A Synchronous Tap Changer Applied to Step-Up Cycloconverters

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Abstract—The operating principles of a transformer tap changing system are presented. The system is named *synchronous tap changer* because it changes taps in synchronism with its input signal. The purpose of a synchronous tap changer is to change the turns ratio of a transformer in a manner which will reduce the distortion content of the incoming signal. In effect, it is an active filter. It is expected to find use in power type systems.

The application of synchronous tap changers to step-up cycloconverters is presented to illustrate the use of this scheme. The system is optimized and results of an experimental one are presented.

Introduction

THERE are many industrial power applications where frequencies higher than commercial line frequencies are either needed or lead to definite advantages in equipment design. Induction heating is a good example of the application of high-frequency power. It is well known that properties of power system components, such as size and weight, are related to operating frequency. In many applications it is worthwhile to convert the frequency of the incoming power to take advantage of the improved physical characteristics of a system's components, such as transformers and filter parts. In addition, high frequencies make possible improved system dynamic performance such as rise and fall time.

This paper is concerned with the conversion of power from low to high frequencies and the improvement of the high-frequency waveform (i.e. reduction of distortion) which may be of very poor quality when simple, economical circuits are used to make the frequency conversion. The frequency conversion is made by a circuit or system which has the generic name *step-up cycloconverter*.

Present step-up cycloconverter systems include motor-generator sets, saturating transformer circuits, and rectifier-inverter combinations. The cycloconverter system presented here converts incoming ac power or rectified ac power directly to high-frequency ac, thus eliminating the need for manipulating the power at a low frequency with magnetic components and/or filter capacitors. This scheme does have one serious disadvantage: the high-frequency ac has the low-frequency source waveform as an amplitude modulation envelope. This distortion needs to be removed for many applications and if the ac is converted to dc, the filtering problem is that of a low-frequency system.

The operating principles and design optimization of a transformer tap changing system, which reduces the distortion of a step-up cycloconverter, are presented. The transformer system is named *synchronous tap changer* because it changes taps in synchronism with the envelope which is being modified. In effect, the synchronous tap changer is an active filter which is believed to have many advantages over a passive type filter. Although this filtering scheme is conceptually quite simple, its design and optimization are rather complex; the results represent a relatively elaborate computational problem.

System Operation

A step-up cycloconverter system is shown in Fig. 1. It consists essentially of an inverter and a filter. Operation is as follows: The low-frequency source voltage is inverted[1] to the desired high frequency; this high-frequency signal is then fed into the synchronous tap changer to reduce its distortion. Additional filtering is accomplished by a passive filter when required by system specifications.

A schematic of the synchronous tap changer power section is shown in Fig. 2. It consists of a transformer with a number of taps which are selected by a set of switches, 1 through N. The inverter output voltage e_I is applied to terminals 1 and 2 of the transformer. The secondary voltage amplitude e_s for a given period is a function of the amplitude e_I and the transformer turns ratio which is controlled by the switches, i.e.,

$$e_s = \frac{N_s}{N_p} e_I. \tag{1}$$

From (1) it follows that the peak values of the secondary voltage waveform can be held constant if the turns ratio of the transformer is varied in proportion to the input envelope. This would require a tap for each cycle of the inverter frequency during the period of the low-frequency energy and would produce an output envelope free of distortion in the ideal case. However, complexity, cost, and

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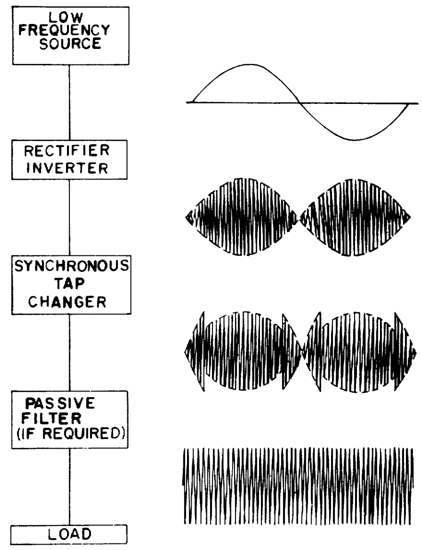


Fig. 1. Block diagram of a step-up cycloconverter.

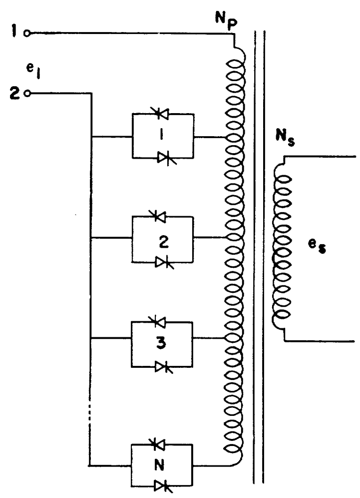


Fig. 2. Power section schematic of synchronous tap changer.

reliability considerations limit the number of taps a designer would want to use in a practical circuit.

Two questions must be answered concerning the synchronous tap changer from an engineering point of view to meet a given distortion specification. First, how many taps are required and, second, at what times must these taps be switched for optimum performance?

The problem will be solved by optimizing the switching intervals and turns ratios for different numbers of taps.

System Analysis

If the inverter of Fig. 1 is assumed to produce a high-frequency, sinusoidal output whose envelope is equal to the absolute magnitude of the incoming low-frequency ac signal, then the output e_I of the inverter can be expressed as

$$e_I = |E_p \sin \omega_s t| \sin \omega_c t \tag{2}$$

where E_p is the peak value of the low-frequency signal of frequency ω_s and ω_c is the inverter frequency. The Fourier Series expansion for $|\sin \omega_s t|$ is [2]

$$|\sin \omega_s t| = \frac{2}{\pi} - \frac{4}{\pi}\left(\frac{\cos 2\omega_s t}{2^2 - 1} + \frac{\cos 4\omega_s t}{4^2 - 1} + \ldots\right). \tag{3}$$

Substituting this expression into (2) and collecting terms yields

$$e_I = \frac{2E_p}{\pi}\left(\sin \omega_c t - \frac{\sin(\omega_c + 2\omega_s)t + \sin(\omega_c - 2\omega_s)t}{3} - \frac{\sin(\omega_c + 4\omega_s)t + \sin(\omega_c - 4\omega_s)t}{15} - \ldots\right). \tag{4}$$

Equation (4) represents a waveform composed of a *carrier* with *sidebands* $\pm\ 2n\omega_s$ from the inverter frequency ω_c. It also illustrates the disadvantages of this type of frequency changer system. First, the peak value of the desired signal is $2/\pi$ times the peak value of the low-frequency input to the inverter. This results in an increased installed capacity for the inverter because it must manipulate a waveform of magnitude E_p to yield a usable waveform of only $2E_p/\pi$. Second, the sidebands represent unwanted distortion and a filter to remove them may be large and expensive. The closer these sidebands are to the carrier, the more difficult they are to attenuate. In practical cases, the nearest sidebands may be only 120 Hz from a carrier frequency of 20 000 Hz or more.

For example, a second order LC filter would require a Q of[2]

$$Q = \frac{\omega_c}{4\ \omega_s} \tag{5}$$

to attenuate the power in the sidebands adjacent to the carrier by a factor of 2. For attenuation by a factor of 10, the Q is given by[3]

$$Q = \frac{\omega_c}{\omega_s}. \tag{6}$$

Thus, if the ω_c/ω_s ratio is 1000, a circuit Q of 250 is required for a 2 to 1 reduction of the amplitude of the adjacent ($\pm\ 2\omega_s$) sidebands. A Q of 1000 would be required for a 10 to 1 reduction. Obviously, these values of Q are impractical for high-power systems.

A solution to the increased installed capacity required of the inverter and the distortion is to remove or alter the term $|\sin \omega_s t|$. Ideally, this term should be a constant equal to unity. In the system presented here the envelope term will be modified by an adjustment of the turns ratios and switching intervals of the synchronous tap changer transformer. (See Fig. 2.)

Given the problem of modifying the signal envelope, the question of what should be considered to be the optimum arises. As noted previously, the perfect case is easy to define, but a criterion which will allow optimization for a practical number of taps is not obvious. For any assumed number of taps there are two quantities to be defined for an optimum case: the turns ratios for each tap and the time at which the taps are changed.

One method for optimizing the turns ratios and switching intervals is suggested by consideration of a square wave. A full wave rectified square wave has the same average and peak voltage levels and is, therefore, a pure dc voltage. Thus, a solution to the problem is to modify $|\sin \omega_s t|$ to the extent that the envelope's average and peak values approach each other as closely as possible for a given number of taps.

Another possible solution would be to adjust the turns ratios for the transformer taps such that the average value of the rectified output waveform over the switching interval for each tap is the same. Other candidate solutions are: adjust the turns ratios to make the peak value of each interval equal to unity (on a normalized basis); or minimize the magnitudes of selected sidebands, making the carrier as large as possible.

For any of these criteria, a Fourier Series expansion of the synchronous tap changer output can be derived and its coefficients manipulated to give optimum results. Because a Fourier Series expansion of the synchronous tap changer's waveform for a set of linearly independent switching intervals is unwieldy for the general case of many such intervals, this expansion will be written for many small, equal segments. The final switching intervals thus will be written for many such segments, each combination not necessarily containing the same numbers of segments as another. Interval and segment numbers refer to divisions in one half of the periodic output waveform (see Fig. 3). The second half of the waveform is the mirror image of the first half.

For example, if three switching intervals are assumed, 12 equal segments might be chosen for the expansion. Then the first switching interval could include segments 1, 2, and 3; the second switching interval could include 4 and 5; and the third could include 6, 7, 8, 9, 10, 11, and 12.

The Fourier Series expansion of the synchronous tap changer waveform is

$$f(\omega_s t) = \frac{2E_p}{\pi}\left[\sum_{k=1}^{T} R_k \left(\cos\,(\mathrm{k}-1)\frac{\omega}{2T} - \cos\frac{k\pi}{2T}\right) - \sum_{n=1}^{\infty}\left(\left(\sum_{k=1}^{T} R_k \frac{\cos\,(1+2n)\dfrac{k\pi}{2T} - \cos\,(1+2n)(k-1)\dfrac{\pi}{2T}}{1+2n} + \frac{\cos\,(1-2n)\dfrac{k\pi}{2T} - \cos\,(1-2n)\,(k-1)\dfrac{\pi}{2T}}{1-2n}\right)\cos n\omega_s t\right)\right] \tag{7}$$

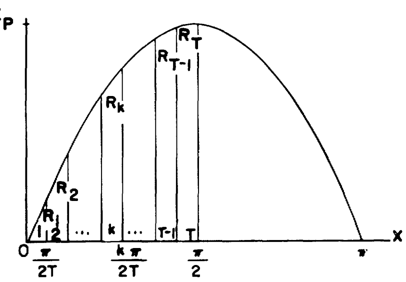


Fig. 3. Switching segments used in derivation of Fourier Series expansion.

where the first term represents the $a_0/2$ component and the second term (enclosed by brackets) represents the nth harmonic term of the general Fourier Series expansion for an even function

$$f(x) = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos nx. \tag{8}$$

Figure 3 illustrates the terms used in (7). Term R is the ratio of the secondary turns to the primary turns and T is the total number of segments in half of the waveform. In deriving the equation it is only necessary to integrate over half a cycle because of quarter wave symmetry. This symmetry also causes all odd order harmonics to have zero coefficients.

The turns ratios and number of segments for each set of switching intervals have been varied separately using a digital computer and the resulting synchronous tap changer output has been evaluated against the criteria suggested above. The total number of segments [T in (7)] was set to 6 for preliminary studies. A later increase of T to 12 for certain of the criteria did not produce results that varied significantly for a low number of taps. However, a specific application would justify obtaining more complete results[4] than are presented here.

Samples of the criteria and program results (normalized by the removal of E_p) are given in Table I with Fig. 4 illustrating the predicted synchronous tap changer output envelope and spectra. These are the data a designer needs, although judgment is required to select between the results for application of the data to a particular situation.

For example, a designer may find it most economical to minimize only the lowest frequency distortion terms and use passive filtering for the higher terms. This suggests the use of criterion 2. Note, however, that even though criterion 2, with three taps, produced a higher energy carrier and lower energy sidebands than did criterion 3, with six taps, the output satisfying criterion 2 has more than twice the crest factor of the other case. Therefore, additional installed system capacity must be alloted to pass the higher peak currents and voltages.

A comparison of the spectra of Fig. 4 is significant. The two-tap case yields a decrease in the first sideband of 30 percent and increases the carrier by 13.4 percent. For the

TABLE I

OPTIMIZED TURNS RATIOS AND SWITCHING INTERVALS FOR DIFFERENT NUMBERS OF SYNCHRONOUS TAP CHANGER TAPS WITH THE OUTPUT WAVEFORM'S AVERAGE VALUE, CREST FACTOR, AND FIRST FIVE HARMONIC COEFFICIENTS OF FOURIER SERIES EXPANSION

Criterion	Number of Taps	Segment Number (Switching Interval, see Fig. 3)	Turns Ratios R	Average Value ($a_0/2$ term in Fourier Series Expansion)	Crest Factor	Harmonic $2n$	Fourier Series Coefficient a_n
Full wave rectified sine wave (for comparison)	1	—	1.0	0.6366	1.414	2	0.4250
						4	0.0848
						6	0.0313
						8	0.0202
						10	0.0129
1) Ratio of the total waveform's average value to its peak value approximates unity	2	1, 2	2.0	0.7219	1.306	2	0.2975
		3, 4, 5, 6	1.0			4	0.0595
						6	0.1043
						8	0.1192
						10	0.0758
2) Magnitudes of first five harmonic coefficients minimum	3	1	8.1	0.9224	2.163	2	0.0289
		2, 3	1.8			4	−0.0022
		4, 5, 6	1.0			6	0.0622
						8	−0.0145
						10	0.0056
3) Peak value of each switching interval is one (taking switching interval combination that gives highest average value)	6	1	7.66	0.8466	1.043	2	0.1497
		2	3.86			4	0.0464
		3	2.61			6	0.0720
		4, 5	1.64			8	0.0314
		6, 7	1.26			10	0.0426
		8, 9, 10, 11, 12	1.00				

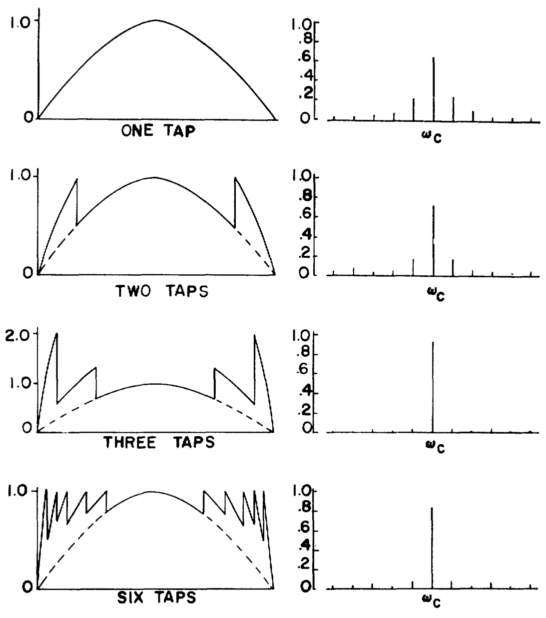


Fig. 4. Synchronous tap changer output waveforms and frequency spectra from data in Table I.

price of a third tap the first sideband is reduced by a factor of 93.2 percent and the carrier is increased by 45 percent. However, the basis of comparison is not completely honest since different optimization criteria are used. The six-tap case shows no improvement over the three-tap one because of the optimization criterion used.

Criterion 2 may be the most useful of the criteria considered. Additional results from this criterion are shown in Table II. Note that distortion reduction continues as the number of taps increase.

Another point of importance to the designer is the fact that relatively high peak currents may be required from the inverter by some turns ratios. Thus, an inverter capable of efficient operation over a large range of loads (impedances reflected into the primary of the synchronous tap changer transformer) will be required. Criterion 2, with its large crest factors, is an example where large changes in reflected impedance will occur. Work is underway on a new type of inverter circuit which is especially well suited for the synchronous tap changer application.

AN EXPERIMENTAL SYSTEM

A system has been built and evaluated that inverted the 60-Hz line frequency to 20 kHz. A series inverter[5] was used to supply a synchronous tap changer with two taps. Criterion 1 was chosen for the optimization. Figure 5 contains a diagram of the synchronous tap changer control circuitry.

The input power is inverted and applied to the synchronous tap changer. A synchronization signal is obtained by a full wave rectifying the incoming energy and producing a timing pulse each time the line waveform passes through

TABLE II
OUTPUT CHARACTERISTICS OF SYNCHRONOUS TAP CHANGERS WITH TWO AND FOUR TAPS OPTIMIZED TO CRITERION TWO

Number of Taps	Segment Number	Turns Ratios	Average Value	Crest Factor	Harmonic	Fourier Series Coefficient
		R	$a_0/2$		$2n$	a_n
2	1	3.7	0.6952	1.327	2	0.3152
	2, 3, 4, 5, 6				4	−0.0021
					6	−0.0179
					8	0.0033
					10	0.0317
4	1	8.2	0.9310	2.177	2	0.0162
	2	1.9			4	−0.0047
	3	1.8			6	0.0690
	4, 5, 6	1.0			8	−0.0046
					10	0.0006

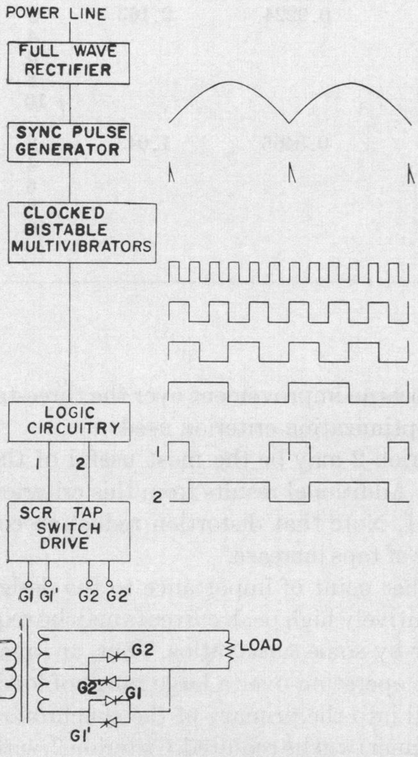
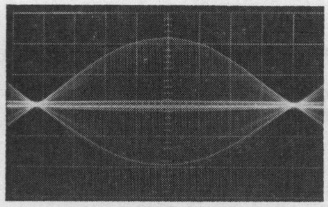
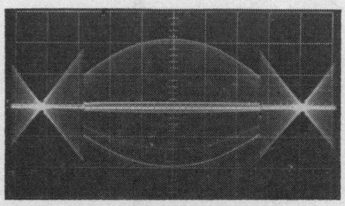


Fig. 5. Experimental synchronous tap changer system diagram.



$V_{av} = 6.27$ volts dc $V/cm = 5.0$ volts
$V_{120} = 2.5$ volts peak $t/cm = 1.0$ ms
$V_{240} = 0.5$ volts peak
Tap changer waveform for two taps.



$V_{av} = 5.70$ volts dc $V/cm = 5.0$ volts
$V_{120} = 3.5$ volts peak $t/cm = 1.0$ ms
$V_{240} = 0.62$ volts peak
Tap changer waveform for one tap.

Fig. 6. Output waveforms and data from system.

zero. (See Fig. 5.) The timing pulse is used to synchronize a bistable multivibrator which divides each half of the periodic output waveform into six equal segments. The outputs of additional synchronized multivibrators are used by the logic circuitry to uniquely identify the number of segments in each switching interval and properly order the sequence of changing taps.

Actual output waveforms for one and two taps are presented in Fig. 6 along with the average value of the waveforms and the peak values of the 120- and 240-Hz components which, in this case, are the first and second harmonic terms of the distortion envelope. These were measured after rectifying the output of the synchronous tap changer and filtering the high-frequency components which are harmonics of the carrier signal.

The actual and theoretical values compare as follows: for the ratio of the average value of the two-tap waveform to the average value of the single-tap waveform, the measured value is 1.12 while the computed value is 1.13; for the 120-Hz component, the ratio of the measured value is 0.71 while that of the computed value is 0.701; and for the 240-Hz component, the measured value is 0.81 while the computed value is 0.702. These results illustrate the increase in average value and decrease in immediate sideband voltage levels predicted by the theory. They also validate the physical circuit concepts involved.

Conclusion

A system has been presented that transforms low-frequency to relatively high-frequency energy. It minimizes distortion in an optimum manner by modifying the voltage envelope with a synchronous tap changer. This tap changer is a transformer whose turns ratio can be varied by switching its taps in synchronism with the incoming power signal. The transformer can produce an output waveform whose average value is higher and whose immediate sideband components are lower than those of the inverted waveform.

It is believed that the step-up cycloconverter system described here represents a useful method of obtaining high-frequency power from a low-frequency source.

Design data for synchronous tap changers are presented.

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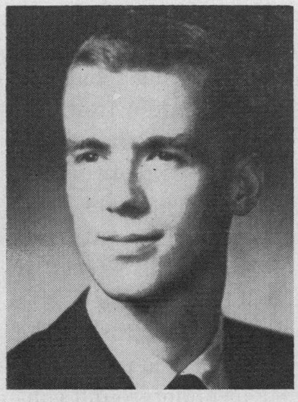

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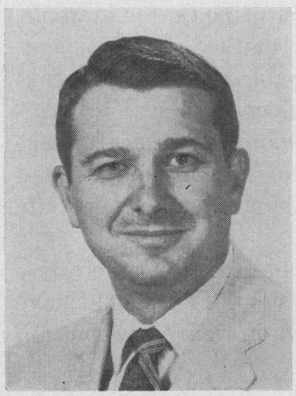

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