ANALOG AND HYBRID COMPUTER SIMULATION OF STATIC POWER CONVERSION SYSTEMS

T. A. Lipo
Department of Electrical and Computer Engineering
University of Wisconsin
Madison, Wisconsin

ABSTRACT

A historical discussion of differential analyzers as well as the significant developments in simulation techniques as applied to static power conversion and AC drives is presented. Simulation principles for modeling both force commutated and naturally commutated thyristor devices are discussed. Significant present-day applications of analog computation to the design of modern AC drives are discussed and illustrated with representative simulation traces.

INTRODUCTION

The digital computer is being extensively used in the analysis of static power conversion systems. There is an extensive and ever continuing effort to improve and expand the capabilities and applications of the digital computer. For many years the electronic differential analyzer (analog computer) has provided the analyst with an alternative method of analysis. The analog computer has been successfully utilized to study both steady state and transient behavior of a wide variety of circuits involving power electronic components. This type of computer offers the capability of parallel integration, providing an advantage in computational speed which it still maintains over the digital computer.

In this paper the evolution of the analog computer is discussed briefly with particular reference to its use in static power conversion. Next, example applications of analog computers to power conversion problems are given including square wave voltage and current source inverter drives, PWM voltage source drives, cycloconverter drives, and both machine and forced commutated synchronous motor drives. In each case representative recordings of computer studies are given.

HISTORICAL PERSPECTIVE

It was nearly 100 years ago that James Thomson presented his classic paper "On an integrating machine having a new kinematic principle" [1]. Professor Thomson conceived an integrating machine integration without the troublesome slippage problem which had plagued previous inventors. The importance of J. Thomson's machine was instantly recognized by his brother Lord Kelvin who proposed use of the integrator to solve nonlinear differential equations [2]. Although an iterative approach was originally proposed, Lord Kelvin was surprised to find that these equations could be solved implicitly in a single process by connecting the output of the last integrator back to the input of the first. Hence, Lord Kelvin discovered the basic principle behind what was later to be called simulation. However, his ideal languished for 50 years largely because of a lack of a precision variable-speed motor needed to dirve the numerous mechanical linkages.

The modern era of simulation had its beginnings largely through the efforts of Dr. Vannevar Bush who with R. D. Booth proposed a general approach to solving power system transients involving integration of the system differential equations rather than by use of circle diagrams or various other graphical and algebraic methods then in use [3]. Although the initial approach involved a finite increment method requiring hand computation, Dr. Bush recognized the important implications of Lord Kelvin's machine in providing an implicit solution. After continuous development and improvement for the next six years the device was, in 1931, christened the differential analyzer [4]. The differential analyzer of this era contained all the elements of a modern-day analog computer including summers, integrators, multipliers, and function generators. It is significant that almost immediately the differential analyzer was applied to the study of power system transients [5]. By 1945 the simulation of power systems including synchronous and induction machines, transformers, transmission lines, capacitors and the like were becoming routine.

Ragazini, Randall, and Russell are generally credited with providing the impetus which resulted in the development of electronic differential analyzers (analog computers). In 1947 they described use of a DC coupled amplifier to realize integration, summation, and differentiation and discuss its application in simulating a number of practical problems [6]. Within five years a number of companies were manufacturing analog computers. The era of reliable, precision, analog computation is generally considered to have begun with the appearance of the EAI 31R, 131R and 231R computers during the years 1954-59. The early 1960's saw the emergence of analog computing as an important tool in the analysis of solid state power conversion systems. This era began in 1959 when Lind and Schmitz described the first simulation of a unidirectional element (i.e. a diode) [7]. Gerecke and Badr, in 1962, were the first to treat the simulation of thyristors in a motor drive system [8]. In 1963 the first simulation of a rectifier bridge was reported [9]. An analog computer simulation of a cycloconverter was described by Amato in 1966 [10]. The development of the major types of power converters was essentially completed when analog computer simulations of a six step voltage inverter, a PWM voltage inverter and a switching regulator were reported in 1967 [11,12,13]. The first simulation of a more recent device, the current source inverter, first appeared in the literature in 1979 [14].

SIMULATION PRINCIPLES

In general, simulation of switching devices in power converter circuits can be segregated into two classes, forced commutation and natural commutation. In the forced commutation case the commutation energy is stored in capacitors which are found in auxiliary networks and can be considered as internal to the switching network. In this case, commutation typically takes place in such a short time that the switching device can be replaced with an ideal switch. Figure 1 shows an analog computer simulation diagram which has been successfully used to model a PWM voltage inverter. In general, the inverter model is made to switch whenever the output of the comparator changes state. The diamond shaped symbol denotes the signal which is fed to drive the contacts of a relay which produces switching of one of the inverter thyristors in the simulation. Commutation effects, however, have been accounted for by introducing a delay in the switching to prevent commutations from occurring at a rate greater than the ability of the thyristors to recover blocking ability. Such a "lockout" device is a normal feature of an inverter in order to prevent shoot-throughs or commutation failures in the inverter. It can be noted that the lockout is achieved in the simulation by a monostable pulser which is set in this case at 140 microseconds (real time).

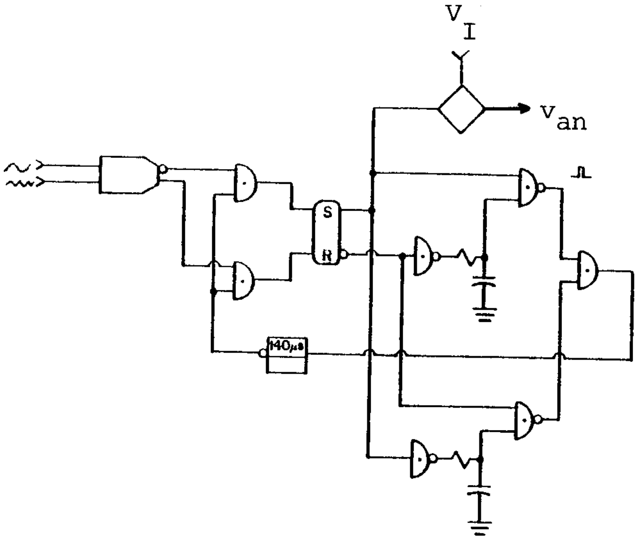

Fig. 1 Simulation of Force Commutated Thyristor

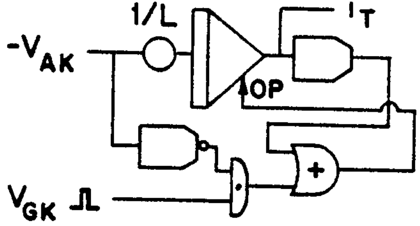

Fig. 2 Simulation of Naturally Commutated Thyristor

The basic building block for the natural commutated situation is shown in Figure 2. In this case, the thyristor is modeled as a device which has a small inductance in the positive direction and an infinite impedance in the reverse direction. The current flow in the thyristor is obtained by integrating the voltage across the thyristor. Triggering of the thyristor is obtained from a firing pulse or pulse train. The pulse is processed together with two logic signals using an AND and an OR gate. The first logic signal detects the polarity of the voltage across the thyristor. The second signal is used to determine whether current flow exists in the thyristor itself. This logic signal is used to determine the latching effect of the four layer thyristor device. Hence, the thyristor is defined to be in conduction when a firing pulse appears at the gate terminal and the voltage across the thyristor is in such a direction as to support conduction or when there is current flow in the thyristor.

TYPICAL APPLICATIONS

In this section application of analog computation in each of the major areas of AC static power conversion applied to motor drive are discussed. The first such system is a six step voltage inverter drive such as that shown in Fig. 3 [15]. In this case the voltage inverter is modeled as a set of ideal switches similar to that shown in Fig. 1. However the lockout effect was not modeled since the operating frequency was assumed sufficiently low that thyristor recovery times were not of concern. The six pulse thyristor bridge on the input side was modeled as naturally commutated devices by the method shown in Fig. 2. A typical computer trace illustrating behavior of this system is shown in Fig. 4. In particular, this trace shows a start up transient in which the entire system was energized at the same instant rather than utilizing a precharged DC link. Note the discontinuities in the DC link current which occur during the acceleration transient.

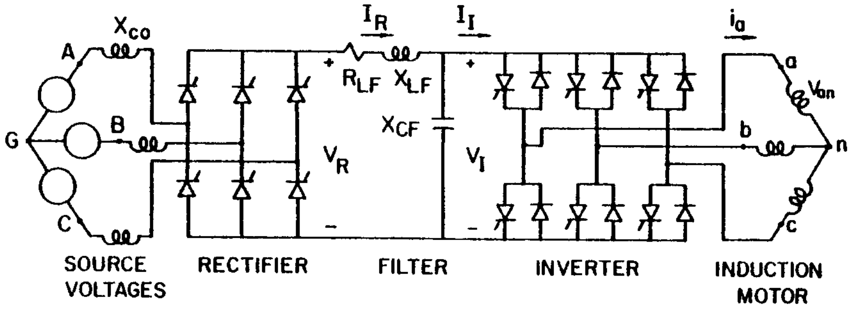

Fig. 3 Six Step Voltage Source Inverter Drive

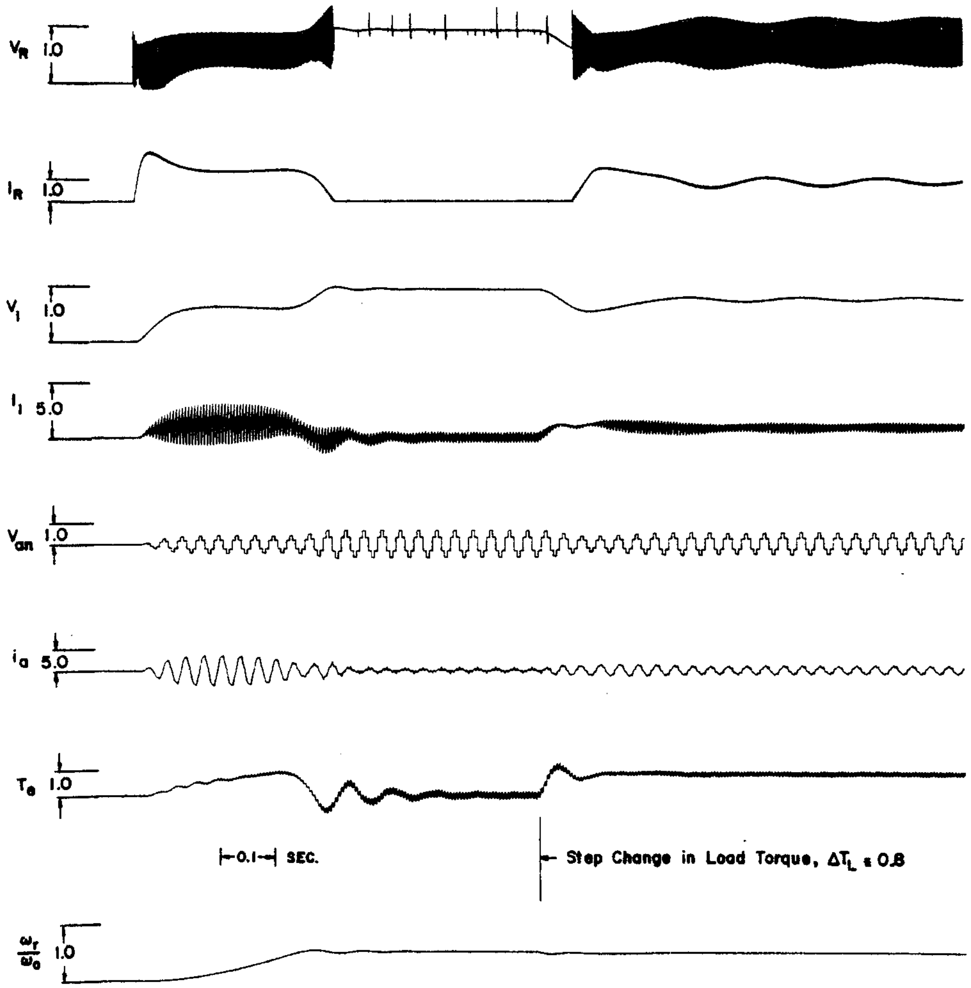

Fig. 4 Free Acceleration of Drive from Rest at 30 Hz when DC Link is Initially Unenergized

Another application which involves the modeling of thyristors as ideal switches is the PWM inverter shown in Fig. 5 [16]. In this case the modulation frequency was sufficiently high that recovery time was important so that inverter lockout was modeled as shown in Fig. 1. In the application studied, power was available from a DC source and converted to three phase AC in order to supply power to an induction motor. The frequency of the inverter output voltage was controlled so that the motor operated over the design range of slip frequency was adjusted as a function of frequency so as to maintain the proper value of flux within the machine. One feedback scheme which achieves these requirements is also given in Fig. 5. In order to control the amplitude and frequency of the inverter, a fixed amplitude triangle wave was compared to a three phase set of variable frequency, variable amplitude control voltages mechanized from a frequency command f^* and amplitude command signal v^*. Intersections of the triangle and sine wave produced logic transitions which, in turn, switched the six thyristors of the inverter.

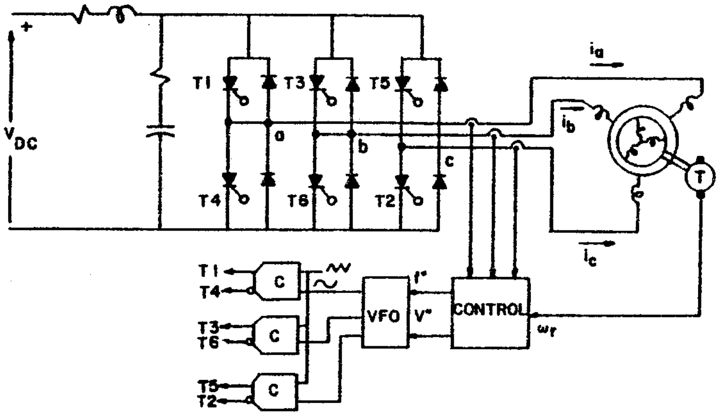

Fig. 5 PWM Voltage Source Inverter Induction Motor Drive

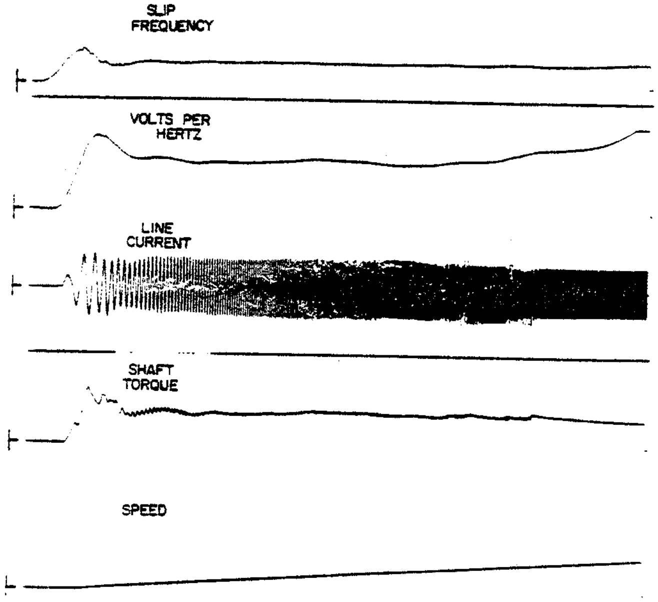

Fig. 6 Step Response from Rest Illustrating Effects of Pulse Dropout

A linear relationship between the amplitude of the control voltage and the fundamental component of the inverter output voltage can be maintained until the sine wave control voltage reaches the amplitude of the triangle wave. At this point, the lockout effect of Fig. 1 prevents the width of the narrowest pulse from changing. Linearity between the input command and actual output voltage is disturbed until the pulse drops out when a sine-triangle intersection disappears. This effect produces sudden discontinuities in the inverter output voltage which results in current transients which can be clearly seen in the trace of Fig. 6. Note also the corresponding changes in electromagnetic torque which also occurs at the instant of pulse dropout.

An example of a naturally commutated power converter is the ring connected cycloconverter shown in Fig. 7 [17]. In this application, three six pulse thyristor bridge circuits are connected in a delta configuration. The cycloconverter is supplied from three three-phase secondaries of a transformer. The three secondaries are phase shifted from each other by an angle α. The bridges are controlled so that only two groups conduct at any one time in order to prevent short circuit paths. Hence at any instant the cycloconverter operates in an open delta mode. Study of the idealized waveshapes sketched in Fig. 7 demonstrates that when trigger pulses are properly fed to the thyristors, the DC currents in the three bridges can be controlled to as to produce AC currents in the line. Figure 8 shows a typical recording from an analog computer study of the ring connected cycloconverter connected to a three phase induction motor in an AC drive application. In the recording shown, the cycloconverter output frequency has been set at 10 Hz and the motor is loaded to 0.4 pu. The input frequency to the cycloconverter is 60 Hz. It is apparent from the trace that a considerable amount of harmonics are present in the line currents. In particular, a second harmonic component occurs which results in a substantial third harmonic pulsating torque at the shaft of the induction motor. Note that in this case, open circuits in the line of the motor momentarily occur and the simulation must be arranged to properly represent an open circuit condition in any motor phase. Of particular interest in this study was the effect changes in the transformer phase shift angle α has in reducing the output harmonics. It is apparent that such a study is straightforward once the simulation has been mechanized but is extremely cumbersome when conducted using hardware.

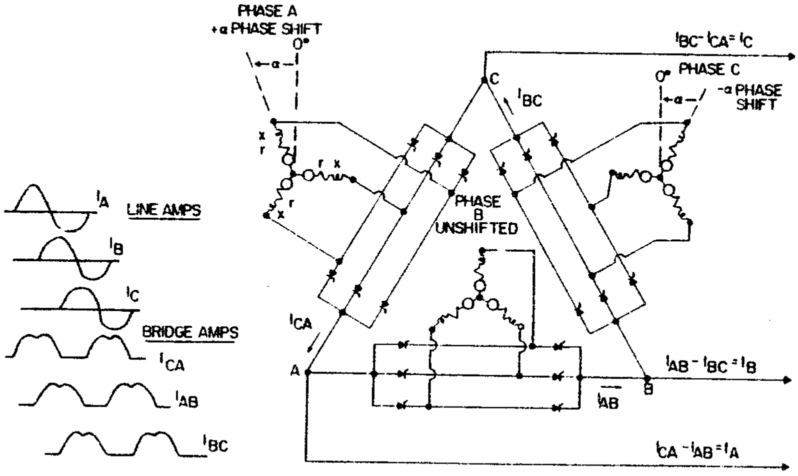

Fig. 7 Ring Connected Cycloconverter

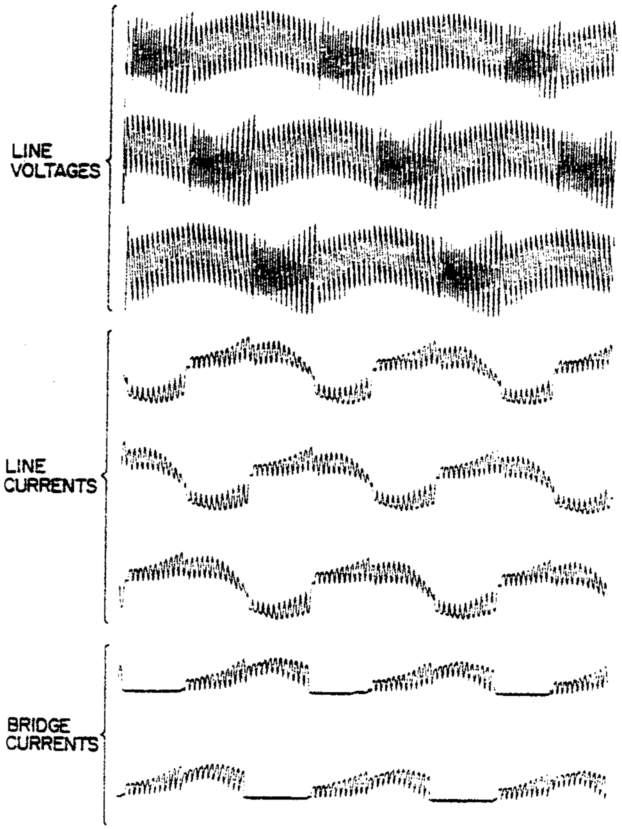

Fig. 8 Performance of Ring-type Cycloconverter at 10 Hz with Induction Motor Load

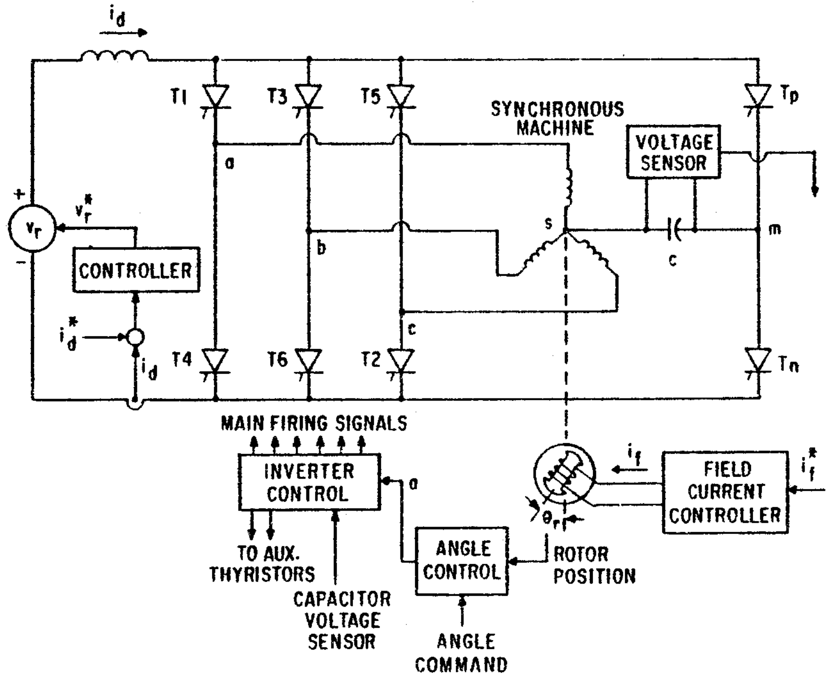

Fig. 9 Load Commutated Synchronous Motor Drive with Third Harmonic Force Commutation Starting Circuit

Another type of naturally commutated system that has achieved commercial success in very high horsepower sizes is the load commutated synchronous motor drive of Fig. 9 [18]. One substantial problem in the application of such a drive is in starting the system since the motor voltages are then not sufficiently large to commutate the machine-side converter bridge. Figure 9 shows an alternative forced commutation system connected to the neutral of the machine which can be used only during the starting phase of operation and then disabled when the motor voltages are sufficient to commutate the machine-side connected bridge. Figure 10 gives a computer trace which illustrates switching from forced to natural commutation and then allowing a decrease of rotor speed until the machine voltages are insufficient for commutation and commutation failure ensues. Note the large torque pulsations which may occur under such a condition.

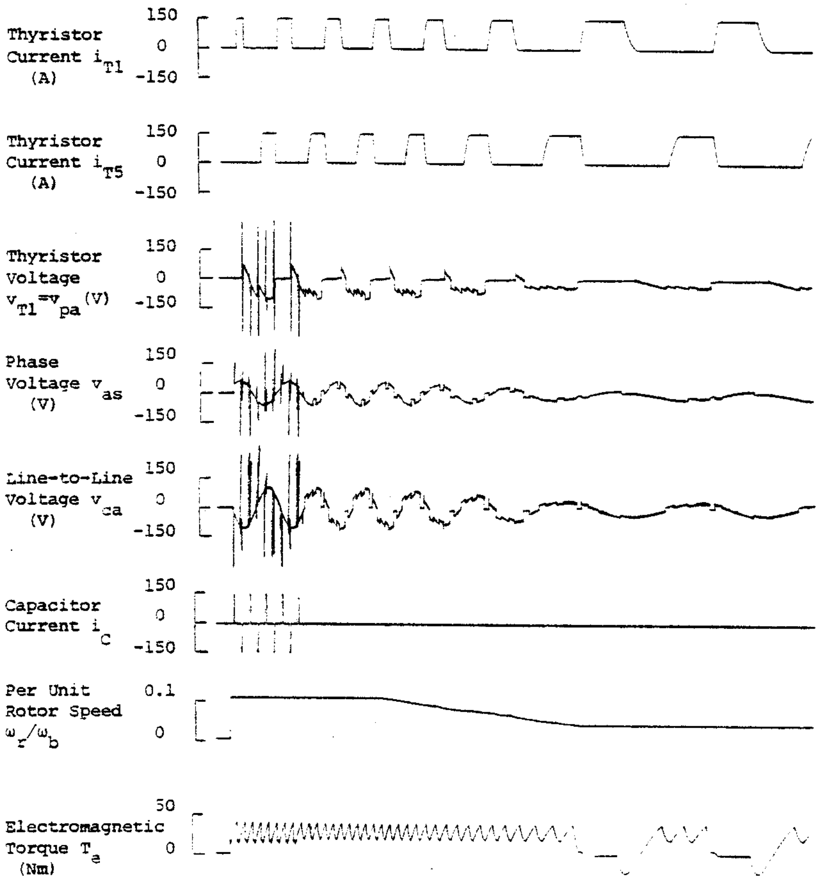

Fig. 10 Effect of Decreasing Rotor Speed on Load Commutation

The last major type of solid-state AC power converter is the current source inverter drive or CSI as shown in Fig. 11 [19]. In this case the inverter is again force commutated, this time by means of the delta connected capacitors in the top and bottom halves of the bridge. However, in this case commutation typically does not take place as rapidly as for the voltage source inverter since the voltage available for commutation must overcome the counter emf of the motor before transfer of current actually takes place. Hence, a more accurate representation of the commutation phenomena using the naturally commutated thyristor model of Fig. 1 is typically needed. A typical computer trace showing a number of key variables for the current source inverter system is shown in Fig. 12. Of particular interest in systems of this type is the magnitude of the voltage spikes which typically ride on top of the machine voltage waveform since this quantity fixes the size of the commutation capacitors and rating of the blocking diodes. Another important consideration in the application of such systems is the severity of the sixth harmonic pulsation which can be observed in the electromagnetic torque trace. Analog computer simulations of this type have proven themselves as a useful tool in accessing how such problems affect system performance.

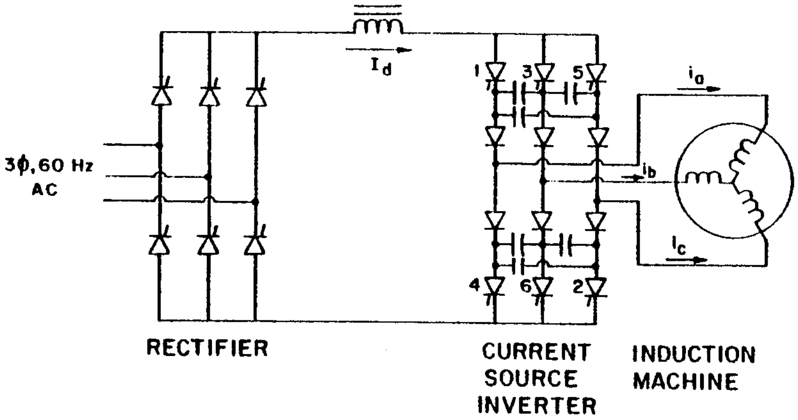

Fig. 11 Current Source Inverter Drive

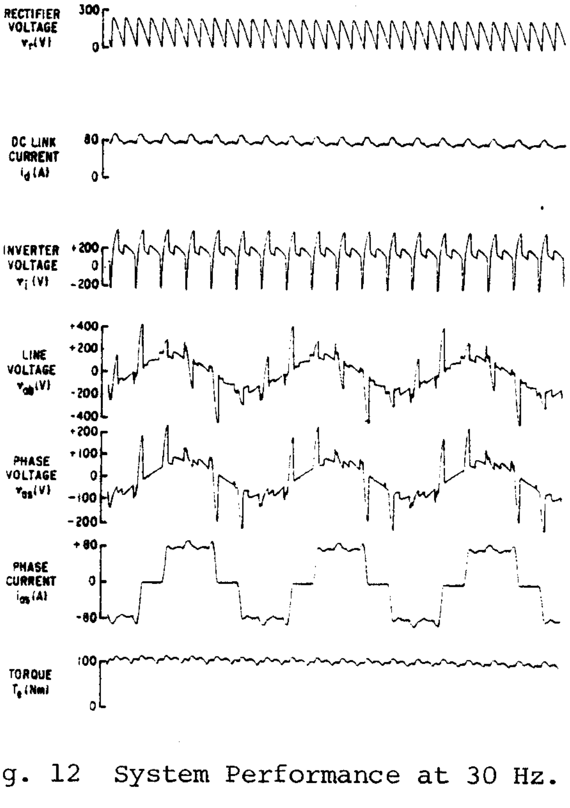

Fig. 12 System Performance at 30 Hz.

CONCLUSIONS

Simulation of static power converters by use of analog computers has matured to the point that simulation of fully detailed motor drive systems can almost be considered as routine. On the other hand, advances in the state of the art in digital computation continue at a breathtaking place. Although the convenience, computational speed, turn around time, and the ease of graphic output of an analog computer simulation is not often matched by a digital computer installation, it is apparent that this time will be shortly at hand. However, the conversion from the analog to the digital world should not prove difficult since modern simulation programs such as SUPERSCEPTRE and EMTP have been written to emulate an analog computer. Hence, the techniques used to implement an analog simulation are directly applicable on the digital computer. In effect, the digital computer is being programmed to simulate an analog computer. For those involved in modeling power converters the next decade is clearly looked upon with enthusiasm and excitement.

REFERENCES

1) J. Thomson, "On an integrating machine having a new kinematic principle," Proc. Royal Soc., Pt. A, vol. 24, pp. 262-265, 1876.
2) W. Thomson, (Lord Kelvin), "Mechanical integration of linear differential equations of the second order with variable coefficients," Prof. Royal Soc., Pt. A, vol. 24, pp. 269-271, 1876.
3) V. Bush and R. D. Booth, "Power system transients," AIEE Trans., vol.44, pp. 80-103, Feb. 1925.
4) V. Bush, "The differential analyzer - A new machine for solving differential equations," Franklin Inst. J., vol. 212, no. 4, pp. 447-488, Oct, 1931.
5) L. Teplow, "Stability of synchronous motors under variable-torque loads as determined by the recording product integraph," Gen. Elec. Rev., vol. 31, no. 7. pp. 356-365, July 1928.
6) J. R. Ragazzini, R. H. Randall, and F. A. Russell, "Analysis of problems in dynamics by electronic circuits," Proc. IRE, vol. 35, pp. 444-452, May 1947.
7) E. R. Lind and N. L. Schmitz, "Analysis of a-c servomotors operated from impedances," AIEE Trans. (Applic. Industr.), vol. 78, no. 46, pp. 476-481, 1959 (Jan. 1960 section).
8) E. Gerecke and H. Badr, "Induction machine with controlled valves in the primary circuit," Neue Technik (in German), pp. 125-134, 1962.
9) H. Winograd, L. E. Nickels, and R. A. Hedin, "Design of HVDC power supply for experimental d-c transmission test facility," 1963 IEEE Winter General Meeting, Paper CP 63-334.
10) C. J. Amato, "Analog computer simulation of an SCR as applied to a cycloconverter," IEEE Trans. Ind. Gen. Appl., vol. IGA-2, pp. 137-140, Mar./Apr., 1966.
11) M. Stiebler, "Analog computer simulation of thyristor-driven variable speed induction motors," Fifth International Congress of the Assoc. for Analog Computation (AICA), Lausanne, Switzerland, 28 Aug. - 2 Sept. 1967. Brussels, Belguim: Presses Academiques Europeennes, 1968, pp. 784-195.

12) E. Gerecke and T. Muller, "Analog simulation of thyristor controlled squirrel cage induction motors," Fifth International Congress of the Assoc. for Analog Computation (AICA), Lausanne, Switzerland, 28 Aug. - 2 Sept. 1967. Brussels: Presses Academiques Europeennes, pp. 709-718, 1968 (in German).

13) B. A. Wells, B. T. Brodie and I. M. H. Babaa, "Analog computer simulation of a DC-to-DC flyback converter," IEEE Trans. (Aerospace & Electronic Systems), vol. AES-3, no. 6, Supplement, pp. 399-409, Nov. 1967.

14) T. A. Lipo, "Simulation of a current source inverter drive," IEEE Trans. on Indus. Elect. and Control Inst., vol. IECI-26, no. 2, pp. 98-103, May 1979.

15) P.M. Espelage, J.A. Chiera and F.G. Turnbull,"A wide-range static inverter suitable fo AC induction motor drives," IEEE Trans. Ind. Gen. Appl., vol. IGA-5, pp 438-445, July/Aug. 1969.

16) A.B. Plunkett and D.L. Plette,"Inverter-induction motor drive for transit cars," IEEE Trans. Ind. Appl., vol IA-13, pp. 26-37, Jan./Feb. 1977.

17) B.L. Goss and H.W. Weiss,"Developments in adjustable speed AC drive systems," Proc. of American Power Conf., vol. 33, pp. 369-376, 1971

18) R.L. Steigerwald and T.A. Lipo,"Analysis of a novel forced-commutation starting scheme for a load-commutated synchronous motor drive," IEEE Trans. Ind. Appl., vol IA-15, No. 1, pp. 14-24, Jan./Feb. 1979

19) L.H. Walker and P.M. Espelage,"A high-performance controlled-current inverter drive," IEEE Trans. Ind. Appl., vol. IA-16, pp. 193-202, Mar./Apr. 1980.