500 V	(ii)		1698.0	2078.4	2504.4	2962.8	3448.8	3960.0
	(iii)		2079.4	2276.7	2591.4	3018.1	3554.8	4200.3
		Total	5666.4	6442.2	7780.2	9660.6	12076.7	15025.1

		% Load					
		0	20	40	60	80	100
450 kW - 250 V (i)		2832.6W	3127.1W	4010.5W	5482.5W	7543.5W	10193.4W
(ii)		1340.7	2314.5	3551.1	4962.3	6519.3	8202.3
iii)		2338.8	3008.7	3753.1	4734.4	5938.7	7359.9
	Total	6712.1	8450.3	11314.7	15179.2	20001.5	25753.6
450 kV - 500 V (ii)		2547.0	3117.6	3756.6	4444.2	5173.2	5940.0
(iii)		2928.7	3231.1	3722.6	4395.2	5245.5	6272.2
	Total	8308.3	9475.8	11489.7	14321.9	17962.2	22405.6
600 kW - 250 V (i)		3320.2	3672.0	4727.5	6486.2	8948.6	12114.6
(ii)		1787.6	3086.0	4734.8	6616.4	8692.4	10936.4
(iii)		3556.1	4166.2	5109.4	6335.7	7826.3	9570.7
	Total	8663.9	10924.2	14571.7	18434.6	25467.3	32621.7
600 kW - 500 V (ii)		3396.0	4156.8	5008.8	5925.6	6897.6	7920.0
(iii)		4081.4	4468.4	5075.1	5890.7	6910.9	8133.8
	Total	10797.6	12297.2	14811.4	17298.8	22757.1	28168.4

The tabulated efficiencies (% of full load at no load, tare loss) can now be tabulated thus:

	% Load					
	0	20	40	60	80	100
30 kW - 250 V	2.65%	86.36%	90.83%	91.93%	92.14%	91.99%
30 kW - 500 V	3.79	83.01	89.34	91.19	91.78	91.86
60 kW - 250 V	2.21	88.14	92.01	92.97	93.16	93.05
60 kW - 500 V	3.27	84.93	90.63	92.29	92.85	92.95
90 kW - 250 V	2.16	88.33	92.09	93.01	93.19	93.05
90 kW - 500 V	3.22	85.10	90.70	92.31	92.82	92.89
150 kW - 250 W	1.93	89.56	92.97	93.78	93.91	93.78
150 kW - 500 V	2.28	88.65	92.88	94.06	94.41	94.43
300 kW - 250 V	1.53	91.25	94.00	94.62	94.70	94.56
300 kW - 500 V	1.89	90.30	93.91	94.91	95.21	95.23
450 kW - 250 V	1.49	91.42	94.09	94.68	94.74	94.59
450 kW - 500 V	1.85	90.47	94.00	94.96	95.25	95.26
600 kW - 250 V	1.44	91.66	94.28	95.13	94.96	94.84
600 kW - 500 V	1.80	90.70	94.19	95.42	95.47	95.52

Although the 500 V units appear less efficient at the lower power levels, and have higher tare losses, the preceding analysis shows this to be due to snubber loss contributions. Higher di/dt and dv/dt rated devices would change this situation, and since the 500 V units show lower load bearing loss, being in fact more efficient at full load for the higher powers, we propose to use 500 V designs only for the advanced concepts.

It is seen that the higher power units can meet efficiency goals (albeit barely) while the 30 to 90 kW units apparently do not. However, they are close enough that there is reasonable expectation that improved designs could.

7. ADVANCED DESIGNS

It is readily apparent from the results presented in Section 6 that the front-end dc-to-dc converters are major cost and loss contributors to the baseline designs. It is, therefore, obvious that the main thrust of advanced designs should be the elimination of these converters. The dc-to-ac converters can usurp the function of the dc-to-dc converters, in these systems, if they are converted to multi-pattern programmed wave operation.

If this is done, the primary purpose of waveform programming is fundamental (60 Hz) amplitude control in the dc-to-ac converters' output voltage. Harmonic control is a secondary objective, and in the main should not be attempted to the extent of trying to reduce ac interface costs for 12- and 18-pulse units. However, it is desirable that the wave programming eliminate the need for L-C-L filters in the 6-pulse units, since those filters were seen to be major cost contributors.

A preliminary pattern investigation, using digital computer analysis, revealed that patterns attempting to neutralize (eliminate) the lower order harmonic components were not fruitful. Such patterns have two disadvantages; first, over the fundamental voltage control range needed to cope with the combined effects dc input voltage range, ac system voltage tolerance and ac system voltage unbalance, they lead to wave switching intervals (notches) so narrow and so critical as regards width and position as to raise doubts as to their realizability. Second, they enhance those immediately higher order harmonics not neutralized to such an extent that ac interface costs are substantially increased from those of the baseline designs, and to the extent that increasingly complex patterns (higher switching rates) produce no discernible ac interface cost reductions.

These results are, of course, rather disappointing. However, further investigation revealed that patterns chosen for the objective of minimizing total rms current distortion in a simple inductive ac tie showed considerably more promise. A set of patterns can be generated, at 540 Hz switching rate, which permit the concurrent objectives to be met for 12 (and higher) pulse number systems, i.e.,

1. The patterns appear to be realizable.

2. The fundamental control range needed can be obtained.

3. Harmonic specifications can be met with an inductive tie at 0.45 per unit.

However, the 6-pulse case obstinately refused to yield such benefits, even with higher switching rates. A compromise solution was found, still requiring an L-C-L filter to meet harmonic requirements but switching at only 420 Hz and reducing total per unit L to 0.6 per unit and per unit C to ≃ 0.45 per unit.

Thus for the 12- and 18-pulse units, this approach requires a 540 Hz converter switching rate and causes a slight increase in ac interface costs, as compared to baseline designs. For the 6-pulse units, a 420 Hz rate reduces interface costs substantially. In both cases, further complicating the patterns (increasing the switching rate) produced such small reductions in interface size, cost and loss as to be outweighed by increased converter costs and losses.

With a determination that a programmed wave approach appears feasible and should afford considerable benefits, attention turned to other areas for potential improvement. Those areas identified in Phase I, control and assembly labor costs, were also present here and were attacked in much the same way. Projections for reductions are not quite so optimistic as for the Category I power conditioners because we anticipate lower production volumes for Category II.

There is yet another area in the Category II designs, and one in which the adoption of programmed-wave techniques gives considerable incentive. That is the possible adoption of switching devices other than thyristors, namely transistors or GTO's. In discussing the baseline designs, both were rejected because of either unavailability or circuit development required. The advanced designs contemplate their use, with potential technical, economic and efficiency gains therefrom.

It behooves us first to execute a comparison between these two classes of device, in an effort to determine which might be better suited to our application. A point-by-point comparison will best serve our purpose.

Point 1: Presently available devices and information strongly suggest that it is easier to make GTO's than transistors and that GTO's are and should continue to be cheaper for the V-I ratings needed in our family of power conditioners. Plus one for GTO's.

Point 2: Transistors have lower conducting voltage drops than GTO's. Minus one for GTO's.

Point 3: It appears much easier to produce GTO's with 1000V and up blocking voltage rating than it is to make such transistors, at the current ratings we need. Plus one for GTO's.

Point 4: The gate/base drive requirements for GTO's and Darlington power switching transistors are almost indistinguishable. Neutral.

Point 5: Partly because of their higher conducting drop, GTO's have reserve switching capability when operating at thermal limits (e.g., a GTO which can continuously conduct 60 amperes can safely switch about 200). Transistors, typically, have no such reserve. This is an operational advantage for the GTO. Plus one-half for GTO's.

Point 6: GTO's, once conducting, can survive considerable overcurrent without damage provided no attempt is made to turn this device off while current exceeds rated turn-off levels. Transistors have problems with overcurrent, being subject to thermal (or forward-biased second breakdown) destruction unless the designer assures they do not pull out of near saturation. Since transistor beta falls rapidly with current increasing beyond rated peak, it is difficult and costly to design for transistor overcurrents. Plus one-half for GTO's.

Point 7: Both transistors and GTO's are currently available to serve in the 30 kW bridge; the GTO's are much lower cost (≈ 25% of present transistor costs). Neither is currently available to serve in a 150 kW bridge using one device per switch position, but there is no reason to believe that large enough transistors will appear before large enough GTO's appear, nor is there any reason to believe that such transistors will be cheaper than such GTO's. Plus one-half for GTO's.

Point 8: Transistors have lower switching losses than and can be switched at higher rates than GTO's. However, since we do not propose to use a switching rate higher than 540 Hz, transistors offer us no advantage. Neutral.

Point 9: The dI/dt and dV/dt capabilities of transistors are generally greater than those for GTO's of similar V-I ratings. This can be considered an advantage (more nearly ideal converter waveforms) or a disadvantage (greater difficulties with stray inductance effects) for transistors. Arbitrarily, minus one-half for GTO's.

Point 10: The faster switching capability of transistors make it possible to realize waveform patterns with higher precision. However, we have elected to use patterns needing relatively low precision, finding that they are in fact better than those requiring higher accuracy in switch placement and width. Still, minus one-half for GTO's.

The net score from this assessment is plus one and one-half for GTO's; this is, for us, sufficiently decisive, and we have elected to eliminate transistors from consideration and base our advanced designs on GTO's as far as possible. We still have the problem that we do not at present have large enough GTO's for a 150 kW bridge. For the following section of this report, it is shown that for the immediate future thyristors are better at that rating; if and when larger GTO's become available at competitive prices, they can easily be incorporated into our family.

None of the arguments used to justify our choices of converter technology and switching devices are negated by alternate family structures. They remain valid for all rational family organizations covering the Category II power range, and indeed apply equally well to Category I with the possible exception of the GTO/transistor trade-off which then might still favor the transistor because of the lower voltage requirements. Hence, we are confident that while the actual numbers for costs and losses would obviously change, the pattern of specific costs which we develop in the next section would not change as a result of rational family organizational changes. Indeed, if changes in cost patterns were found to occur, we would regard that not as evidence favoring some particular oganizations over these, but rather as evidence of significant errors in our cost and loss calculation procedures.

8. COST, LOSS, SIZE AND WEIGHT ESTIMATES FOR ADVANCED DESIGNS

For the advanced designs, costing was done under the same rules as for the baseline designs with two exceptions:

1. Labor costs were trimmed by 25% across the board, presuming a more efficient manufacturing facility.
2. The ICS ratio was reduced to 1.6, on the same presumption.

As discussed in Section 7, 30, 60 and 90 kW units were GTO based. An elementary schematic of a dc-to-ac converter pole is shown in Figure 8.1, ac interfaces for 6-, 12-, and 18-pulse units are depicted in Figure 8.2, and the dc interfaces are also depicted in Figure 8.2. A major difference in the 6-pulse interface is that the filter kVA requirement is significantly reduced by waveform patterning (420 Hz rate - see Section 7). All designs are for 500 V maximum (300-500 V source range), since the results from the baseline design (and the characteristics of presently available GTO's) indicate that the higher voltage range should be preferred in the long term. Even higher voltage (600 V to 750 V maximum) might further reduce costs and losses, but was not explored because of uncertainty regarding its impact on solar photovoltaic array costs.

Cost estimates proceeded as follows:

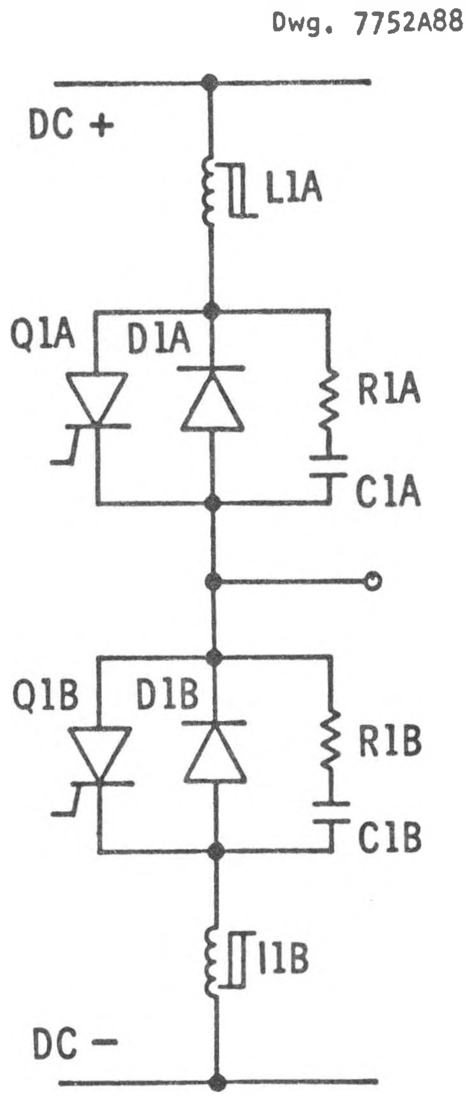


Fig. 8.1—DC to AC converter pole with GTOs

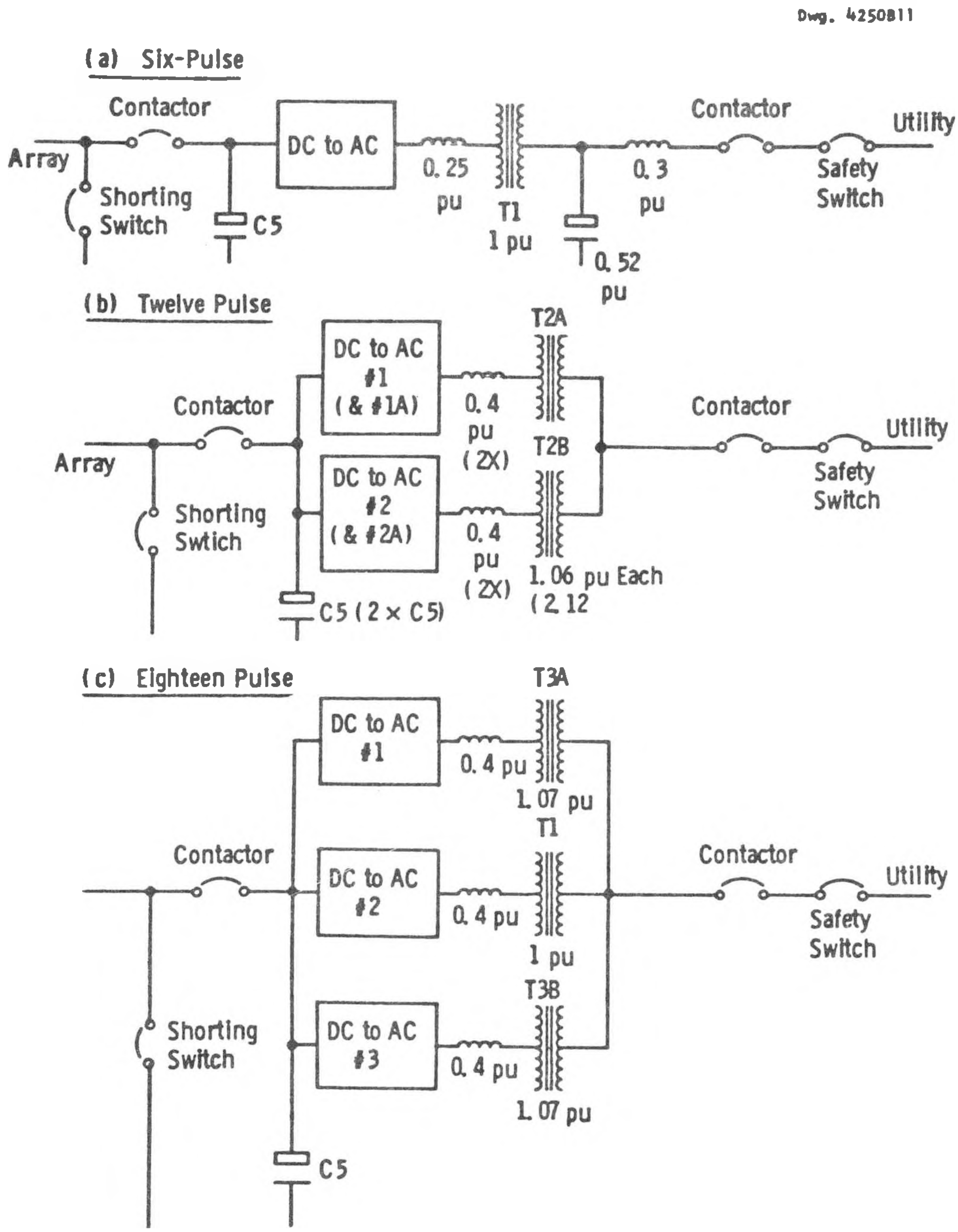


Fig. 8.2—AC and DC interfaces for advanced designs (one line diagrams)

30 kW pole:

GTO - Q1	$ 88.00	
Diode - D1	28.75	
Heat Sink	10.12	
Gate Drive	52.50	($30 material + $22.50 Labor)
Assembly Labor	15.00	
	$ 194.37	
Snubber C-C1	11.02	
Labor	4.50	
Snubber R-R1	9.94	
Labor	4.50	
dI/dt L-L1	31.16	
Labor	13.50	
	268.99	
x 2	537.98	
x 3	$1613.94	30 kW bridge cost

AC interface for 30 kW:

Transformer	$ 470.60
Labor	132.65
L2A (.25 pu)	96.98
Labor	39.26
L3 (0.3 pu)	110.79
Labor	42.67
Capacitors (C3)	104.82
Labor	27.00
	$1024.77
Contactor	383.00
Labor	38.72
Safety Switch	83.00
Labor	44.90
	$1574.39

DC interface for 30 kW:

DC Capacitors	$ 153.60
Labor	54.00
Switchgear	320.00
Labor	58.00
	$ 585.60

Giving 30 kW cost excluding cabinet, metering/instrumentation and control as $3773.93; control cost is assessed at $210, metering and instrumentation at $377. Cabinet size was assessed at 36 in x 36 in x 90 in, overall weight at 1042 lb, cabinet cost at $466 with associated assembly labor $47.33. Thus the total 30 kW unit manufacturing cost is estimated at $4874.26. With an ICS of 1.6, the estimated selling price is $7799 or $260/ kW, and it is quite clear that there is little hope of meeting the cost goal ($140/ kW) in this size unit. This conclusion is, of course, in line with the conclusion that there is little hope of meeting $200/kW with a 10 kW single phase unit that was expressed in the Phase I report.

For the 60 kW unit AC interface costs are:

Transformers	$ 984.22
Labor	276.12
2 x L2B (0.4 pu)	276.88
Labor	99.30
Contactor	383.00
Labor	38.72
Safety Switch	155.00
Labor	66.50
	$2279.74

DC interface costs are:

Capacitors	$ 153.60
Labor	54.00
Switchgear	410.00
Labor	71.50
	$ 689.10

Giving $6196.72 plus cabinet etc. The control cost is estimated at $315, M&I at $606. The cabinet needed is 36 in x 60 in x 90 in, at $646 total. weight 1597 lb, associated assembly labor $73.20 for a manufactured cost total of $7836.92, estimated selling price $12539 or $209/kW.

For the 90 kW unit, ac interface costs are:

Transformers	$1467.70
Labor	411.93
L2B's	415.32
Labor	148.95
Contactor	646.00
Labor	58.45
Safety Switch	224.00
Labor	87.20
	$3459.55

DC interface costs are:

Capacitors	$ 153.60
Labor	54.00
Switchgear	624.00
Labor	113.60
	$ 945.20

Other costs are:

Control	$ 420.00	
M&I	735.00	
Cabinet	873.00	36 in x 90 in x 90 in
Labor	102.60	2311 lb total
	$2130.60	

Total manufactured cost is thus $11377.17, estimated selling price $18203 or $202/kW.

The preceding costs for 30, 60 and 90 kW GTO designs are for 100 quantities. Costs in 1000 quantities can be expected to be ≃ 70%-84% of the numbers developed, and hence the 60 and 90 kW units stand a chance of meeting cost goals if volume requirements are high enough. The 30 kW unit would still not meet that goal - 10,000 lots are needed for it to have a chance.

As discussed in Section 7, it proved necessary to stay with a thyristor design for the upper half of the power range. Further developments in GTO's may enable them to be used, and further cost reductions should ensue in that case.

Cost estimates for a 150 kW pole are as follows: (it is not identical to the pole of the baseline design because of variable DC voltage and the higher operating frequency).

Thyristor, Q1	$ 218.00	
Diode, D1	31.75	
Heat Sink	15.83	
Labor	30.00	
Gate Drive	42.50	($20 Material + $22.50 Labor)
	$ 338.08	
x 2	676.16	Main devices in pole
Commutating Thyristors (2)	218.00	
Heat Sink	15.83	
Labor	22.00	
Gate Drives (2)	85.00	
	$1016.99	All devices in pole
Commutating Capacitor	162.78	
Labor	13.50	
Commutating Inductor	36.41	
Labor	13.50	

Snubber Capacitors (3)	$ 51.93	
Labor	13.50	
Snubber Resistors (3)	29.82	
Labor	13.50	
Saturable Reactors (3)	177.87	
Labor	13.50	
	$1543.30	Pole cost
x 3	4629.90	Bridge cost

AC interface costs for the 150 kW unit develop as follows:

Transformer	$1627.71
Labor	421.93
.25 pu Reactor	325.28
Labor	96.32
.3 pu Reactor	377.87
Labor	145.93
Capacitors	524.10
Labor	135.00
	$3654.14

Contactor	646.00
Labor	58.45
Safety Switch	224.00
Labor	87.20
	$4669.79

150 kW unit DC interface costs are:

DC Capacitors	$ 768.00	
Labor	270.00	
Switchgear	624.00	
Labor	113.60	
	$1775.60	

Other costs are:

Control	$ 210.00	
M&I	1131.00	
Cabinet	741.00	30 in x 78 in x 84 in
Labor	74.10	gross wt. 3003 lb
	$2156.10	

Total manufactured cost $13231.39, estimated selling price $21170 or $141/kW is very close to the goal.

300 kW AC interface costs are:

Transformers	$3390.50
Labor	877.67
.4 pu Reactors	941.20
Labor	265.30
Contactor	1905.00
Labor	162.88
Safety Switch	583.00
Labor	214.90
	$8340.45

DC interface costs are:

DC Capacitors	$ 768.00
Labor	270.00
Switchgear	1256.00
Labor	228.48
	$2522.48

Other costs are:

Control	$ 315.00	
M&I	1818.00	
Cabinet	871.00	36 in x 96 in x 84 in
Labor	87.10	gross wt. 4502 lb
	$3091.10	

Total manufactured cost $23213.83, selling price $37142 or $124/kW, well within our goal.

450 kW AC interface costs are:

Transformers	$ 5064.95
Labor	1311.25
.4 pu Reactors	1411.80
Labor	397.95
Contactors	1905.00
Labor	162.88
Safety Switch	989.00
Labor	336.70
	$11579.53

DC interface costs are:

DC Capacitors	$ 768.00
Labor	270.00
Switchgear	1728.00
Labor	299.20
	$3065.20

Other costs are:

Control	$ 420.00	
M&I	2205.00	
Cabinets	1482.00	2 @ 36 in x 78 in x 84 in
Labor	148.20	gross wt. (both) 6844 lb
	$4255.20	

Manufactured cost $32789.63, estimated selling price $52463 or $117/kW.

600 kW AC interface costs are:

Transformers	$ 5784.52
Labor	1476.17
.4 pu Reactors	1882.40
Labor	530.60
Contactors	2766.00
Labor	227.45
Safety Switch	1696.00
Labor	548.80
	$14911.94

DC interface costs are:

DC Capacitors	$1536.00
Labor	540.00
Switchgear	2660.00
Labor	459.00
	$5195.00

Other costs are:

Control	$ 525.00	
M&I	2592.00	
Cabinets	1742.00	2 @ 36 in x 96 in x 84 in
Labor	174.20	gross wt. (both) 8151 lb
	$5033.20	

Manufactured cost $43659.74, estimated selling price $69856 or $116/kW. Collecting estimated selling prices, we have:

	100's	1000's
30 kW	\$260/kW	\$182 - 218/kW
60 kW	\$209/kW	\$146 - 175/kW
90 kW	\$202/kW	\$141 - 169/kW
150 kW	\$141/kW	\$ 99 - 118/kW
300 kW	\$124/kW	\$ 87 - 104/kW
450 kW	\$117/kW	\$ 82 - 98/kW
600 kW	\$116/kW	\$ 81 - 97/kW

It is clear that the higher power units will have no trouble meeting the cost goal. Low power units above, say, 50 kW may reach it, but the very lowest power units probably will not even in 1000 quantities.

Loss calculations were made as they were for the baseline designs. Results are now presented, beginning with ac interface losses:

30 kW unit:

	% Load					
	0	20	40	60	80	100
.3 pu reactors	51.3 W	56.5 W	72.1 W	98.2 W	134.7 W	181.6 W
Capacitors	26.1	26.1	26.1	26.1	26.1	26.1
Transformer	220.8	243.6	311.9	425.7	585.2	790.1
.25 pu reactors	44.4	48.9	62.4	85.0	116.5	157.1
TOTALS	342.6	375.1	472.5	635.0	862.5	1154.9

60 kW unit:

	% Load					
	0	20	40	60	80	100
Transformers	461.2 W	508.6 W	650.9 W	887.9 W	1219.9 W	1646.6 W
.4 pu reactors	129.2	142.2	180.8	245.4	336.0	452.2
TOTALS	590.4	650.8	831.7	1133.3	1555.9	2098.8

90 kW unit:

Transformers	689.6	759.8	970.2	1320.9	1812.0	2443.3
.4 pu reactors	193.8	213.3	271.2	368.1	504.0	678.3
TOTALS	883.4	973.1	1241.4	1689.0	2316.0	3121.6

150 kW unit:

.3 pu reactors	174.0	193.1	247.8	339.1	467.0	631.3
Capacitors	130.5	130.5	130.5	130.5	130.5	130.5
Transformer	765.6	845.1	1083.4	1480.7	2036.9	2752.0
.25 pu reactors	151.0	167.1	215.4	295.8	408.4	553.2
TOTALS	1221.1	1335.8	1677.1	2246.1	3042.8	4067.0

300 kW unit:

Transformers	1586.0	1752.9	2253.6	3088.1	4256.3	5758.4
.4 pu reactors	441.6	487.2	623.8	851.4	1170.4	1580.2
TOTALS	2027.6	2240.1	2877.4	3939.5	5426.7	7338.6

450 kW unit:

Transformers	2379.6	2625.8	3364.2	4595.1	6318.3	8533.8
.4 pu reactors	662.4	730.8	935.7	1277.1	1755.6	2370.3
TOTALS	3042.0	3356.6	4299.9	5872.2	8073.9	10904.1

600 kW unit:

Transformers	2716.2 W	3003.6 W	3865.9 W	5303.0 W	7315.0 W	9901.8 W
Reactors	883.2	974.4	1247.6	1702.8	2340.8	3160.4
TOTALS	3599.4	3978.0	5113.5	7005.8	9655.8	13062.2

The only other losses in the advanced designs are, of course, those associated with the dc-to-ac converters and dc capacitance. Because of higher switching rates, snubber losses tend to be higher; because of fault considerations, dI/dt had to be restricted to 100 A/μs or less, but device dV/dt capabilities, both GTO and thyristor, were increased to 200 V/μs (which is still a factor of two less than data sheet figures, and so represents conservative design). Losses for a 30 kW GTO bridge tabulate as follows:

In 30 kW unit (420 Hz):

	% Load					
	0	20	40	60	80	100
GTO's	0 W	62.2 W	149.4 W	252.8 W	369.3 W	497.1 W
Snubbers	201.6 at all loads					
Reactors	0	0.6	2.2	5.0	8.8	13.8
DC Capacitors	36.0	36.4	37.5	39.4	42.1	45.5
TOTALS	237.6	300.8	390.7	498.8	621.8	758.0

In the 60 and 90 kW units (540 Hz) the snubber losses increase to 259.2 watts for totals of:

295.2	358.4	448.3	556.4	679.4	815.6

(per bridge). Total losses for 30-60-90 kW units are thus:

	% Load					
	0	20	40	60	80	100
30 kW	580.2 W	675.9 W	863.2	1133.8 W	1484.3 W	1912.9 W
60 kW	1180.8	1367.6	1728.3	2246.1	2914.7	3730.0
90 kW	1769.0	2048.3	2586.3	3358.2	4354.2	5568.4

Efficiencies/tare losses %

30 kW	1.93%	89.88%	93.29%	94.07%	94.18%	94.01%
60 kW	1.97	89.78	93.28	94.13	94.28	94.15
90 kW	1.97	89.78	93.30	94.15	94.30	94.17

The tare losses meet the 2% goal. Efficiences fail to meet full-load goals (95%) but exceed part-load goals. They would meet full-load goals if either of two improvements are invoked.

1. dv/dt increased to 400 V/μs.
2. GTO forward drop reduced.

The thyristor design for the 150 kW bridge contains more loss producing components. Again, for the 150 kW unit operation is at a 420 Hz switching rate, for the 300, 450, and 600 kW units, operation is at 540 Hz. Losses per bridge are tabulated as follows:

In 150 kW unit:

	% Load					
	0	20	40	60	80	100
Main Thyristors	429.6 W	667.2 W	960.6 W	1290.0 W	1648.2 W	2031.6 W
Snubbers	604.8 at all loads					
DC Capacitors	180.0	181.9	187.6	197.1	210.4	227.5
SUBTOTALS	1214.4	1453.9	1753.0	2091.9	2463.4	2863.9
Commutating Thyristors	858.6 at all loads					
Snubbers	302.4					
Commutating Capacitors	49.2					
Commutating Inductors	18.6					
TOTALS	2443.2	2682.7	2981.8	3320.7	3692.2	4092.7

In 300, 450 and 600 kW units:

Main Thyristors	552 W	789.6 W	1083.0 W	1412.4 W	1770.6 W	2154.0 W
Snubbers	777.6 at all loads					
DC Capacitors	180	181.9	187.6	197.1	210.4	227.5
SUBTOTALS	1509.6	1749.1	2048.2	2387.1	2758.6	3159.1
Commutating Thyristors	1104.0					
Snubbers	388.8					
Commutating Capacitors	63.3					
Commutating Inductors	23.9					
TOTALS	3089.6	3329.1	3628.2	3967.1	4338.6	4739.1

Adding in ac interface losses gives total losses and efficiencies as follows:

	% Load					
	0	20	40	60	80	100
150 kW	3664.3 W 2.44%	4018.5 W 88.19%	4658.9 W 92.79%	5566.8 W 94.17%	6735.0 W 94.69%	8159.7 W 94.84%
300 kW	8206.8 2.74%	8898.3 87.08%	10133.8 92.21%	11873.7 93.81%	14103.9 94.45%	16816.8 94.69%
450 kW	12310.8 2.74%	13343.9 87.09%	15184.5 92.22%	17773.5 93.82%	21089.7 94.47%	25121.4 94.71%
600 kW	15957.8 2.66%	17294.4 87.40%	19626.3 92.44%	22874.2 94.03%	27010.2 94.67%	32018.6 94.93%

Again, we just miss the full load efficiency goal, handily make the part-load goal. Tare losses exceed the goal, though not disastrously. The reasons are connected with the increased commutation rate - high commutating device losses and snubber losses. A large GTO with suitable characteristics (and price) would clearly enable us to meet all goals.

9. CONCLUSIONS

Our technology choice was based on heuristic arguments supported by:

(a) irrefutable logic (see Section 4)

(b) the data matrix of the Phase I report*

The preferred technology is voltage-sourced, self-commutated, programmed-wave dc-to-ac conversion. Baseline designs used fixed patterns and a dc-to-dc boost converter; they failed to meet cost goals (by quite a margin at the low power end of the Category II range) and failed to meet efficiency goals by a narrow margin.

Advanced designs used multi-pattern waves and no dc-to-dc converter. Low power units failed to meet cost goals in 100 quantities, but conceivably could in 1000 quantities. Higher power units met cost goals in 100 quantities. Across the board improvements in efficiency were obtained, but full-load goals were not quite met. Improvements in device characteristics and types are foreseeable so that all goals could be met.

For the power range 30-500 kW it is necessary to utilize at least two module sizes to achieve cost effective designs across the range. The choice of module size does not significantly affect cost or loss patterns, and should be made on the basis of markets perceived.

Category II power conditioners can meet the goals in the 100-500 kW range and may be able to, in high enough volumes, in the 30-100 kW range. It should be noted that Category I cannot, as concluded in Phase I, largely because of the burden of enclosure, instrumentation, switchgear and assembly labor costs. This burden spreads over larger powers in Category II, reducing its $/kW impact.

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* loc. cit. pages 93-95.

APPENDIX A

INTERFACE OF TWO UNBALANCED AC SYSTEMS - GENERAL THREE-WIRE CASE

Given a three-wire ac system having per unit voltage magnitudes V_a, V_b, V_c and taking the A (AB) phase as the phase reference for the analysis. It can be shown that this system posseses per unit real (cosine) and quadrature (sine) positive and negative sequence voltage constituents of magnitudes: a. (real positive sequence), b. (real negative sequence), c. (quadrature positive sequence), and d. (quadrature negative sequence) given by:

$$c = -d = (V_b^2 - V_c^2)/2\sqrt{3}\, V_a$$

$$a = (V_a + Z/\sqrt{3}\, V_a)/2$$

$$b = (V_a - Z/\sqrt{3}\, V_a)/2$$

where $Z^2 = V_a^2(V_b^2 + V_c^2 - V_a^2) + V_b^2(V_a^2 + V_c^2 - V_b^2) + V_c^2(V_a^2 + V_b^2 - V_c^2)$

Let this system interface with another unbalanced system, having corresponding symmetrical components of per unit magnitude a', b', c', and d', through an intertie reactance x per unit, and let the total power transferred be 3 per unit (1 per unit nominal in each phase). There are two possible sets of criteria that might be applied. First, let $P_a = P_b = P_c = 1$ per unit and $Q_a + Q_b + Q_c = 0$, i.e., let the real powers be balanced and the reactive powers sum to zero. Then it is necessary that:

$$a' = a + \frac{cx}{a^2 - b^2}$$

$$b' = b + \frac{cx}{a^2 - b^2}$$

$$c' = c - \frac{ax}{a^2 - b^2}$$

$$d' = -c + \frac{bx}{a^2 - b^2}$$

In this case, the individual per unit reactive powers are given by:

In the ac system (a, b, c, d):

$$Q_a = 2c/(a - b) = (V_b^2 - V_c^2)/Z$$

$$Q_b = -c/(a - b) - \sqrt{3}(ab - c^2)/(a^2 - b^2) = (V_c^2 - V_a^2)/Z$$

$$Q_c = -c/(a - b) + \sqrt{3}(ab - c^2)/(a^2 - b^2) = (V_a^2 - V_b^2)/Z$$

where Z was previously defined.

In the converter (a', b', c', and d'):

$$Q_a' = Q_a + \Delta Q_a$$

$$Q_b' = Q_b + \Delta Q_b$$

$$Q_c' = Q_c + \Delta Q_c$$

where:

$$\Delta Q_a = x(2V_b^2 + 2V_c^2 - V_a^2)/Z^2$$

$$\Delta Q_b = x(2V_a^2 + 2V_c^2 - V_b^2)/Z^2$$

$$\Delta Q_c = x(2V_a^2 + 2V_b^2 - V_c^2)/Z^2$$

The other criteria are for the per unit reactive powers Q_a, Q_b, and Q_c to be balanced and zero, the per unit real powers P_a, P_b, and P_c to be unbalanced but sum to 3 per unit.

Then:

$$a' = a + \frac{cx}{a^2 + b^2 + 2c^2}$$

$$b' = b - \frac{cx}{a^2 + b^2 + 2c^2}$$

$$c' = c - \frac{ax}{a^2 + b^2 + 2c^2}$$

$$d' = -c - \frac{bx}{a^2 + b^2 + 2c^2}$$

are the necessary relationships. Note that $a^2 + b^2 + 2c^2 = (V_a^2 + V_b^2 + V_c^2)/3 = D$.

The per unit real powers in this case are given by:

$$P_a = P_a' = V_a^2/D$$

$$P_b = P_b' = V_b^2/D$$

$$P_c = P_c' = V_c^2/D$$

Control for such a system would present a formidable manipulative problem with either set of criteria, since the relationships between a', b', c', and d' and a, b, c, and d are neither simple nor linear, and it is not easy to physically resolve an unbalanced system into its symmetrical components nor is it easy to physically create, using the actual variables available in a converter system, the voltage set corresponding to a given set of symmetrical components. If one system, the converter, is constrained to be balanced, i.e., if b' = d' = 0, then the solutions are for $P_a + P_b + P_c = 3$, $Q_a + Q_b + Q_c = 0$.

$$a' = a + \frac{a(b^2 + c^2) + cx}{a^2 + c^2}$$

$$c' = c + \frac{c(b^2 + c^2) - ax}{a^2 + c^2}$$

$$P_a = P_a' = 1 + [(2V_a^2 - V_b^2 - V_c^2) - \sqrt{3}D(V_b^2 - V_c^2)/x]/(3(D + Z/\sqrt{3}))$$

$$P_b = P_b' = 1 + [(2V_b^2 - V_a^2 - V_c^2) - \sqrt{3}D(V_c^2 - V_a^2)/x]/(3(D + Z/\sqrt{3}))$$

$$P_c = P_c' = 1 + [(2V_c^2 - V_a^2 - V_b^2) - \sqrt{3}D(V_a^2 - V_b^2)/x]/(3(D + Z/\sqrt{3}))$$

$$Q_a = (Z/\sqrt{3}x)(1 - (V_a^2 + Z/\sqrt{3})/(D + Z/\sqrt{3})) + (V_b^2 - V_c^2)/(\sqrt{3}(D + Z/\sqrt{3}))$$

Q_b and Q_c are similar with V_a^2 replaced by V_b^2 and V_c^2, respectively, and $V_b^2 - V_c^2$ replaced by $V_c^2 - V_a^2$ and $V_a^2 - V_b^2$, respectively.

$$Q_a' = Q_a + \Delta Q_a,\ Q_b' = Q_b + \Delta Q_b,\ Q_c' = Q_c + \Delta Q_c$$

with

$$\Delta Q_a = 2x/(D + Z/\sqrt{3}) - (V_b^2 - V_c^2)/(\sqrt{3}(D + Z/\sqrt{3})$$

$$+ (2V_b^2 + 2V_c^2 - V_a^2)(D - Z/\sqrt{3})/(3x(D + Z/\sqrt{3}))$$

ΔQ_b and ΔQ_c are similar, $V_b^2 - V_c^2$ replaced by $V_c^2 - V_a^2$ and $V_a^2 - V_b^2$ respectively, $2V_b^2 + 2V_c^2 - V_a^2$ replaced by $2V_a^2 + 2V_c^2 - V_b^2$ and $2V_a^2 + 2V_b^2 - V_c^2$ respectively.

The control is not formidable in this case, since it reduces to a system with two orthogonal variables (magnitude and torque angle) and there is no need to resolve a system into symmetrical components nor to synthesize one therefrom.

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