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# DC-LINK APPROACH TO CONSTANT-FREQUENCY AIRCRAFT POWER

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This paper discusses a hybrid high-power aircraft electrical system that has very difficult and complex operating requirements. Many issues raised in selecting an approach for this application are similar to those that must eventually be addressed for a large all-electric aircraft. The requirements for this specific system are reviewed, a solution for those requirements is proposed, and some explanation is provided for the choice. Because the system requires a substantial amount of 400-Hz power, a dc-link system was selected to provide that power. The highlights of the power system are

(1) Load requirements of 13.2 kV dc, 400 Hz ac, and 28 V dc (pulsed)
(2) Four channels
(3) Outputs paralleled to feed total load
(4) Load requirements satisfied by three of four channels
(5) Single generator for each channel
(6) Power conditioning remotely located (100 ft) from generator

The load profile (fig. 1) shows that the large power requirements associated with the 13-kV output are only required above 83-percent engine speed. The 28-V pulsed output is a very small part of the overall system requirements on a percentage basis. In going through the selection process and adopting the priority of power level, we will cover the 13-kV requirements first, then cover the 400-Hz requirements, and then lightly touch on the 28-V dc supply considerations. The simple system line diagram for the single-channel configuration is shown in figure 2. The power system contains four identical channels. The loads are now sized for each particular output for the single channel. In figure 2 the approximate distances between generator, power conditioning equipment, and loads are given because they are significant in the overall system considerations and affect which conversion schemes are selected. The evaluation criteria are electrical performance and risk, weight, efficiency, volume, cost, and reliability. Obviously with any airborne system, size and weight are very important selection criteria. However, in a new and complex system such as this, electrical performance and risk must be an important part of the selection process.

The preliminary ground rules for system evaluation are as follows:

(1) Six-phase generator (minimum filtering requirements)
(2) High speed and high frequency
 (a) Minimum generator weight
 (b) Minimum filtering
 (c) Maximum speed, ~25 000 rpm
 (d) Minimum frequency, ~1200 Hz
 (e) Acceptable transmission losses
(3) High transmission voltage
 (a) Minimum transmission losses
 (b) Generator corona considerations, ~ 250 V rms nominal maximum
 (c) Minimum voltage at 53-percent speed, > 120 V rms
(4) Major impact of 13-kV, 270-kW output in determining overall system configuration and parameters

(5) 28-V dc output (4-percent system rating) addressed after 13-kV dc and 400-Hz outputs satisfied

Obviously, in power conversion apparatus, maximizing the pulse number minimizes the filtering requirements. This points in the direction of a six-phase system rather than a three-phase system for the generator. There is obviously a range of practical frequencies bounded, say, on the lower end by minimum frequencies required by certain power conversion schemes and limited at the upper end by losses in high-power rectifiers, transformers, and other such equipment. Minimum voltage requirements are imposed on the generator by various power conversion schemes, and of course maximum voltages are imposed on the system from consideration of corona and other such parameters. Again, power output tends to influence strongly the design priorities. So with this sort of groundwork layed, these ground rules allow us to establish the following set of conversion options:

(1) Starting system parameters
 (a) Six-phase generator-feeders
 (b) Generator voltage L-N, 264 V rms at 100-percent speed
 (c) Generator frequency, 2500 Hz at 110-percent speed
(2) Ripple considerations
 (a) Ripple requirement of 0.26 kV, 2 percent
 (b) Six-pulse rectified voltage with 9.3-percent ripple
 (c) 12-pulse rectified voltage with 2.3-percent ripple
(3) Option 1 - single transformer with delta/wye secondaries
(4) Option 2 - two identical transformers with six-phase supply

The power system will probably be a six-phase system with a generator voltage of about 260 V and a frequency of 1000 to 2000 Hz. The relationship between pulse number and ripple voltage leads to the conclusion that only 12-pulse conversion processes are really practical in meeting the 13-kV ripple requirement. Going through all of this you come to two options for the 13-kV system. Option 1 (fig. 3) is a single transformer with delta/wye secondaries to give a 12-pulse ripple in the output frequency and to minimize filtering. Option 2 (fig. 4) is two identical transformers. This implies a six-phase generator, where the phase displacement for the 12-pulse requirement comes from the phase displacement between the two groups of three feeders in a six-phase supply.

Comparing the advantages and disadvantages of these two approaches to 13-kV conversion shows that

(1) Option 1 (the single transformer) will be somewhat lighter in weight and smaller in volume

(2) Option 1 has more complex insulation requirements with twin secondaries and higher voltage in delta-connected windings (5000 V rms vs. 2900 V rms for wye)

(3) Option 2 will require less filtering for the same level of ripple and distortion

(4) Option 2 requires twin three-phase breakers

(5) Option 2 provides improved heat transfer

Considering the complete conversion stage including transformer, rectifier, filter, and cooling system, option 2 (two transformers with six-phase supply) was chosen.

In selecting control options the operating considerations of steady-state voltage regulation (12 to 13.7 kV dc), current limiting at 1.2 per unit load, and load sharing under paralleling point toward maintaining constant transformer primary voltage. This would allow the natural droop of the paralleled transformer-rectifier units to provide current sharing. Current limiting would also be implemented on the primary (low) voltage side. This leaves three options for voltage and current control:

(1) Voltage control (VC) and current limiting (CL) via generator excitation control (fig. 5)
(2) Voltage control and current limiting via reverse parallel-connected thyristors (fig. 6)
(3) Voltage control via field control and current limiting via thyristor control (fig. 7)

The first option (fig. 5) will impose some constraints on the other power conditioning subsystems, but as later analysis showed, this option does not impose a severe burden on the design requirements for these systems. Overall it has significiant system appeal. As for the second option (fig. 6) a tradeoff between the primary and secondary would quickly show that it is preferable to put the phase-controlled arrangement on the primary side rather than on the high-voltage side. The unfortunate aspect of this approach is that the primary electronics now have to be rated for the full system throughput and there is an additional filtering burden imposed on the secondary filter with this type of arrangement. Obviously there is a compromise (option 3, fig. 7) where voltage control would be used during normal operating modes with field control maintaining the phase-controlled rectifier in a full-on condition. This would not impose a severe requirement on the filtering and, if the load could tolerate it, phase control could be used just for current limiting. Unfortunately, the problem of the high rating required for the electronics portion of this process still exists.

In the final analysis we recommend the most simple and straightforward method - option 1, using the process of field control for voltage control and current limiting. Our analysis indicates that this method of control is compatible with actual load requirements, does not unduly penalize the design of the 400-Hz output, and provides a very efficient and highly reliable power conditioning subsystem.

Selection of a 400-Hz conversion option was based on the following considerations:

(1) Kilovolt-amperage management
(2) Neutral forming
(3) Feeder and generator utilization
(4) Interaction with the 13-kV supply

The state of the art for the conversion of bulk, variable-frequency ac power to constant-frequency ac power (VSCF) by solid-state means offers two general solutions: direct ac-to-ac conversion systems and ac-to-dc-to-ac conversion systems. System parameters chosen thus far (i.e., voltage and frequency) leave open the consideration of these two options:

Option 1 - cycloconverter
Option 2 - dc-link inverter

Figure 8 is a rough diagram of option 1, cycloconverter power stage - repeated three times for each of the three output phases. It gives an idea of the complexity and brings out some significant points - especially that with this scheme the neutral must be brought out from the generator.

Option 2, the dc-link inverter (fig. 9), does have to have a neutral forming transformer to provide the fourth wire; however, it does not require the fourth wire, or the neutral, to be brought out from the generator. The scheme that we recommend for operating the inverter stage is a fixed pattern controlling the bridge switches - say the transistors - that would then determine output frequency and distortion factors. Voltage traditionally is controlled by regulating the link voltage. In this case, because of the choices already made on the 13-kV system, a preregulator stage is needed for the dc-link system to compensate for the generator voltage variation over the speed range.

Table 1 summarizes some of the critical differences between the two systems. Some of the important points are the neutral currents, the filter currents in fault, the weight of the feeder cables, and the weight of the neutral feeder as compared to the neutral forming transformer. The table implies a bias, considering weight only, toward the dc-link option. In other words, the power stages are about equivalent for this comparison between the two approaches, so a trade-off results between the neutral coming from the generator and the neutral former in the dc-link option. On a weight basis the dc-link is favored. However, weight is not the only consideration. First, the cycloconverter circulates reactive power through the feeder system and the generator. In contrast, the dc-link system constrains the reactive current flow to the output stage of the inverter. That is significant. Second, under unbalanced conditions, an undesirable 800-Hz modulation effect is imposed on the generator terminals. The modulation is reflected into the 13-kV supply. Obviously the filter - for a 12-pulse output - is not designed for 800-Hz disturbances. That imposes a severe penalty on the filtering in the 13-kV supply and also creates a problem with the feeding of faults - where significant reactive power is circulated through 110 ft of feeder. There is also the other constraint of maintaining minimum voltages on the generator output so that the supply can meet its other output requirements, such as the 28-V dc system.

If all of these constraints are taken into consideration, for this particular application a dc-link system offers some significant advantages. The input stage does have additional complexity: it is not a rectifier; it now becomes a phase-controlled bridge; it requires some additional filtering on the link. However, on an overall system basis, considering weight, reliability, and efficiency the trade-off works in favor of the dc-link system. Now that we have made that determination, we can briefly review the kind of control strategies that would be applicable (figs. 10 and 11). Some of these have almost been discounted but are included for the sake of completeness.

The first option (fig. 10) is to use field control on the generator. That is a viable option and is obviously the simplest. The same statements hold true here as for the 13-kV system. However, having chosen field control for the 13-kV system implies a separate generator to feed the dc-link system. In the ground rules established by the application requirements, there was a specific requirement of a single generator and that meant a single, physical generator, not necessarily a single generator designed within that physical envelope.

The second option for voltage control is the use of gate-controlled thyristors shown in figure 11. The input stage is in error. The input stage really has to be a phase-controlled bridge. When considering interactions between the systems, the phase-controlled front end does provide a one-way buffer between the 13-kV system and the 400-Hz system. There is also the question of transient response. The faster response time of option 2 and its effect on transient response at the output of the 400-Hz system more than compensates for the increased complexity. Option 2 also provides buffering of the 400-Hz output due to sudden load changes in the 13-kV output. Although there will be some interaction between the 13-kV and 400-Hz outputs, the controlled rectifier will help to minimize these effects. Option 2 was selected as the preferred approach for the overall system.

In the preceding discussion a selection of the generator configuration has been implied. However, for the sake of completeness, I will briefly cover various generator feeder options. A consideration is that the generator and feeder configurations are interrelated. Also single physical generator requirements constrain dedicated generators to a single shaft. System interaction is an important criterion when evaluating feeder configurations. And generator rating and phase currents must be established to size feeders. The following options will be considered:

(1) Separate electromagnetic design with dedicated feeders
(2) Single generator with dedicated feeders
(3) Single generator with common feeders

Figure 12 is the result of a rating analysis derived from figure 1. Basically it shows that from 0 to 83-percent speed the high-power output is not on. If you control the output in a linear fashion, constant voltage over frequency, the requirements on the electromagnetic devices, like the 13-kV transformers, will be maintained. Sufficient voltage will be produced to power the 400-Hz output. The design rating point after further calculations for the generator turns out to be the 83-percent speed point. Considering different feeder configurations and load requirements results in the set of currents shown at the bottom of the figure.

One of the approaches (option 1, fig. 13) is to have two isolated electromagnetic generators on a common shaft. This is a very simple scheme for voltage regulation. A highly desirable aspect of option 1, from the standpoint of the power conversion equipment, is that it provides the maximum independence and isolation between the 13-kV and 400-Hz outputs. Of course this would be compatible with a simple scheme of field control for both outputs.

Another approach (option 2, fig. 14) is a single generator, which obviously will be less complex and lighter in weight, with dedicated feeders. The figure shows currents and nominal voltages. The distance to the feeders is normally 100 ft. The feeders are all the same size, are tightly bundled, and are a fairly sizable weight consideration in the overall system tradeoff.

The last approach (option 3, fig. 15) would be to run a single set of feeders down to the branch point and then branch off to the two different power conditioning subsystems. This, obviously, is the lightest weight approach.

Table II shows an approximate calculation which reveals that feeder weight, approximately 43 lb, is more important than the kilovolt-amperage of the generator. However, weight alone cannot be used to make the choice. The other aspects that need to be considered between these three options are as follows

(1) Option 1 offers maximum isolation of the 13-kV and 400-Hz outputs and a simple, reliable method of voltage control.

(2) Option 1 generator has a reactive power penalty and a weight penalty, added mechanical complexity, and a possible 43-lb feeder penalty.

(3) Options 2 and 3 offer a lighter, simpler generator.

(4) The 43-lb weight saving of option 2 over option 3 is obtained at the penalty of isolation between the two outputs.

(5) Option 2 represents a compromise solution between options 1 and 3 in that the 13-kV and 400-Hz units can interact only through the generator's subtransient inductance but not through feeder inductance.

Making a choice is a trade-off among complexity, reliability, weight, and isolation or interdependence between the two supplies: the 400 Hz and the 13 kV. Choosing a single feeder to the branch point results in interactions between the 13-kV and 400-Hz subsystems, which occur not only through the generator subtransient reactance, but also, through the reactance of the feeder cables. And that can be quite significant. The choice then is between an interaction criterion and a weight criterion. At this point, we recommend option 2, probably because of a risk consideration. We would start by limiting the interaction to just the generator subtransient reactance, using the feeder cables as a buffer between the two supplies. Hardware tests may be needed to finally determine which is the better trade-off - the 43 lb or the final weight of the control circuits - to get these two supplies to operate reliably off the same generator. So tentatively we would select option 2 and carry the 43 lb as a potential weight saving after further analysis and tests.

In conclusion, the 28-V dc system, even though it is a pulse system, represents only about 4 percent of the total system, or channel, rating. There are two obvious design approaches: to design the power stage configuration for peak power throughput or to design a system that provides for energy storage. Cost and weight considerations come into play here and tend to bias toward an energy storage approach. The average power on the supply system is only of the order of 600 W because of the very low duty cycle in the output of the 28-V dc system. Also it might be determined that the three-phase supply is satisfactory and that a six-phase supply is not needed for this power level.

Westinghouse finally selected an energy storage approach fed by a very simple current source power-conditioning subsystem (fig. 16). The control options for this type of system with a large capacitor and three or four parallel systems is not as simple as it might seem at first. How natural unbalances in capacitor values and leakage currents are accounted for is fairly significant consideration but beyond the scope of this discussion. Figure 17 shows the final system configuration. The design approach discussed in this paper should be applicable to a variety of aircraft including a large transport with all-electric secondary power.

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TABLE I. - 400-Hz CONVERSION OPTIONS

| Load Condition | Option 1 Cycloconverter | | Option 2 DC-Link Inverter | |
|---|---|---|---|---|
| | Steady State | Sh. Ckt. | Steady State | Sh. Ckt. |
| Load KVA | 120 | NA | 120 | NA |
| Load Power Factor | 1 | NA | 1 | NA |
| Load Current, Amp | 348 | NA | 348 | NA |
| Filter Current, Amp | 174 | ~0 | 162 | ~0 |
| Converter Output, Amp | 389 | 1,044 | 384 | 1,044 |
| DC-Link Current, Amp | NA | NA | 456 | ~0 |
| Input Phase Current, Amp | 220 | 591 | 186 | ~0 |
| Neutral Current at 1/3 Load Imbalance, Amp | 116 | | 116 | |
| 110 Ft. Feeder Wt., Lb. at .27 Lb./A/Phase/100 Ft. | 392 | | 331 | |
| 110 Ft. Neutral Feeder Wt., Lb. | 35 | | NA | |
| Neutral Forming Transformer, Wt., Lb. | NA | | 18 | |
| Total Feeder + Neutral Forming Wt., Lb. | 427 | | 349 | |

For purposes of this comparison, the weight of the two converters is assumed to be comparable. In addition to the above tabulated net feeder weight penalty of 78 lbs./channel, there is a further weight penalty to the cycloconverter generator.

TABLE II. - GENERATOR-FEEDER OPTIONS

| Option | 1 | 2 | 3 |
|---|---|---|---|
| Approximate Feeder Weight, Lb.* | 367 | 367 | 324 |
| Approximate Generator KVA (Extrapolated to 100% Speed) | 588 | 574 | 574 |

*Copper Wire (Aluminum wire weight is ~50% less)

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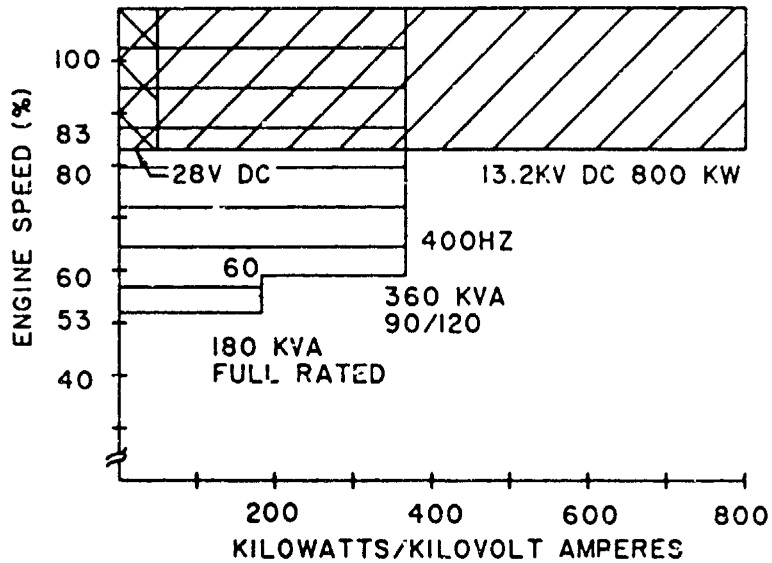


Notes: 1) 28 VDC and 13 KVDC operate only above 83% speed
2) 400 Hz. channel rating is 60 KVA at 53% speed, 120 KVA at 60% speed and above

Figure 1. - Utilization equipment - total load profile.

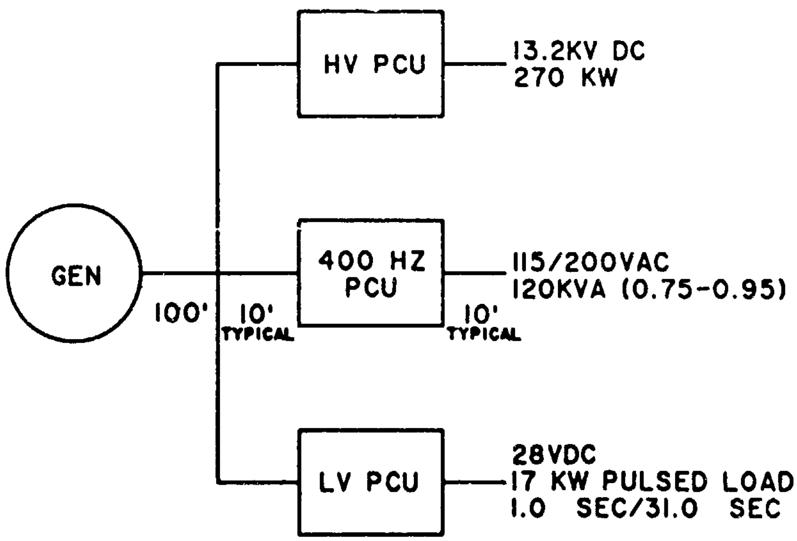


Figure 2. - Single-channel configuration.

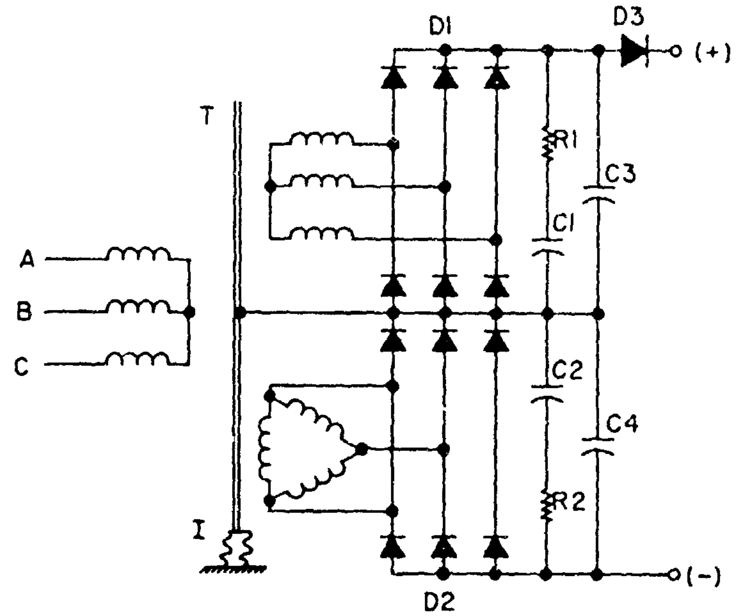


Figure 3. - 13-kV conversion options - option 0, single transformer with delta/wye secondaries.

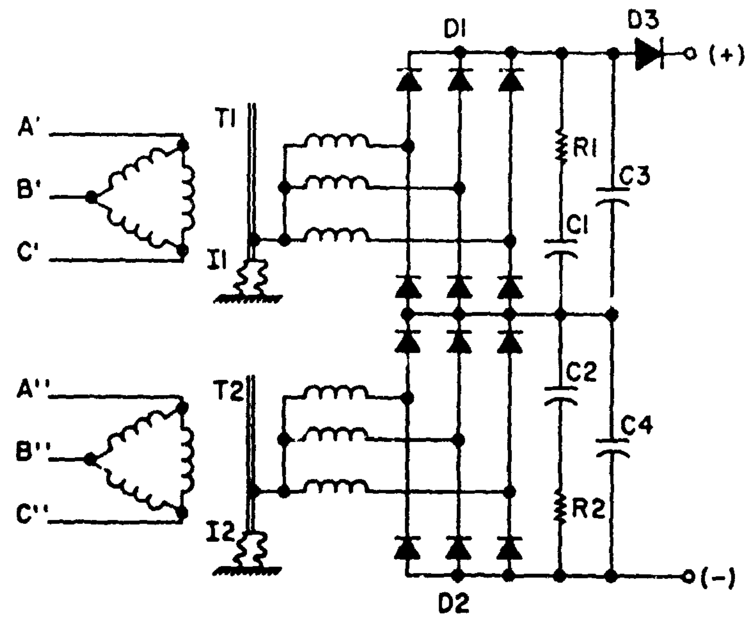


Figure 4. - 13-kV conversion options - option 2, two identical transformers and six-phase supply.

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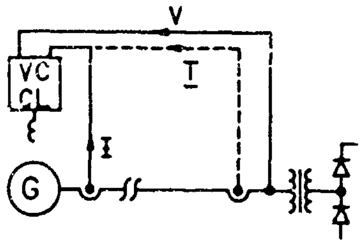
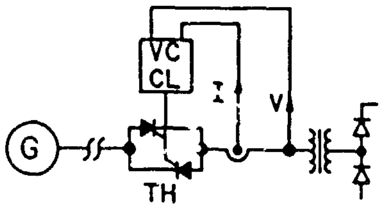


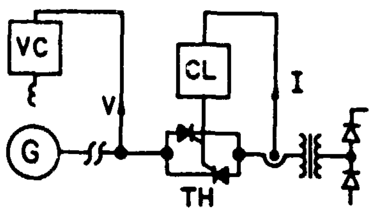

**This is the simplest method of control requiring no extra electronics. Requires generator of sufficient voltage range to supply other system elements or constrains their design.**

Figure 5. - 13-kV control options - option 1, voltage control and current limiting through generator excitation control.




**Provides maximum independence of elements fed from a common generator at the expense of additional power electronics rated for total throughput. Requires additional filtering and damping.**

Figure 6. - 13-kV control options - option 2, voltage control and current limiting through thyristor control.




**Compromise solution which maintains generator voltage reasonably constant and avoids chopping action except under overload. Still requires additional power electronics. Has advantage over Option 2 only if higher ripple under overload is acceptable.**

Figure 7. - 13-kV control options - option 3, voltage control through field control and current limiting through thyristor control.

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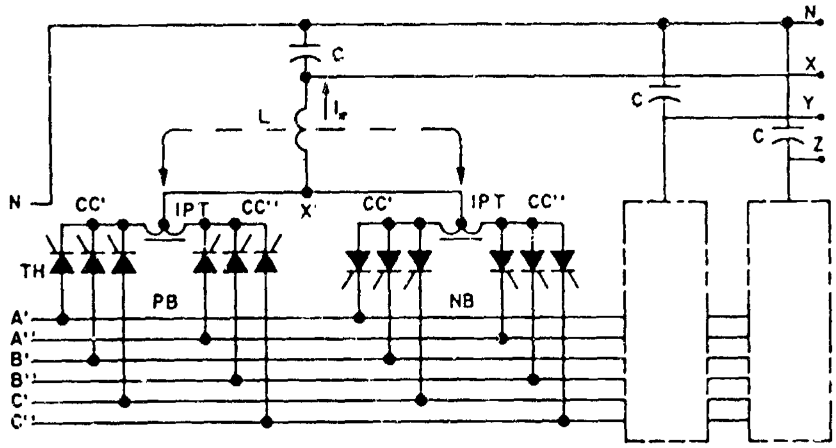
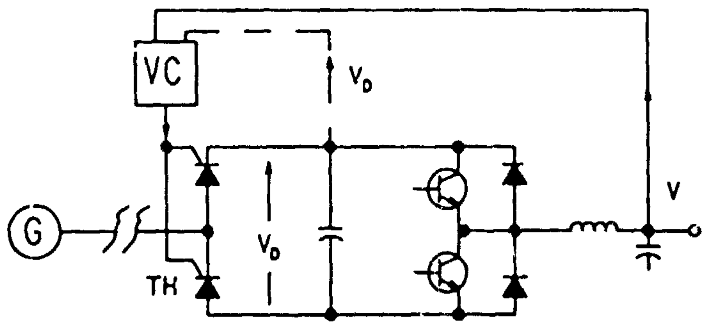


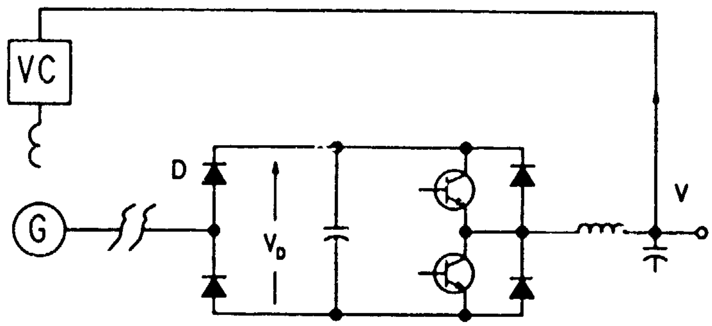

Output voltage quality and steady state and transient regulating accuracy depend to a large extent on the performance of a complex control circuit detecting critical timing of 36 thyristors and selection of six thyristor banks. Cycloconverter has a fixed ratio of net converter output current and input phase current (feeders and generator) of 0.566 and requires a generator neutral feeder cable rated for 33-1/3% nominal output current.

Figure 8. - 400-Hz conversion options - option 1, cycloconverter.



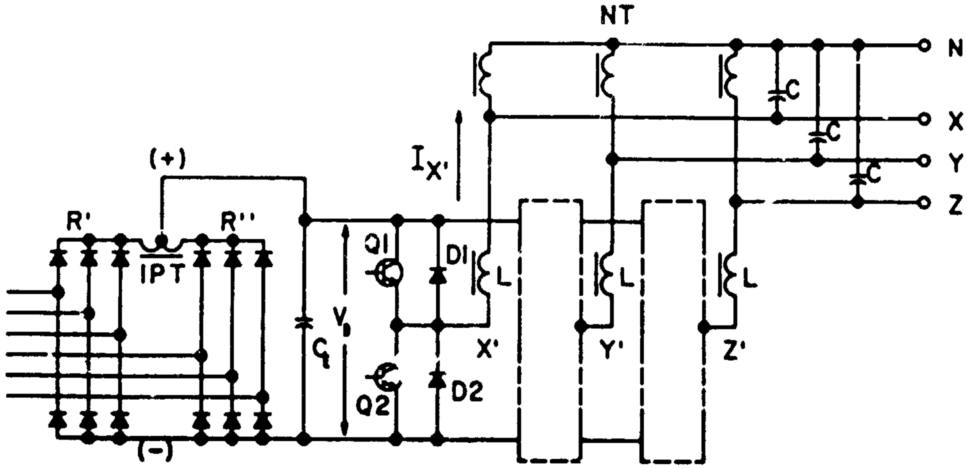

Using a fixed PWM digitally derived waveform pattern, the steady state and transient accuracy of the output voltages depend on the accuracy and speed of the link voltage control. A DC Link system has a ratio of 1.31 (real component of net inverter output current and DC Link current) and 0.71 (DC-Link current and input phase current) and requires a neutral forming transformer.

Figure 9. - 400-Hz conversion options - option 2, dc link.




This is the simplest method of control but requires a dedicated generator or a change in the 13 KV output design approach (i.e., thyristor control). It also fixes the generator voltage at approximately 130 VRMS causing a feeder weight and loss penalty.

Figure 10. - 400-Hz control options - option 1, voltage control through field control.




This approach requires circuitry to control twelve thyristors, is somewhat more lossy in the rectifier stage and requires relatively more filtering of the link voltage. However, it does not have the disadvantages of Option 1 and provides twenty times the response time of Option 1.

Figure 11. - 400-Hz control options - option 2, voltage control through gate control of thyristor rectifiers.

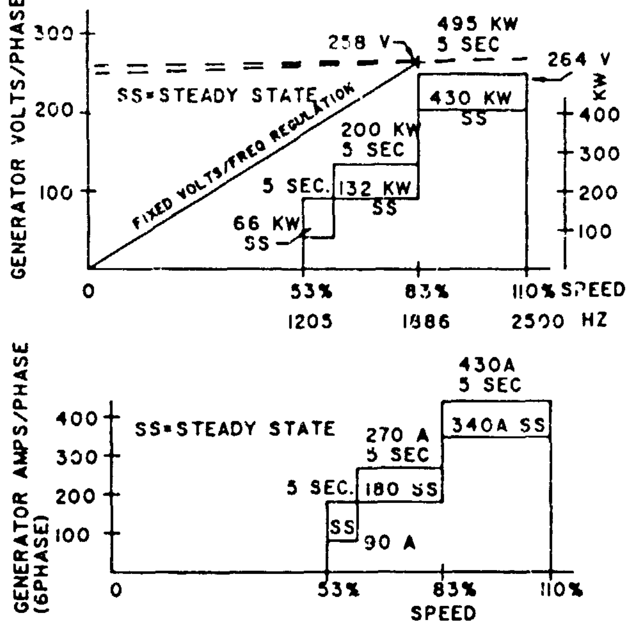
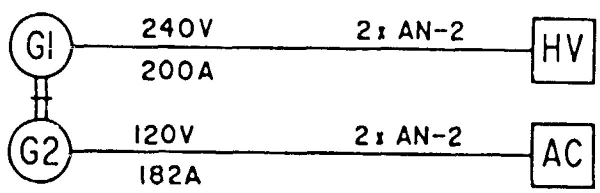



Figure 12. - Generator rating analysis.




**This option provides for the maximum isolation between the 13 KV and 400 Hz. outputs. However, it does require a more complex and heavier generator.**

Figure 13. - Generator feeder options - option 1, separate electromagnetic design with dedicated feeders.

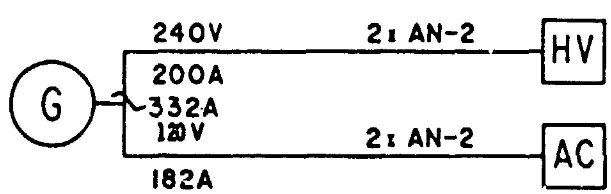
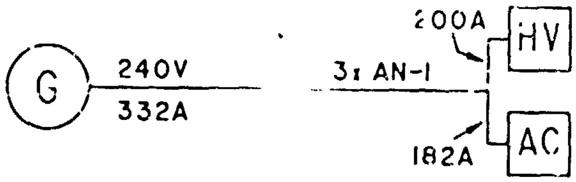



**Figure 14. - Generator-feeder option 2 - single generator and dedicated feeders. (This option provides for the lightest and simplest generator configuration. It does not provide the degree of isolation that option 1 provides.)**




**This option provides the simplest and lightest feeder configuration but the least amount of isolation between the 13 KV and 400 Hz outputs.**

Figure 15. - Generator-feeder options - option 3, single generator and common feeders.

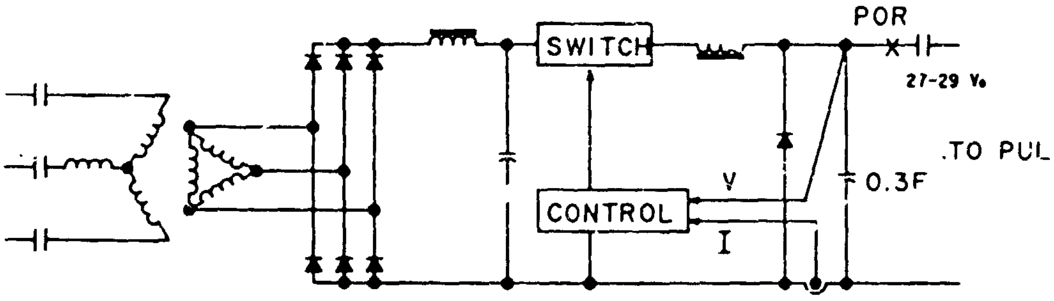



Figure 16. - 28-Vdc system approach - controlled current source with capacitive energy storage.

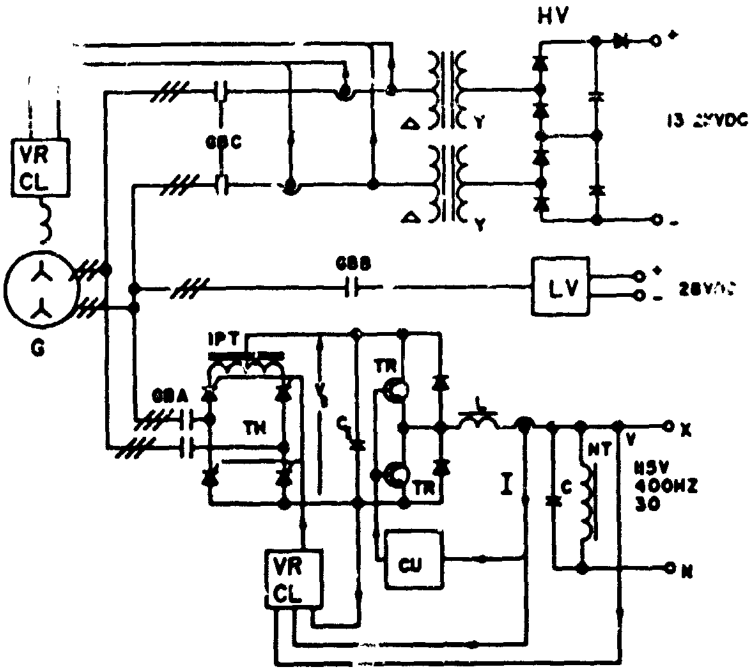



**Figure 17. - Final system configuration.**