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Voltage Source AC-to-DC Converters for High-Power Transmitters

R. Cormier
Radio Frequency and Microwave Subsystems Section

This work was done to optimize the design of the components used for the beam power supply, which is a component of the transmitters in the DSN. The major findings are: (1) the difference in regulation between a six-pulse and a twelve-pulse converter is at most 7 percent worse for the twelve-pulse converter; (2) the commutation overlap angle of a current source converter equals that of a voltage source converter with continuous line currents; (3) the sources of uncharacteristic harmonics are identified with SPICE simulation; (4) the use of an imperfect phase-shifting transformer for the twelve-pulse converter generates a harmonic at six times the line frequency; (5) the assumptions usually made in analyzing converters can be relaxed with SPICE simulation. The results demonstrate the suitability of using SPICE simulation to obtain detailed performance predictions of ac-to-dc converters.

I. Introduction

Large power converters (rated in megawatts) operate from three-phase power lines. Full-wave bridge rectifiers are utilized exclusively, resulting in six-pulse converters. By combining bridge rectifiers and an appropriate phase-shift transformer, multiples of six-pulse operation are obtained. The original transmitter beam supplies in the DSN are all six-pulse. Recently installed beam supplies, rated 75 kW and 2.25 MW, operate as twelve-pulse converters. These beam supplies are for klystron microwave amplifier tubes that require low values of ripple and good stability.

This investigation includes the results obtained for six-pulse and twelve-pulse operation. Two areas of particular interest for twelve-pulse operation are regulation and the effects of imperfections and approximations in the design and manufacture of the phase-shifting transformer on uncharacteristic harmonics. The twelve-pulse converter has been faulted for poor regulation. This, as will be shown, appears to be an exaggeration. Two types of harmonics are generated in converters. Characteristic harmonics result from operation under ideal conditions; the characteristic harmonics have been analyzed extensively, and numerous books have been published on the subject (e.g., [1]). Uncharacteristic harmonics are due to various imperfections in the generator and the converter. Measurements of the power supplies at Goldstone and in the laboratory yield significant values for uncharacteristic harmonics; the SPICE program has been used to identify their source. Current source converters provide a constant dc current to a load by the use of an inductor filter. Voltage source converters provide a constant dc voltage to a load by the use of a capacitor filter. The analysis found in the literature is limited to current source converters and voltage source converters with discontinuous line currents, but the operation of voltage source converters with continuous line currents has not been analyzed previously. All the power supplies used in the DSN are voltage source converters with continuous line currents. The results of the SPICE simulation indicate that both types of converters have many similarities, but important differences do exist. The applicability of current source equations to voltage source converters is investigated in this article.

A. Assumptions

The mathematical analysis of any converter is based on assumptions that the transformer and the rectifiers meet the conditions known as regular connection and regular operation. For regular connection three conditions must be met. These are:

(1) The total of all ampere-turns on each transformer leg is zero at any instant. The excitation current is excluded from this condition.

(2) Line currents total zero at any instant. There are no zero- or negative-sequence components, and the excitation current is excluded.

(3) Each successive interval of operation is identical to all other intervals.

Condition 2 for regular connections is never met in practice because power sources have distortion and practical transformers have stray capacitances. The distortion is equivalent to a negative-sequence component. The stray capacitances provide a path for the zero-sequence component.

For regular operation, three conditions must be met. These are:

(1) The rectifiers are arranged in a regular connection, i.e., the dc provides a balanced dc line load.

(2) For a current source converter, the load circuit contains an infinite inductance so that the current is constant. For a voltage source converter, the load circuit contains an infinite capacitance so that the voltage is constant.

(3) The ac source has no impedance and the transformer has no leakage inductance. The individual commutations do not overlap, but they may occur simultaneously.

The conditions for regular operation are even more restrictive than those for regular connection. In practice, for a current converter the load inductance is not infinite; thus it follows that the direct current is not constant and consequently contains ripple. Similarly, the load capacitance of a voltage source converter is not infinite, and the direct voltage is not constant. Practical generators and power distribution systems have inductances. Transformers have leakage inductance. The following analysis uses the SPICE program to analyze circuits that do not meet the conditions for regular operation.

B. Sequence Component Analysis

A standard method for the analysis of multiphase circuits is the use of the symmetric components (see [2]). The phase voltages are related to the symmetric components by the equation

$$\mathbf{V}_p = \mathbf{A}\mathbf{V}_s \tag{1}$$

where $\mathbf{V}_p$ and $\mathbf{V}_s$ are column vectors. The components of $\mathbf{V}_p$ are V_a, V_b, and V_c, and those of $\mathbf{V}_s$ are V_0, V_1, and V_2. Given a set of three-phase voltages designated by the vector $\mathbf{V}_p$, these phase voltages can be resolved into a zero-, a positive-, and a negative-sequence set of components designated by the vector $\mathbf{V}_s$. For a three-phase source the matrix $\mathbf{A}$ is

$$\mathbf{A} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \tag{2}$$

and the inverse is

$$\mathbf{A}^{-1} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \tag{3}$$

where $a = 1\underline{/120^\circ}$. Solving for the symmetric components

$$\begin{pmatrix} V_0 \\ V_1 \\ V_2 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{4}$$

From the above equations it is seen that the positive-sequence component (V_1) may be simulated by three voltage sources, one for each leg, and the negative-sequence component (V_2) by the addition of three series voltage sources of opposite phase rotation (see Fig. 1). The zero-sequence component (V_0) should be zero because the neutral wire is not connected to the load from the generator.

Any set of six-phase voltages can be represented by the addition of six symmetrical sequence components.

These are shown in Fig. 2. The zero- and the third-order-sequence components must have a neutral wire in order to exist. The positive- and second-order-sequence components rotate counterclockwise, while the negative- and fourth-order-sequence components rotate clockwise. Figure 3 shows the voltage vectors required for a twelve-pulse converter. The two sets of three-phase are phased 90 deg from each other, and in Fig. 3(a) the rotation is opposite, while in Fig. 3(b) the rotation is in the same direction. These are referred to respectively as counter rotation and synchronous rotation.

For a six-phase system, Eq. (1) can be written in terms of components

$$\begin{pmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \\ V_f \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -a & a^2 & -1 & a & -a^2 \\ 1 & a^2 & a & 1 & a^2 & a \\ 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & a & a^2 & 1 & a & a^2 \\ 1 & -a^2 & a & -1 & a^2 & -a \end{pmatrix} \begin{pmatrix} V_0 \\ V_1 \\ V_3 \\ V_4 \\ V_5 \end{pmatrix} \tag{5}$$

where $a = 1/\underline{120^\circ}$.

To calculate the sequence components from the phase voltages, the inverse matrix $\mathbf{A}^{-1}$ is calculated

$$A^{-1} = \frac{1}{6} \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -a^2 & a & -1 & a^2 & a^2 \\ 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & a^2 & a & 1 & a^2 & a \\ 1 & -a & a^2 & -1 & a & -a^2 \end{pmatrix} \tag{6}$$

and

$$\mathbf{V}_s = \mathbf{A}^{-1}\mathbf{V}_p \tag{7}$$

For the combination of two full-wave bridge rectifiers to form a twelve-pulse converter, a set of components that satisfies $\mathbf{V}_p$ is

$$\mathbf{V}_p = \left(V_a \; V_b e^{j30} \; V_c e^{j120} \; V_d e^{j150} \; V_e e^{j240} \; V_f e^{j270}\right)^t \tag{8}$$

This represents a synchronous rotating set of vectors. A counter rotating set, $\mathbf{V}_p'$, becomes

$$\mathbf{V}_p' = \left(V_a \; V_d e^{j150} \; V_c e^{j120} \; V_b e^{j30} \; V_e e^{j240} \; V_f e^{j270}\right)^t \tag{9}$$

The symmetrical sequence components necessary to generate these phase voltages were calculated from Eq. (7). One solution for the synchronous rotating set is

$$\mathbf{V}_s = \begin{pmatrix} 0 & 0 & 0.2588e^{j75} & 0 & 0 & 0.9659e^{-j15} \end{pmatrix}^t \tag{10}$$

Another is

$$\mathbf{V}_s = \begin{pmatrix} 0 & 0 & 0.7071e^{j75} & 0 & 0 & 0.7071e^{-j15} \end{pmatrix}^t \tag{11}$$

An example of a counter-rotating set is

$$\mathbf{V}_s' = \begin{pmatrix} 0 & 0.5e^{j90} & 0.5 & 0 & 0.5e^{-j90} & 0.5e \end{pmatrix}^t \tag{12}$$

C. Commutation Overlap

The commutation overlap angle μ is used to calculate the regulation, E_d/E_{do}, of a converter. The equation for the regulation of six-pulse converter is

$$E_d/E_{do} = 1/2\left[\cos\alpha + \cos(\alpha + \mu)\right] \tag{13}$$

for $\mu < 60$ deg, and α is the angle introduced when phase control thyristors are used to control the output voltage. Since $\alpha = 0$ when the converter is implemented with rectifiers, this equation simplifies to

$$E_d/E_{do} = 1/2[1 + \cos\mu] \tag{14}$$

This same equation applies to a twelve-pulse converter for μ less than or equal to 30 deg. For angles greater than 30 deg, a new phenomenon is observed in a twelve-pulse converter. The angle μ remains fixed at 30 deg and there is a delay in the start of commutation between the two converters. This phenomenon is described in [3]. The regulation equation derived for this mode is

$$E_d/E_{do} = \cos 15^\circ \cos(\alpha + 15^\circ) \tag{15}$$

The α in this equation is the same as that of the previous equation. The phase delay obtained with thyristors in a six-pulse converter appears as an automatic delay for a twelve-pulse converter, the result of interaction between the two six-pulse converters that make up the twelve-pulse operation. The two equations are identical, however, as can be seen from the trigonometric identity

$$\cos x \cos y = 1/2\left[\cos(x + y) + \cos(x - y)\right] \tag{16}$$

Let $x = \mu/2$ and $y = (\alpha + \mu/2)$. Substituting these values for x and y in the trigonometric identity, Eq. (16), and

Eqs. (13) and (15) are identical. This implies that to calculate the regulation for a twelve-pulse converter with μ greater than 30 deg, first determine μ for the equivalent six-pulse converter and subtract 30 deg to find α. This is then used to calculate the regulation from either equation. The equations are valid for all values of $(\alpha + \mu) < 60$ deg. Equations (13) and (15) are derived in [3].

The conversion of ac to dc generates harmonics both on the dc side of the converter and on the ac lines. For a perfect system, only characteristic harmonics are generated; in practice, other harmonics are also generated. The characteristic harmonics are of the order np on the dc side and $np \pm 1$ on the ac lines, where n is the harmonic number and p is the converter pulse number. The current source converter has been analyzed and equations derived to calculate harmonics. The voltage source converter has not been analyzed. The applicability of the equations derived for the current source converter is limited and care must be exercised in making calculations with these equations. For example, the equation for the amplitude of the characteristic dc voltage harmonic for a current source converter is

$$C_n = \frac{2E_{do}}{(n^2 - 1)} \tag{17}$$

A similar equation is used to calculate the amplitudes of the characteristic current harmonics for a voltage source converter

$$C'_n = \frac{2I_{sc}}{(n^2 - 1)} \tag{18}$$

Equation (17) applies to an ideal converter operating at light load from a voltage source generator with zero line inductance. Equation (18) applies when the converter is operating into a short circuit from a voltage source generator with line inductances. With commutation overlap, the amplitude of the principal characteristic harmonic (C_q) increases with commutation angle. For a six-pulse current source converter the value may be calculated with the equation

$$C_q = \frac{E_{do}}{70}\sqrt{78 - 70\cos 2\mu + 28\cos 5\mu - 20\cos 7\mu} \tag{19}$$

provided the commutation angle is less than 60 deg. (This equation is derived from [4].)

Equation (19) *cannot* be applied to a voltage source converter. The values of harmonics are a maximum at short circuit and decrease with decreasing current. Unfortunately, no equation is available to calculate harmonics at operating load.

The operation of current and voltage source converters is similar even though not all equations can be applied to both. Large ac-to-dc power supplies are usually assumed to operate from a voltage source with negligible inductance. The outputs of the rectifiers are connected to a choke that provides constant dc current. However, it has been known for many years that a better solution is to operate multiphase converters into a capacitor in place of a choke. Power systems, either utility or auxiliary, have appreciable inductances. This results in the generation of voltage spikes at the output of the converter when operating into a choke. The problem of voltage spikes was experienced in the DSN when the high-power transmitters were first installed (see [5]). This caused the problem of initial failures of the filter chokes. The solution was to add a capacitor on the converter side of the choke. The generators had enough inductances so that line currents are continuous; otherwise the rms line currents become very large. The major advantage is the elimination of spike voltages and reduced ripple at the output of the converter.

If a current source generator were available, the converter would operate with no commutation overlap. (In fact, simulation of a voltage source converter was made and the output current was independent of the line inductance. For a discussion of the current versus voltage source converter operation, see [6].) This is not the case with a voltage source generator and line inductances. The commutation overlap angle is almost equal for both converters. Actually, the major portion of the inductance is located in the generator. A generator has three different values of inductances depending on the time of measurement after the initiation of the short circuit. The sustained value of the short circuit determines the synchronous reactance. The initial period is divided into two parts. The first cycle after initiation of the short is known as the subtransient reactance, followed by a longer period called the transient reactance. During converter operation, the commutation momentarily shorts the generator for a few degrees of a cycle. The response of the generator is based on the subtransient reactance, and this is the value used to determine the referenced short current. For the 400-Hz generators in the DSN, the subtransient inductance is roughly one-third that of the steady-state short-circuit inductance. The inductances should not be so large that the converter is operating in a higher mode (commutation overlap angle $\mu > 60$ deg), as such converter operation results in poor regulation. The short-circuit current is defined as that current which would be obtained with the operational inductances in the ac lines. These are the subtransient inductance of the generator plus the wiring and the leakage inductance of the transformers.

D. Other DC Ripple Harmonics

Other types of distortions, such as harmonics of the line frequency, are also present. These harmonics may be simulated by a harmonic voltage in series with each main generator's phase voltage. Low-frequency amplitude modulations may also be present; these are generally called subharmonics even though technically they are not necessarily frequency-related to the line frequency. In order to analyze the converter operation with different types of subharmonic distortion it is possible to introduce a set of positive- or negative-sequence components at various frequencies. However, the use of a single set of voltage sources does not represent the usual subharmonic distortion, which requires the insertion of two series sources to simulate amplitude modulation. As the armature rotates, the amplitude of the output line voltage varies, which results in amplitude modulation at a frequency below that of the line frequency. When the distortion is in the form of a low-frequency amplitude modulation, then the instantaneous voltage is

$$E_m(t) = V \sin w_c t + \frac{mV}{2}\left[\sin(w_c - w_s)t + \sin(w_c + w_s)t\right] \quad (20)$$

The first term represents the main generator voltage, and the second term represents the sidebands. The sidebands form the envelope that rides on top of the carrier. Although this equation is usually written in terms of cosines, the results remain unchanged when written in terms of sines. The use of sines is preferred because of the transients generated by the start of a cosine wave. Another type of distortion is frequency modulation, but this has not been investigated as it is not a usual distortion in power systems (see [7]).

II. Six-Pulse Converter Analysis

The circuit used for simulation consists of a three-phase wye-connected generator, a transformer with a delta primary, and an extended delta secondary. The output of the secondary is connected to a three-phase full-wave bridge diode converter. A capacitive filter and a resistive load are connected to the output of the rectifiers. For simulation purposes, two or three voltage sources are connected in series on each leg of the generator. One set generates the fundamental positive-sequence component, the other sets introduce the various types of distortions being investigated. The results of the simulation are given in Tables 1 through 8. A listing of the basic circuit is given in Table 9; the listing was modified as appropriate for each test. Only steady-state conditions are of interest, therefore a delay in recording data was introduced so that initial turn-on transients did not contribute to the data. The capability of SPICE to analyze the converter operation is evaluated on the basis of a comparison of the values for the characteristic harmonics obtained from the simulation and those calculated. Various types of distortions are simulated and the resulting uncharacteristic harmonics identified.

A. DC-Side Ripple Harmonics

Table 1 lists the values of the characteristic harmonics obtained with the SPICE simulation for a voltage source converter. Column four lists the values for the current harmonics obtained; the next column contains the theoretical values calculated by Eq. (18). For example, when the principal harmonic at 2400 Hz is compared to the calculated theoretical value, a difference of only 0.06 dB was obtained. For a six-pulse converter, the characteristic harmonics are multiples of six times the line frequency; in our case the line frequency is 400 Hz. The significance of this result is twofold. First, there is close agreement of the SPICE simulation with calculated values. Second, the equations derived on the basis of E_{do} remain valid when I_{sc} is substituted for E_{do}, at least for this one equation. Note that the values of the characteristic harmonics are independent of the line inductances when the value is normalized to the dc short circuit current.

The excellent results obtained confirm the applicability of SPICE simulation for the analysis of the operation of converters. A second check of the capabilities of the SPICE program is the calculation of the uncharacteristic harmonics that are theoretically equal to zero. The values obtained are less than 60 dB from those for the characteristic harmonics, and this indicates an error of less than 0.1 percent for the capability of SPICE (see Table 2).

B. Commutation Overlap

Voltage converter harmonics are maximum at short circuit and decreased at rated load. Unfortunately, no formula is available to calculate the value of harmonics at reduced current. Operating at 1 MW, the simulation for the voltage source converter yields a commutation overlap angle of 28.8 deg, and the value of the principal harmonic is -36.86 dBI$_{sc}$. This is a decrease of 12 dB from the value at short circuit. At light load of 100 kW, the improvement was 15 dB (see Tables 3 and 4). The value of the principal harmonic for the voltage source converter referenced to the rated current I_d in place of I_{sc} is $-24.86 + 18.35 - 12 = -18.51$ dB. (The -18.35 dB is the difference between short-circuit current and rated current.) This represents an increase of 6.35 dB or a doubling of ripple components in terms of currents. The klystron responds to voltage changes, so the current ripple must be converted to voltage ripple. This can be done provided the value of the filter capacitor is known. For example, using the value of 0.2 μF, the principal harmonic that was calculated as equal to -18.51 dB becomes -34.12 dB when referenced to the dc output voltage E_d.

In order to compare the two types of converters, it is necessary to calculate the value of the principal harmonic for the current source converter operating with the same load. The SPICE listing was modified by replacing the capacitor with a choke filter. The commutation angle measured 30.4 deg. From Eq. (19) a value of -22.24 dBE_{do} was obtained. From Eq. (14), the output voltage is reduced from the light load value by 0.6 dB. Correcting for the change in output voltage, the ripple becomes $-22.24 + 0.6 = -21.64$ dB referenced to E_d. The difference of ripple values between the two converters, namely $-34.12 + 21.64 = -12.48$ dB, is lower for the voltage source converter, which is obtained at the expense of the addition of a 0.2 μF at the output of the converter. The voltage source converter with 0.6 mH of line inductance can operate from a maximum load of 1 MW to a light load of 100 kW before the load current becomes discontinuous. The choice of 0.6 mH is based on the value of subtransient reactance of the present generators that feed the DSN beam supply.

C. Negative-Sequence Component

Next, the effects of generator line distortion are investigated (see Table 5). It should be noted that the generators for the transmitters in the DSN are dedicated and no other loads contribute to the generation of line unbalance. For a capacitive filter, the harmonics are measured as currents and the value of the negative-sequence component is based on the short-circuit current in the same way as for the characteristic harmonics. For a negative-sequence component, the harmonic on the dc side has a frequency of twice the line frequency. As an example, a 1 percent negative-sequence component in a converter with a load of 1 MW and line inductances of 0.6 mH gives a -40.23 dBI_{sc} ripple component at 800 Hz. The generation of the 800 Hz appears to be the result of commutation angle variations. First, the angle is 18.86 deg, next 20.88 deg, and then 16.17 deg. This pattern repeats in a regular cyclic order. In terms of voltage, the component is -27.95 dBE_d. These simulations were performed with both sequence components in phase at startup. For the components out-of-phase, the output harmonic decreased by approximately 3 dB. It should be noted that two out-of-phase sequence components can be resolved into in-phase components. From these results the generator negative-sequence component can be specified.

D. Harmonic Distortion

Simulations of the second, third, and fourth harmonics and both sequence components are made at a distortion level of 1 percent. The output ripple frequency depends on the input harmonic. The lowest output frequency of 400 Hz, which is the hardest to filter, is generated by the +2 and the -4 components. For the +2 component, a 1 percent (-40 dB) input harmonic level results in an output of -40.9 dBI_{sc} at a frequency of 400 Hz. In terms of voltage, the component value is -22.60 dBE_d. For the -4 component, the output is only one quarter as large. The results of the simulation are given in Table 6. Additional testing of other harmonics was not made because these have been analyzed and the results reported in [8] (Table 3.5).

E. Subharmonic Distortion

Another type of line voltage distortion generally present in practical generators is subharmonics of the line frequency. The subharmonics are not true harmonics at all but rather are low-frequency voltage modulations that appear on the lines. The simulated subharmonics are three-phase with either a positive or negative sequence. The first simulation was made with one series voltage source in each leg of the generator. This simulates single sideband distortion (see Table 7). Ripple frequencies appear as the sum or difference between subharmonic and the line frequencies. For a positive-sequence subharmonic, the ripple frequency is the difference frequency, while for a negative-sequence component, the ripple is the sum frequency. The subharmonic affects the commutation overlap angle, which appears to be the cause of the generation of these harmonics. The SPICE listing was changed to include two voltage sources to represent the two sidebands of an amplitude modulated signal. For the negative-sequence component, the ripple harmonics identified, although very weak, were detected at $2f_s$ and $3f_s$ (f_s = subharmonic frequency). When the positive-sequence component was tested, a stronger (-57 dBI_{sc}) single component was observed at the subharmonic frequency. This result, which is included at the bottom of Table 7, is consistent with measurements of transformer rectifier assemblies in service. A ripple of 20 Hz has been observed in the transmitters at Goldstone; this low a frequency is particularly troublesome because of the difficulty in filtering. By introducing a feedback component in the generator field supply, it is possible to reduce this component. The simulation identifies the subharmonic as an amplitude modulation of the output generator line voltage.

F. AC Line Harmonics

The ac line harmonics are found on the current and the voltage waveforms of the ac lines. For the usual current source converter, the line currents carry the harmonics, and the voltages are taken to be without any harmonics. This is changed for a voltage source converter. Ideally, the line currents are free of harmonics and the voltages carry all the harmonics. For an actual voltage source converter, both current and voltage harmonics are present. The theoretical values are calculated from knowing that the values of the ac harmonics are equal to $1/n$, where n is the harmonic number. For a six-pulse converter, n takes the values of 6 ± 1 for the first two harmonics. Values of -14 dB and -16.9 dB are calculated for the fifth and seventh harmonics, respectively (see [9]). The ac harmonics were simulated for various values of line inductances. The values were chosen to give commutation overlap angles from 7.5 deg to 60 deg. From the results, the current harmonics are very large at low values of line inductances. At 7.5 deg, the fifth harmonic current is almost half of the line current. As the commutation angle is increased, the current harmonics decrease and the voltage harmonics increase in value. At 60 deg, the fifth voltage harmonic equals one-fifth the line voltage. The voltage regulation increases as the commutation overlap angle increases (see Table 8, column 7). From these results, voltage converters operating from a voltage source must have line inductances and the operation should be with relatively large commutation overlap angles. The loss of voltage from commutation is nondissipative.

III. Twelve-Pulse Analysis

The generation of twelve-pulse requires a phase-shifting transformer to generate six-phase. If the six phases are connected to a single full-wave bridge, the ripple is not twelve-pulse but only six-pulse. The alternating voltages are pairwise equal and opposite and the result is the superpositioning of the pulses out of the converter. In order to obtain twelve pulses from a six-phase source, the phases must be broken up into two sets of three-phase arranged asymmetrically. This is done when a phase-shifting transformer with delta wye secondaries feeds two full-wave bridge rectifiers. An alternative is the use of two extended deltas, one phase-shifted 15 deg clockwise, the other phase-shifted 15 deg counterclockwise. For simulation purposes, a source with two symmetric components was developed which yielded the basis for comparison of all the other configurations.

A. Sequence Components

The phase-shifting transformer of a twelve-pulse converter can be replaced with a six-phase source. The two symmetric sequence components (V_2) and (V_5), based on Eq. (10), were placed in the SPICE model and the ripple was that of a twelve-pulse converter. To verify the model, an ideal converter and input power source were simulated. The ratio of the highest uncharacteristic harmonic to the principal characteristic harmonic at $12f$, where f is the line frequency, is greater than 80 dB. This represents a residual of less than 0.01 percent, more than adequate for our purposes.

Any distortion in either $\mathbf{V}_s$ or $\mathbf{V}_s'$ yields a harmonic at six times the input line frequency. The ratio of the amplitude of the two sequence components is 3.73, and the angle between the two is 90 deg. When the amplitude of the larger component was decreased by 2.5 percent, the principal characteristic harmonic component of a six-pulse converter appears. The value referenced to the twelfth harmonic increased from practically zero (-95 dB) to -13 dB. Similar results are obtained when the phase is not 90 deg. The same results are obtained when the values of turns ratio or unbalance leakage inductance are simulated in a phase-shifting transformer used to supply a twelve-pulse converter. Other distortion of the three-phase power yields the same uncharacteristic harmonics with a twelve-pulse converter as with a six-pulse converter.

B. Commutation Overlap

For a six-pulse converter, normal operation is taken for μ less than 60 deg, and this is called Mode 1 operation. During Mode 1, the output voltage decreases linearly from 1 to 0.750. A twelve-pulse converter consists of two out-of-phase six-pulse converters. Mode 1 operation exists for μ less than 30 deg only. At $\mu = 30$ deg, the two converters have the same value of regulation. For μ greater than 30 deg, the regulation is worse for the twelve-pulse converter. At $\mu = 60$ deg, the regulation for the twelve-pulse converter is 0.683, a difference of 7 percent. Since the commutation overlap angle is usually made less than 60 deg, the difference in regulation between the two converters does not prevent the use of twelve-pulse converters.

IV. Conclusion

The use of SPICE simulation has made it possible to obtain detailed performance predictions for power converters. For the first time, an analysis of voltage source converters with continuous line current was obtained. The effects of line distortion such as generator harmonics and subharmonics on the output voltage ripple were determined. The effects of line voltage unbalances, both phase and amplitude, on converter operation were greatly simplified by the use of sequence components. The results indicate the ease of design of voltage source converters for medium- and high-power applications.

The use of twelve-pulse converters for the transmitters in the DSN has a number of advantages over six-pulse units. The ripple on the ac lines and on the dc side is reduced and the frequency is increased, resulting in reduced requirements for filtering. The uncharacteristic harmonics are equal for both types of converters. The only disadvantage is the poorer regulation for commutation overlap angles greater than 30 deg. At 60 deg, a penalty of 7 percent is found for the twelve-pulse converter over that of the six-pulse. If the design is limited to commutation of about 30 deg, both types of converters are equal in terms of regulation.

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Table 1. Short circuit test (Fourier components: characteristic harmonics)

Harmonic No.	Frequency, Hz	Current, amp	Normalized, dBI_{sc}	Theoretical, dBr
6	2400	10.83	−24.80	−24.86
12	4800	2.551	−37.35	−37.09
18	7200	1.099	−44.70	−44.16
24	9600	0.6913	−48.70	−49.17
30	12000	0.4294	−52.83	−53.05
36	14400	0.2518	−57.47	−56.22
42	16800	0.2176	−58.74	−58.90
48	19200	0.1861	−60.09	−61.23
54	21600	0.1148	−64.29	−63.27

Note: A short circuit dc load of 1 ohm with line inductance of 0.6 mH is the basis for Table 1 data. The short circuit dc current is 188.1 A. The results are independent of line inductances. The values are identical to those obtained with a current source converter.

Table 2. Simulation capability test (uncharacteristic harmonics)

Harmonic No.	Frequency, Hz	Current, amp	Normalized, dBr
1	400	1.092E-3	−104.72
2	800	6.998E-5	−128.59
3	1200	2.355E-6	−158.05
4	1600	1.441E-5	−142.31
5	2000	7.835E-5	−127.61
7	2800	6.418E-5	−129.34
8	3200	1.501E-5	−141.96
9	3600	1.783E-6	−160.46

Note: A dc load of 1MW and line inductances of 0.6 mH are the basis for Table 2 data.

Table 3. Light load test (Fourier components: characteristic harmonics)

Harmonic No.	Frequency, Hz	Current, amp	Normalized, dBI_{sc}
6	2400	1.884	−39.99
12	4800	0.3057	−55.78
18	7200	0.1180	−64.05
24	9600	0.0616	−69.69
30	12000	0.0374	−74.03
36	14400	0.0248	−77.60
42	16800	0.0174	−80.67
48	19200	0.0128	−83.36
54	21600	0.0097	−85.74

Note: The converter is operating with a light load of 1.964 Adc. The power output is nominally 100 kW. Line inductance 0.6 mH.

Table 4. Full power test (Fourier components: characteristic harmonics)

Harmonic No.	Frequency, Hz	Current, amp	Normalized, dBI_{sc}
24	9600	0.1569	−61.58
30	12000	0.1062	−64.97
36	14400	0.0692	−68.68
42	16800	0.0540	−70.84
48	19200	0.0389	−73.69
54	21600	0.0326	−75.22

Note: The converter is operating with a rated load of 22.75 Adc. The power output is nominally 1 MW. Line inductance 0.6 mH.

Table 5. Voltage converter (negative-sequence component)

Harmonic No.	Frequency, Hz	Current, amp	Normalized, dBI_{sc}	AC Inductance, mH
2	800	4.471	−47.01	0.1
4	1600	1.358	−57.36	0.1
8	3200	0.08348	−67.06	0.1
2	800	4.639	−37.91	0.3
4	1600	0.8611	−52.54	0.3
8	3200	0.4399	−58.37	0.3
2	800	1.831	−40.23	0.6
4	1600	0.3048	−55.81	0.6
8	3200	0.1934	−59.76	0.6
2	800	1.025	−40.94	1
4	1600	0.159	−57.13	1
8	3200	0.1004	−61.12	1

Note: A dc load of 1 MW nominal, which is the rating of the supplies in the DSN, is the basis for Table 5 data. The negative-sequence component had an amplitude of 1 percent or −40 dB with respect to the fundamental component of line voltage.

Table 6. Voltage converter (harmonic distortion)

Input Harmonic No.	Output Frequency, Hz	Output DC Current, amp	Output Normalized, dBr
2	400	1.695	−40.9
−2	1200	0.9058	−46.35
3	800	1.404	−42.54
−3	800	0.4747	−51.96
−3	1600	0.6576	−49.13
−3	3200	0.05475	−70.72
4	1200	0.7734	−47.72
−4	400	0.4281	−52.86
−4	2000	0.4355	−52.71

Note: A dc load of 1 MW nominal, which is the rating of the supplies in the DSN, is the basis for Table 6 data.

Table 7. Subharmonic distortion

Input Frequency, Hz	Input Level, dB	Sequence Component	Output Frequency, Hz	Output Level, dBI_{sc}
		Single-Side-Band Source		
300	1%	pos	100	−57.85
300	1%	neg	700	−38.37
200	1%	pos	200	−48.47
200	1%	neg	600	−36.44
100	1%	pos	300	−43.91
100	1%	neg	500	−36.36
40	1%	pos	360	−41.49
40	1%	neg	440	−38.22
		Double-Side-Band Source		
440/360	1%	pos	40	−57.33

Note: A dc load of 1 MW nominal, which is the rating of the supplies in the DSN, is the basis for Table 7 data. The input level is referenced to the main 400-Hz component of the phase voltage.

Table 8. AC line harmonics

Line Ind., mHy	Voltage $f = 2000$, dB	Current $f = 2000$, dB	Voltage $f = 2800$, dB	Current $f = 2800$, dB	Overlap Angle, deg	Line Regulation, %
0.1	−25.55	− 6.99	−29.55	−14.08	7.5	1.10
0.3	−20.51	−11.26	−28.83	−22.49	18.9	2.57
0.6	−17.26	−13.87	−23.26	−22.79	28.8	5.13
1	−15.36	−16.28	−19.53	−23.36	38.1	8.67
3	−14.03	−24.15	−16.92	−29.97	60	23.6

Note: The values are given in dB referenced to the level of the fundamental 400-Hz component of the phase voltage or the line current as appropriate. A dc load of 1 MW, which is the rating of the supplies in the DSN, is the basis for Table 8 data.

Table 9. Input listing (AC line harmonics, ideal circuit)

```
TRANSFORMER ANALYSIS—2.25 MW, 400Hz ASSEMBLY TAP 8 (ONE PI)
.FOUR 4000 I(V4) V(52)
TRAN 1US 22.5MS 20MS
.WIDTH IN=133 OUT=133
.OPTIONS METHOD=GEAR LIMPTS=6000 NOMOD RELTOL=.03 ITL5=0 ITL4=50 LVLTIM=1
V1 60 1 SIN(0 3000 400 0 0)
V2 61 1 SIN(0 3000 400 0.83333333MS 0)
V3 62 1 SIN(0 3000 400 1.66666667MS 0)
V4 63 60 SIN(0 0 0 0 0)
V5 64 61 SIN(0 0 0 0 0)
V6 65 62 SIN(0 0 0 0 0)
V10 51 63 SIN(0 0 0 0 0)
V11 54 64 SIN(0 0 0 0 0)
V12 57 65 SIN(0 0 0 0 0)
V7 1 0
L1 51 53 3M
L3 57 59 3M
L5 54 56 3M
R1 53 52 50M
R3 59 58 50M
R5 56 55 50M
RP10 52 71 21.96M
RP11 58 81 21.96M
RP12 55 91 21.96M
K123 LP11 LS13 .9999
K175 LP12 LS15 .9999
K148 LP13 LS18 .9999
K112 LSE11 LP11 .9999
K194 LSE19 LP13 .9999
K167 LSE16 LP12 .9999
K131 LS13 LSE11 .9999
K189 LS18 LSE19 .9999
K165 LSE16 LS15 .9999
LSE11 103 116 1.8H
LSE16 106 118 1.8H
LSE19 109 117 1.8H
LP11 91 58 .2H
LP12 81 52 .2H
LP13 71 55 .2H
LS13 116 115 5.408H
LS15 118 113 5.408H
LS18 117 114 5.408H
RS12 502 0 2K
C1 502 700 1UF
RC1 700 0 1
V8 501 502
RS13 116 113 630M
RS14 118 114 630M
RS15 117 115 630M
VD11 603 103
VD12 103 604
VD13 605 109
VD14 109 606
VD15 607 106
VD16 106 608
D11 501 603 DIODE
D12 604 0 DIODE
D13 501 605 DIODE
D14 606 0 DIODE
D15 501 607 DIODE
D16 608 0 DIODE
.MODEL DIODE D
.PRINT TRAN I(VD11) I(VD12) I(VD13) I(VD14) I(VD15) I(VD16) I(V4) V(52)
.END
```

Note: The listings were changed to obtain each of the conditions required for the different tables.

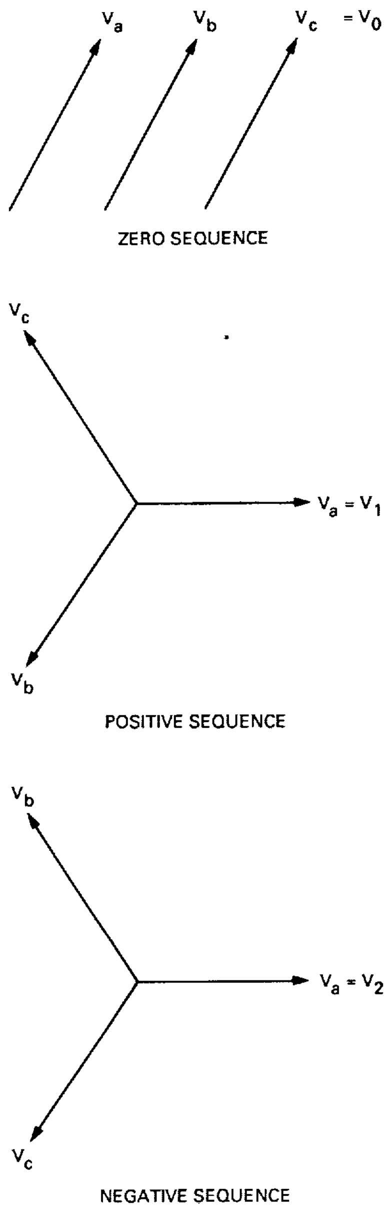


Fig. 1. Three-phase symmetric sequence components.

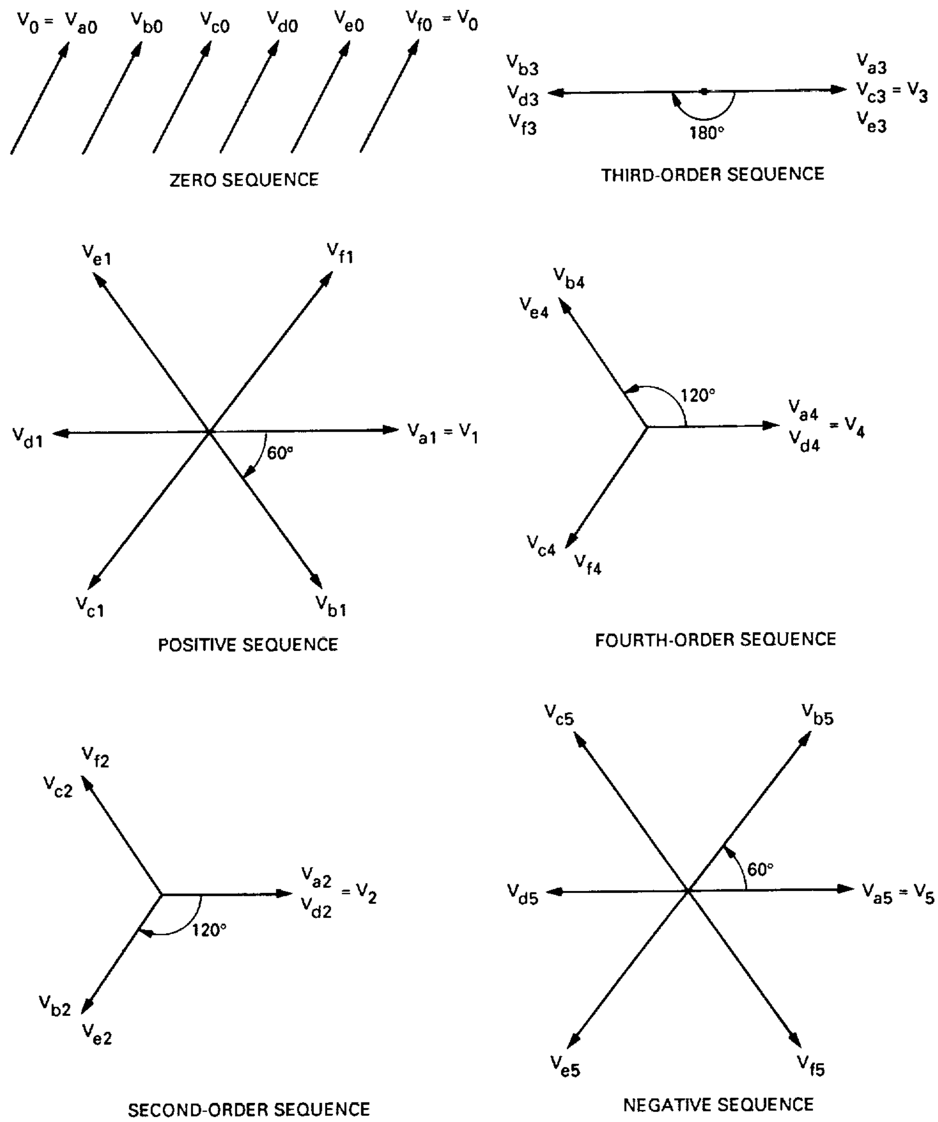
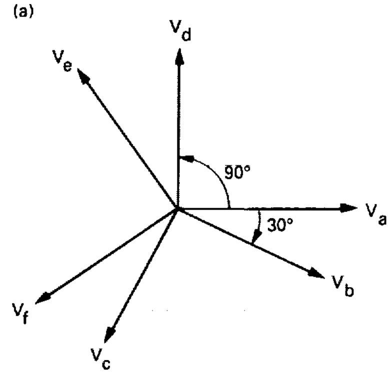


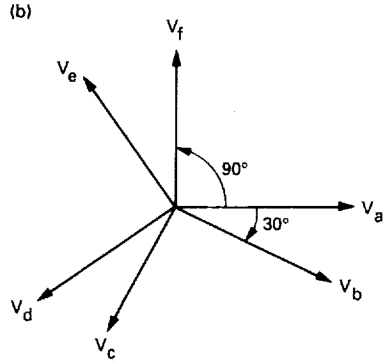
Fig. 2. Six-phase symmetric sequence components.

(a)



OPPOSITE-SEQUENCE ROTATION

(b)



SAME-SEQUENCE ROTATION

Fig. 3. Six-phase voltages required for twelve-pulse converter.