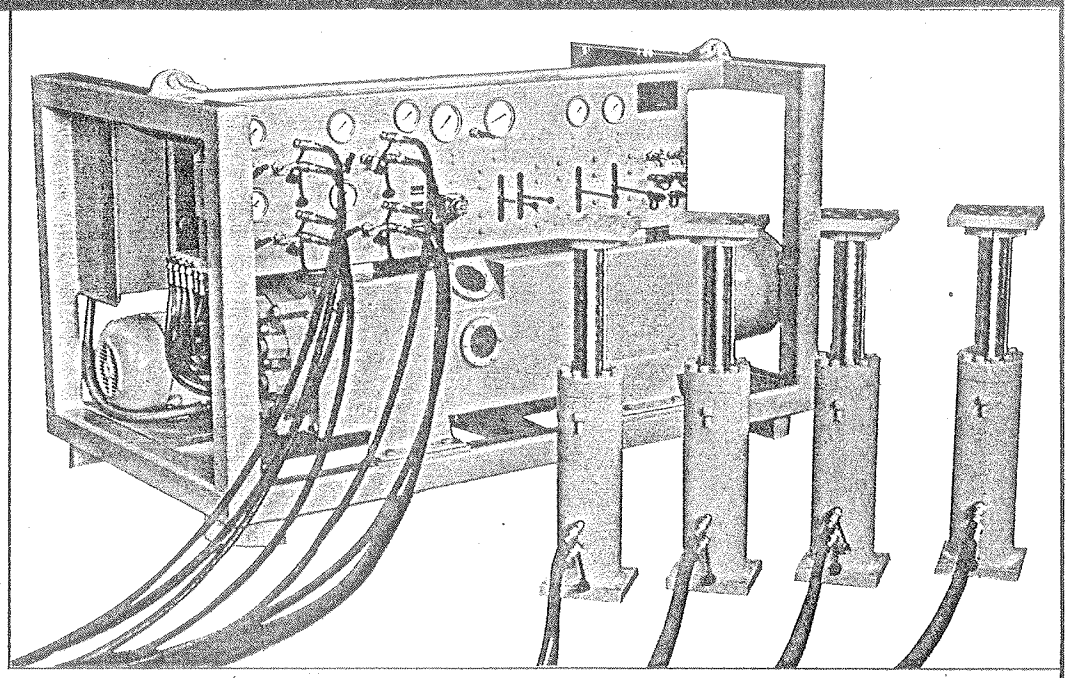
VPD SHEET PROTECTOR PS-3

OPERATING AND MAINTENANCE INSTRUCTIONS

MODERN HYDRAULICS, INC.
WEST CHICAGO, ILLINOIS 60185

UNIFIED HYDRAULIC CONTROL SYSTEMS, HYDRAULIC JACKS

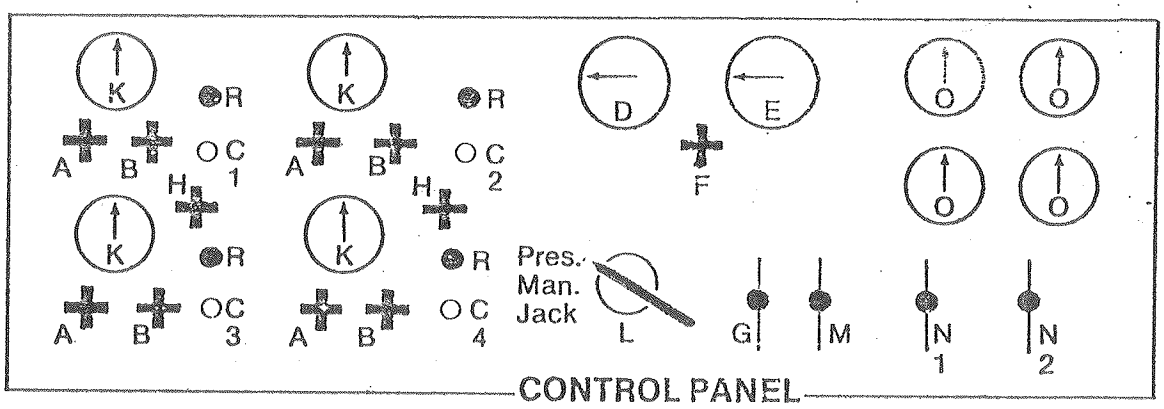


PARTS & SERVICE

VPD SHEET PROTECTOR PS-3

MODERN HYDRAULICS, INC.

OPERATING INSTRUCTIONS - MODEL 12-4-12-50DA
UNIFIED HYDRAULIC JACKING MACHINE



A. UNIFIED VALVES
B. SHUT OFF VALVES (UNIFIED JACKS)
C. QUICK COUPLINGS (UNIFIED JACKS)
D. PRESSURE GAUGE
E. UNIFIED GAUGE
F. MAIN CYLINDER VALVE
G. MAIN CONTROL LEVER
H. SHUT OFF VALVES
K. JACK PRESSURE GAUGE
L. JACKING AND PRESSURIZING VALVE
M. MANUAL CONTROL LEVER
N. CONTROL LEVERS (PUSH JACKS)
O. PUSH JACK GAUGES
R. QUICK COUPLINGS (RETURN UNIFIED JACKS)

TO JACK LOAD

1. CONNECT HOSES VIA QUICK COUPLINGS TO JACKS C COUPLINGS TO BOTTOM OF JACKS R COUPLINGS TO TOP OF JACKS.
2. START MOTOR.
3. MOVE ROTARY CONTROL VALVE L TO PRESSURIZE.
4. OPEN ALL SHUT OFF VALVES B.
5. OPEN ALL UNIFIED VALVES A.
6. OPEN MAIN CYLINDER VALVE F.
7. OPEN ALL JUMPER VALVES H WHEN USING 4 JACKS
   LEAVE VALVES H CLOSED WHEN USING 8 JACKS.
8. RAISE CONTROL LEVER G TO PRESSURIZE JACKS.
9. CLOSE ALL UNIFIED VALVES A.
10. MOVE ROTARY CONTROL VALVE L TO JACKING POSITION.
11. LOWER CONTROL LEVER G TO RAISE LOAD AND RAISE CONTROL LEVER G TO LOWER LOAD.
12. OPEN UNIFIED VALVES A AND RAISE CONTROL LEVER G TO FULLY RETRACT JACKS.

NOTE: To raise or lower individual jack during unified condition.

1. Move control valve L to man. position.
2. Open unified valve A of jack to be raised or lowered.
3. Move control lever M down to raise or up to lower individual jack.
4. Close unified valve of jack being raised or lowered. Return control valve to jack position.

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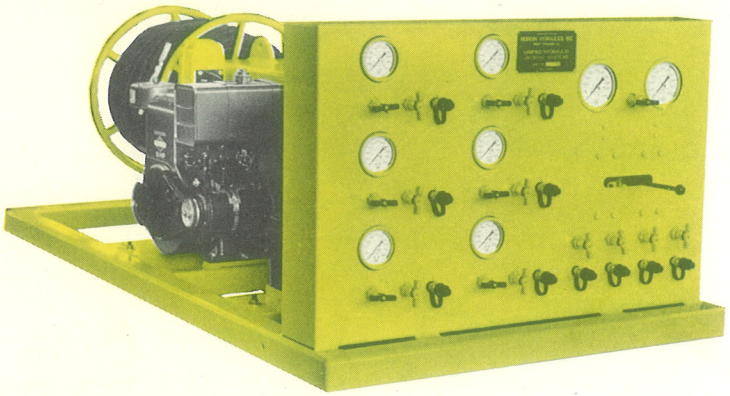


6-JACK UNIFIED SYSTEM
Model 1000-6

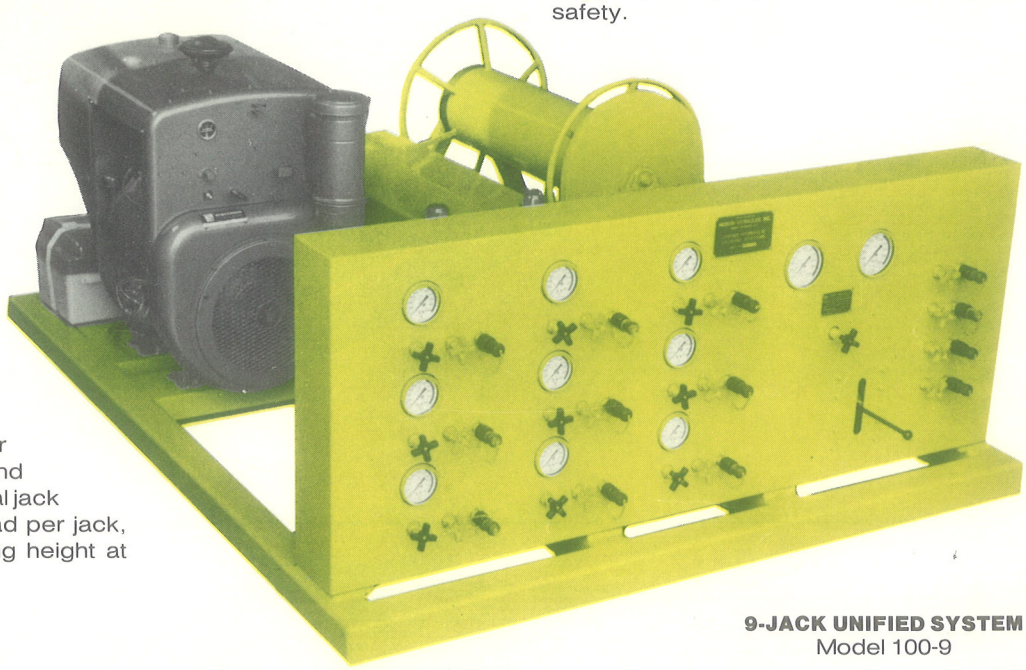
HYDRAULIC JACK CONTROL SYSTEMS

Modern Hydraulics, Inc. unified hydraulic jacking systems provide centralized control for precision multiple jack raising and lowering operations where jacks must move in unison regardless of load variations between the jacks.

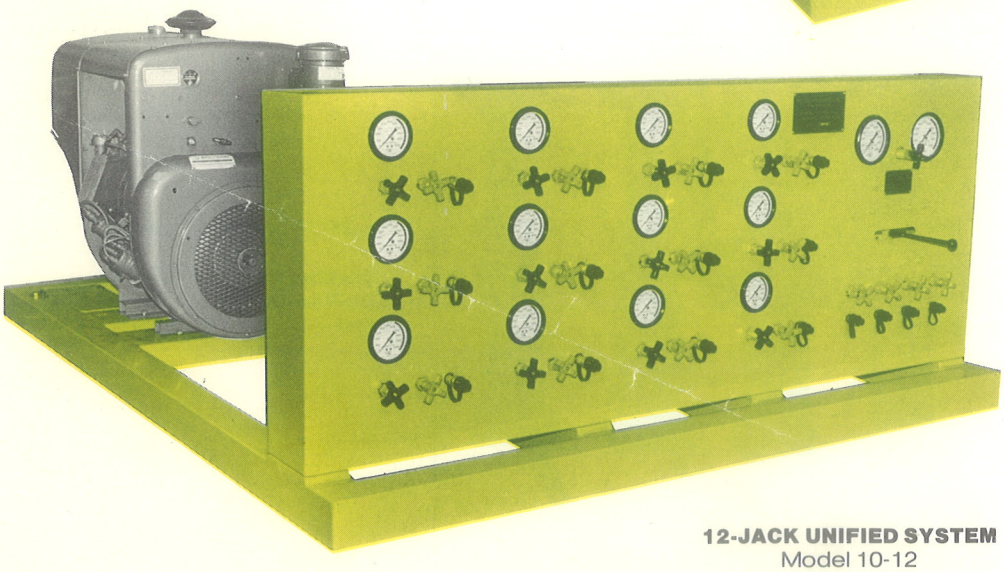
The systems are operated by one man from an independent control panel well removed from the job so that the operator has maximum overall visual control of the jacking operation and complete safety.

The automatic controls assure that all jacks move at the same rate of travel; yet, providing individual adjustment of single jacks or groups of jacks independently of the overall system.

The jacks are first pressurized and extended independently to remove any settlement and to compress the oil. The jacks are then locked together by the unifying system and will raise and lower in unison regardless of individual jack loading. Unit registers continuous load per jack, total combined jack load and jacking height at all times.



9-JACK UNIFIED SYSTEM
Model 100-9

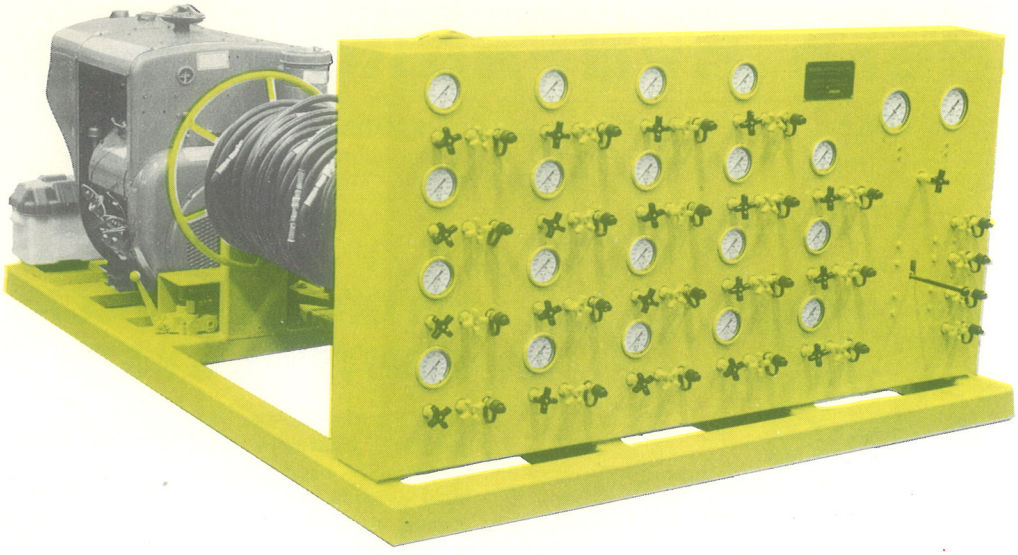


12-JACK UNIFIED SYSTEM
Model 10-12

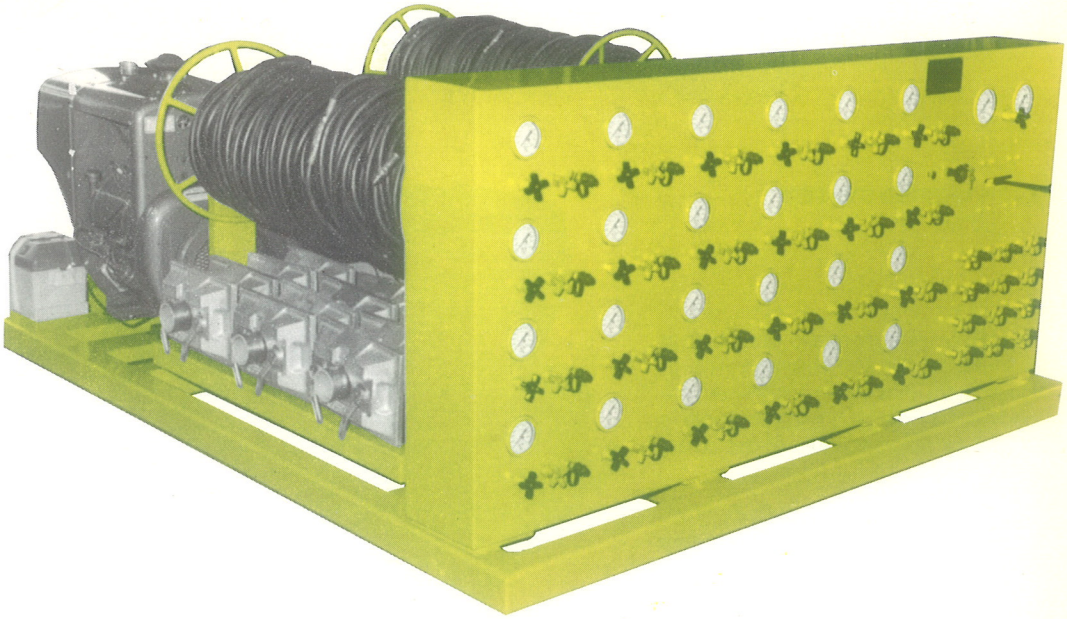
Each unified hydraulic jack is on a separate hyrdraulic circuit and failure in one jack will not cause pressure loss in the other jacks. A variable master control valve regulates the speed of jack travel, and release of this valve causes the load to be locked in position regardless of jack height.

Jacking machines are provided with gasoline engines. Diesel engines or electric motor drives to suit customer's applications. Jacks may be single or double acting. All units have hose storage reels, either manual or hydraulically powered.

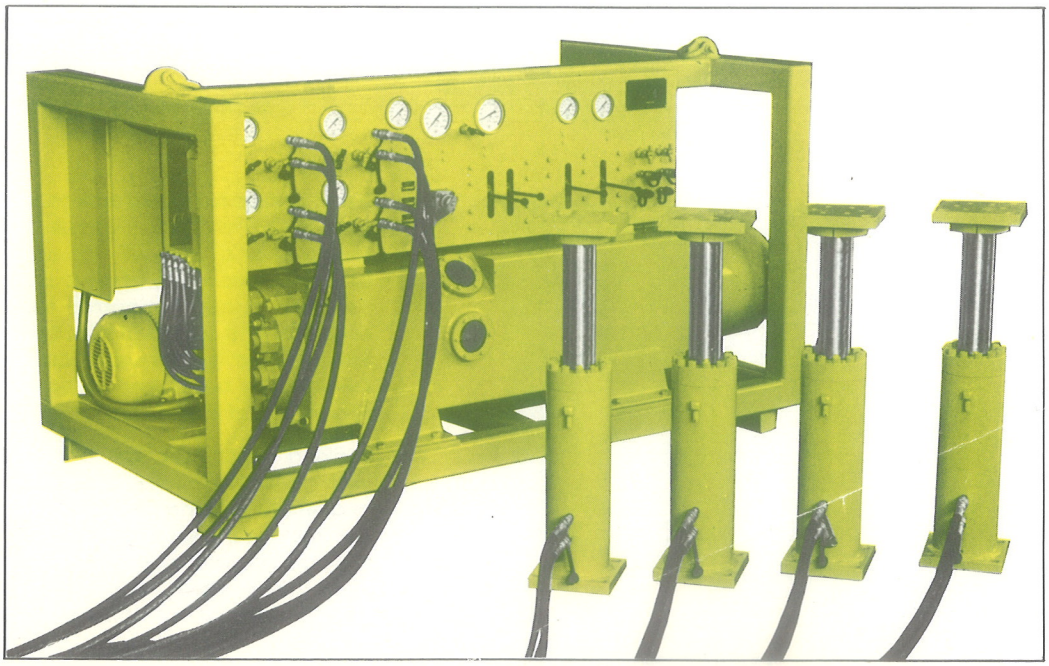
HYDRAULIC JACKS AND HYDRAULIC JACK CONTROL SYSTEMS



19-JACK UNIFIED SYSTEM
Model 10-19



24-JACK UNIFIED SYSTEM
Model 10-24



4-JACK UNIFIED SYSTEM
for
Jacking Legs and Frames
50-Ton or 100-Ton Jacks
Model 4-12-50 Model 4-6-100

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SUBJECT: HYDRAULIC JACKING SYSTEM FOR BØ EQUIPMENT MOVEMENT

NAME: J. Rauch/J. Grimson

DATE: 11/19/82 | REVISION DATE:

HYDRAULIC JACKING SYSTEM SPECIFICATIONS

THESE SPECIFICATIONS COVER A HYDRAULIC SYSTEM COMPLETE WITH ALL NECESSARY EQUIPMENT AND CONTROLS TO HOLD MAXIMUM OPERATING PRESSURE (SIMULTANEOUS) AND OPERATE (NOT SIMULTANEOUS) TWO SEPARATE FUNCTIONS.

MAXIMUM FUNCTIONS REQUIREMENTS:

(A) TO CAUSE EIGHT 500 TON CAPACITY JACKS TO RAISE OR LOWER AT THE SAME SPEED REGARDLESS OF INDIVIDUAL JACK LOADING. JACK TRAVEL AT CAPACITY TO BE 1/2" PER MINUTE. JACKS TO HAVE 13" DIAMETER BORE, 6" STROKE, AND MAXIMUM OPERATING PRESSURE OF 7,500 P.S.I.

(B) TO CAUSE TWO-124 TON CAPACITY PUSH-PULL JACKS TO EXTEND AND RETRACT AT THE SAME SPEED REGARDLESS OF INDIVIDUAL JACK LOADING. JACK TRAVEL AT CAPACITY TO BE 12" PER MINUTE. JACKS TO HAVE 6-1/2" DIAMETER BORE, 36" STROKE, AND MAXIMUM OPERATING PRESSURE OF 7,500 P.S.I.

MINIMUM FUNCTION REQUIREMENTS:

(AA) TO CAUSE FOUR JACKS TO RAISE OR LOWER AT THE SAME SPEED REGARDLESS OF INDIVIDUAL JACK LOADING. JACK TRAVEL CAPACITY TO BE VARIABLE TO OPERATOR DISCRETION, BUT NOT EXCEED OIL FLOW REQUIREMENT IN MAXIMUM FUNCTION "A". JACKS TO HAVE 6-1/4" DIAMETER BORE, 5/8" STROKE, AND MAXIMUM OPERATING PRESSURE OF 7,500 P.S.I.

(BB) TO CAUSE ONE PUSH-PULL JACK (SAME AS MAXIMUM FUNCTION "B") TO EXTEND AND RETRACT AT A JACKING SPEED VARIABLE OF OPERATOR'S DISCRETION, BUT NOT TO EXCEED OIL FLOW REQUIREMENT OF MAXIMUM FUNCTION "B".

EQUIPMENT TO MEET THE FOLLOWING SPECIFICATIONS:

1. HYDRAULIC CONTROL MECHANISM CAUSES EIGHT 500 TON HYDRAULIC JACKS TO RAISE AND LOWER AT THE SAME RATE REGARDLESS OF INDIVIDUAL JACK LOADING.

2. JACKS TO RAISE AND LOWER AT THE SAME RATE REGARDLESS OF INDIVIDUAL LOAD AND PRESSURE TO AN ACCURACY OF ± 1/32" BETWEEN JACKS. VARIATION IN JACK LOAD MAY BE 2 to 1. JACKING SPEED TO BE VARIABLE TO MAXIMUM OF 1/2" PER MINUTE.

3. EACH UNIFIED JACK IS ON A TOTALLY SEPARATE CIRCUIT WITH EACH CIRCUIT OPERATING AT ITS OWN INDIVIDUAL PRESSURE REQUIREMENT TO RAISE THE LOAD. FAILURE IN ONE JACK WILL NOT CAUSE PRESSURE LOSS TO ANY OF THE OTHER JACKS (UNLESS MAXIMUM PRESSURE IS EXCEEDED).

4. JACKS TO RAISE AND LOWER AT THE SAME RATE UNDER THE CONTROL OF ONE MAN ONLY WITH THIS MAN REQUIRED TO MOVE ONE CONTROL LEVER ONLY. (VERTICAL MOVEMENT PREFERRED.)

5. CONTROL OF JACK SPEED FOR RAISING AND LOWERING TO BE ACHIEVED BY THE AMOUNT THE CONTROL LEVER IS MOVED EITHER SIDE OF A CENTER POSITION. RELEASE OF THIS LEVER TO CAUSE THE JACKING OPERATION TO AUTOMATICALLY GO TO A HOLD CYCLE AND JACKS WILL REMAIN IN LOCKED POSITION WITHOUT ANY DRIFT DOWN.

6. FAILURE OF THE HYDRAULIC PUMP DRIVE WILL NOT EFFECT THE PRESSURE IN THE HYDRAULIC CIRCUITS AND THE LOAD WILL HOLD IN PLACE OR MAY BE LOWERED AT THE OPERATORS DISCRETION.

HYDRAULIC JACKING SYSTEM SPECIFICATIONS (Continued)

7. SYSTEM TO PROVIDE COMPENSATION FOR OIL COMPRESSIBILITY AND HOSE LINE EXPANSION TO ASSURE THE EQUAL JACK TRAVEL.

8. INDIVIDUAL JACKS MAY BE ADJUSTED UP OR DOWN INDEPENDENTLY AT ANY TIME DURING A RAISING OR LOWERING OPERATION AND THEN RETURNED TO THE UNIFIED CIRCUIT AND CONTINUE TO RAISE OR LOWER WHILE MAINTAINING THE ADJUSTMENT AND WITH THE CONTINUING ACCURACY OF ± 1/32".

9. CONTROL PANEL TO REGISTER CONTINUOUS LOAD PER JACK, TOTAL LOAD AND JACKING HEIGHT AT ALL TIMES.

10. SYSTEM WILL MAINTAIN LOAD IN A RAISED POSITION FOR A MINIMUM OF 24 HOURS WITHOUT DRIFT OR LOWERING.

11. CIRCUIT ALSO OPERATES TWO PUSH-PULL JACKS TO EXTEND AND RETRACT AT THE SAME SPEED OF 12" PER MINUTE.

12. SYSTEM NOT EFFECTED IN ACCURACY BY NORMAL TEMPERATURE CHANGES. (30°F) 70° ± 30°

13. SYSTEM OPERATES WITHOUT PULSATION TO THE JACKS.

14. UNIT CONTROL PANEL INDICATES WHEN ANY JACK IS OVERLOADED AND WHEN SYSTEM IS OVERLOADED. FAIL SAFE CIRCUIT PREVENTS OPERATION OF SYSTEM BEYOND RATED CAPACITY AND PREVENTS SYSTEM DAMAGE.

15. ELECTRIC MOTOR DRIVING HYDRAULIC PUMP TO BE 460 VOLT A.C., 60 HERTZ, THREE PHASE, AND POWER TO BE SUPPLIED THRU A 125 FT. CORD REEL.

16. ENTIRE UNIT TO BE MOUNTED ON A SUITABLE STEEL FRAME WITH CASTERS AND WITH A MAXIMUM WIDTH OF 48" AND HEIGHT OF 72". 12'

17. 3/8" N.P.T. HYDRAULIC QUICK DISCONNECT COUPLINGS ON PANEL, HOSES, AND JACKS TO HAVE MINIMUM 40,000 P.S.I. BURST IN CONNECTED OR DISCONNECTED POSITION. COUPLINGS TO HAVE LOCKING FEATURE SO THAT THEY CANNOT BE DISCONNECTED ACCIDENTLY. 600 FT. OF 3/8" I.D. HOSES TO BE SUPPLIED IN 25 FT. ATTACHABLE LENGTH.

18. ALL SEALS MATERIAL TO BE BUNA-N.

19. CYCLING SYSTEM IS PERMITTED, BUT MUST BE CAPABLE OF AT LEAST 1/2" STROKE FOR EACH 500 TON JACK OR 12" STROKE FOR EACH 124 TON JACK PER CYCLE.

20. CERTIFICATION THAT FERMILAB SPECIFICATION PARAMETERS WILL BE MET OR EXCEEDED WITH RETURN OF QUOTATION PACKAGE, INCLUDING A DRAWING SHOWING DIMENSIONS OF SYSTEM.

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE

SUBJECT

NAME

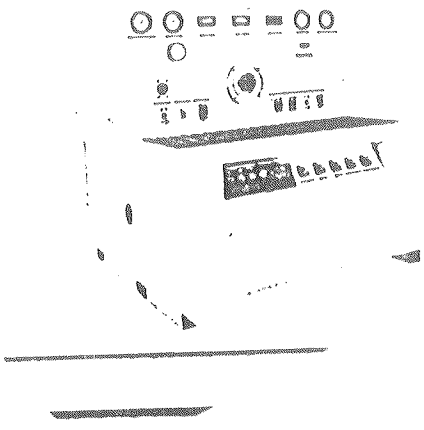
DATE

REVISION DATE

OPTIONAL SOURCES:

MIDWEST HYDRAULIC SERVICE CO.
P.O. BOX 477
375 GUNDERSEN DRIVE
CAROL STREAM, IL 60187
(312) 668-6025
GARY ALEXANDER

THORN EMI HYDRAULICS
P.O. BOX 38213
1250 E. ROUTE 36
URBANA, OHIO 43078
(513) 652-1471
RICK WAGAMAN



Dennis Beck
or
Bill Kresse
Norman Equipment Co.
Power Unit Division
16150 W. Rogers Drive
New Berlin, WI 53151
or call them at
414/784-1700

modern hydraulics, inc.

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AUGUST 11, 1982

MR. JOHN GRIMSON
FERMI NATIONAL ACCELERATOR LABORATORY
P.O. BOX 500
BATAVIA, ILLINOIS 60150

ATTENTION: JOHN GRIMSON

DEAR MR. GRIMSON:

WE ARE PLEASED TO OFFER OUR RECOMMENDATIONS FOR SPECIFICATIONS COVERING THE 500 TON CAPACITY JACKS REQUIRED FOR YOUR LIFTING OPERATIONS. YOU WILL NEED TO ADD THE MOUNTING LUGS AND ANY HOLES REQUIRED FOR INSTALLATION PURPOSES.

SPECIFICATIONS FOR 500 TON CAPACITY JACKS

NOTE: THESE JACKS ARE TO BE USED FOR PRECISION JACKING SEQUENCES WHERE THE JACKS WILL BE CONTROLLED BY A UNIFIED HYDRAULIC JACKING SYSTEM. AFTER INITIAL PRESSUREIZATION OF THE JACKING CIRCUIT EACH JACK WILL BE SUPPLIED WITH AN EQUAL VOLUME OF OIL TO ASSURE EQUAL STROKE REGARDLESS OF INDIVIDUAL JACK LOADING. JACK WORKING AREAS MUST BE IDENTICAL AND ZERO LEAKAGE MUST BE MAINTAINED DURING THE JACKING PERIOD.

(A) WORKING PRESSURE AT 500 TON CAPACITY -7,600 P.S.I. MAXIMUM.

(B) PROOF PRESSURE 10,000 P.S.I.

(C) RETRACT PRESSURE 3000 P.S.I.

(D) ALL ASPECTS OF JACK DESIGN TO HAVE MIN. 2:1 SAFETY FACTOR.

(E) JACK TO ACCEPT A 10% DIRECT SIDE LOAD WITH PISTON AT FULL EXTENSION.

(F) JACK TO HOLD LOAD FOR MINIMUM OF 8 HRS. WITHOUT LEAKING OFF.

(G) JACK WILL WITHSTAND MAXIMUM PRESSURE WITH PISTON FULLY EXTENDED AGAINST TOP NUT.

(H) ALL JACK CYLINDER I.D. DIAMETERS TO BE TO DIMENSION -.000 +.004.

(I) PISTONS TO BE MACHINED FROM SOLID 4140/4142 ALLOY STEEL HEAT TREATED, AND HARD CHROME PLATED.

(J) ALL STATIC O RING SEALS TO HAVE BACK UP WASHERS.

(K) WEAR SURFACES ON PISTON AND HEAD GLAND TO BE MINIMUM 1/16" BRONZE.

(L) HYDRAULIC CONNECTIONS TO CYLINDERS TO BE 3/8" N.P.T.

(M) CLEARANCE BETWEEN PISTON AND HEAD GLAND, PISTON FOLLOWER AND CYLINDER TO BE MAXIMUM .007.

(N) MAXIMUM ALLOWABLE CLOSED HEIGHT ON 3" STROKE JACKS 17½".

(O) RELIEF VALVE TO BE PROVIDED IN RETRACT PRESSURE AREA.

(P) PISTON ROD TO HAVE WIPER.

(Q) NO QUICK COUPLINGS REQUIRED.

AS EXPLAINED DURING OUR RECENT MEETING WE WILL LIMIT JACK SIDE LOADING BY LIMITING THE HYDRAULIC PRESSURE OF THE PUSH PULL CYLINDERS.

YOURS VERY SINCERELY

Robin Renshaw

ROBIN RENSHAW
PRESIDENT

RR:MLH
COPIES: JOHN RAUCH
DEAN LEE

Hydraulics

reliability factors, a systematic matching process yields complete descriptions of specific components.

Design building blocks

Again, a functional building block fulfills an abstract function, but we don't care or need to know how the function is accomplished. For instance, the *power distribution* module of Figure 4 is a black box representing a general function to distribute input power to power output destinations. The general functions are explicitly decomposed into several subfunctions in the decomposition hierarchies.

In fact, Figure 4 actually shows a function decomposition hierarchy of the *power distribution* function module. Power may be distributed either by switching or by multiplexing. Power switching uses a black box to physically channel the power flow routes and activates the black box to switch the actual power flow routes according to the desired schedule.

Activation control requires sensing the triggering activities, scheduling the sequence of activations, and activating each switch. *Routing* involves constructing the multiple branches based on output actuation requirements. Thus, we describe various functional modules and subfunctions in the function decomposition hierarchies with *AND*, *OR*, or *D* relationships. The function decomposition hierarchies presented here can be generalized for applications in other power-flow design domains.

Structural blocks can be identified that correspond to each of these modules. A *channeling element* is a black box that partitions or merges power flow in a hydraulic system. For instance, a general component, such as a 3-way valve, is an implementation of an abstract channeling element module. It can be a 3-way electromechanical directional control (DC) valve when combined with a solenoid operator, or it can be a sequence valve when coupled with a pressure

Continued on page 71

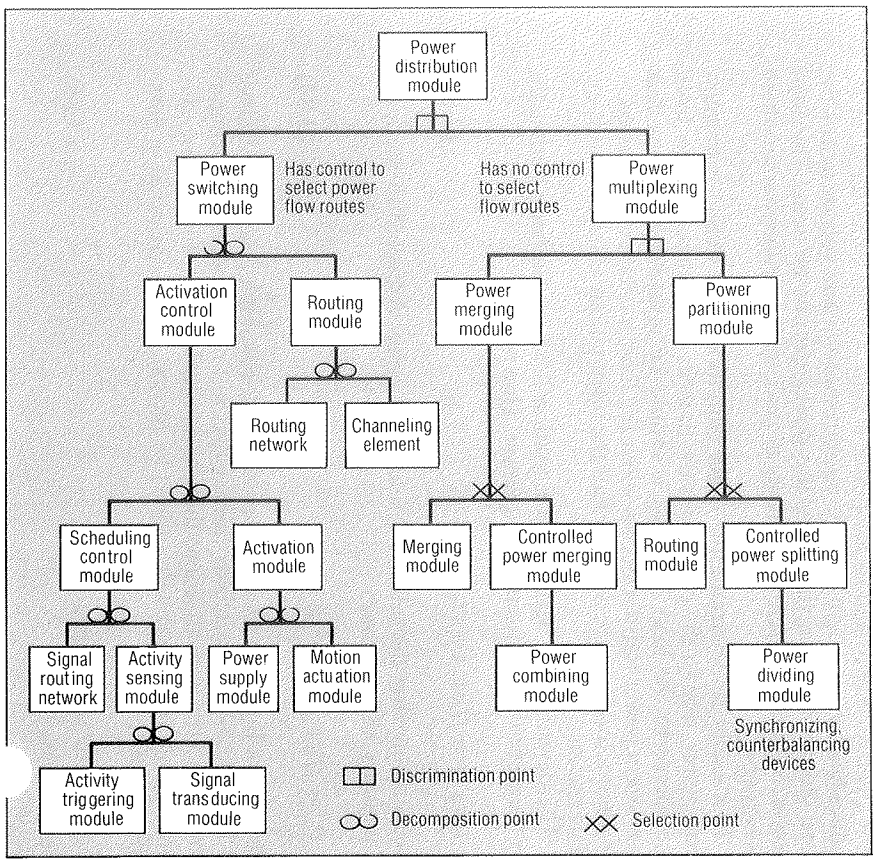


Fig. 4. The power distribution function abstraction/decomposition hierarchy

Basic Electronics for Hydraulic Motion Control

by Jack L. Johnson, PE

Chapter 1 — Essential ideas about calculus

Chapter 2 — Electrical meters and measurement

Chapter 3 — Basic electrical circuit analysis

Chapter 4 — Capacitance and inductance

Chapter 5 — Alternating current circuit analysis

Chapter 6 — Diodes, rectifiers, and power supplies

Chapter 7 — Transistors, operational amplifiers, and other signal processing

Chapter 8 — Sensing for measurement and control

Chapter 9 — Electrohydraulic devices

Chapter 10 — Examples of electrohydraulic control systems

Another part of the new book, BASIC ELECTRONICS FOR HYDRAULIC MOTION CONTROL continues on the next page. HYDRAULICS & PNEUMATICS will publish the serialization of this work every other month until its completion, estimated for the latter part of 1991. The bound text will be available after that time.

The analogous situation for a hydraulic system would be to deadhead a positive-displacement pump. This rarely is done because when deadheaded, most pumps can develop destructive pressures. Nonetheless, we will deal with deadhead conditions analytically even though **a real test may be impractical, dangerous, or destructive.**

Note the dashed curve in Figure 3.34 labeled *Load power*, P_L. An intuitive sense can be gained by considering the nature of power. Recall that power is the product of current times voltage. First consider the open circuit condition, ie $R_L = \infty$, wherein the voltage is at its highest value, but the current is zero. Clearly, the power delivered to the load is zero.

At the other extreme, the short circuit condition, $R_L = 0$, current is at a maximum but the voltage across the load is zero. Again, the volt-ampere product is zero and so the power is zero. On the other hand, at R_L values between zero and infinity, current through and voltage across the load cannot be zero; therefore, the power cannot be zero. The load power, beginning at zero and ending at zero, must maximize somewhere in between.

It is useful to determine the exact conditions that define maximum load power, that is, the conditions for transfer of maximum power from the source to the load. By now, it should be intuitively obvious that maximum power transfer occurs when the load resistance is adjusted to produce a load voltage which is half the open-circuit voltage. This is exactly the case.

The development begins with Equation 3.63, multiplying both sides by the current to form a power equation. That is

$$(I)(V_L) = (I)(V_s) - (I)^2(R_s). \tag{3.83}$$

Recognizing that the left hand side is the power delivered to the load, Equation (3.83) becomes

$$P_L = (I)(V_s) - (I)^2(R_s). \tag{3.84}$$

The plot of Equation (3.84) is a parabola; for example, the dashed curve of Figure 3.34. The calculus teaches that to find the point of maximum power, find the derivative and then set it equal to zero. In this case, differentiating load power with respect to current derives the point of maximum load power:

$$dP_L/dI = V_s - 2(I)(R_s) = 0. \tag{3.85}$$

Now, solving for I,

$$I = V_s/2R_s, \tag{3.86}$$

because

$$V_s/R_s = I, \text{ a short circuit, } = I_N. \tag{3.87}$$

So for maximum power transfer,

$$I = I_N/2. \tag{3.88}$$

Substituting Equation (3.85) into Equation (3.63) provides the load voltage that maximizes power:

$$V_L = V_s - (V_s/2R_s)R_s, \tag{3.89}$$

or

$$V_L = V_s/2. \tag{3.90}$$

Using voltage divider Equation (3.62) for the load voltage, the load resistance that maximizes power is:

$$V_L = V_s/2 = V_sR_L/(R_s + R_L). \tag{3.91}$$

Solving for R_L,

$$R_L = R_s. \tag{3.92}$$

Not surprisingly, power to the load is maximized when the load resistance equals the source resistance.

Impedance matching

The process of designing electronic circuits for maximum power transfer also is referred to as the process of *impedance matching*. Impedance refers to the opposition offered to alternating current in circuits. Impedance has a resistive element identical to the resistance discussed so far, as well as reactive components caused by the other two circuit elements, inductance and capacitance. They will be addressed later.

When the conditions of Equation (3.92) are met, the source has been matched to the load or the *impedances have been matched*. Strictly speaking, meeting Equation (3.92) results only in a resistive match. Even so, the more general term *matching impedance* permeates industrial jargon.

Thus, when a design matches impedances, maximum power tra[illegible] is automatically achieved. It can be shown similarly that the more g[illegible]ral

case of AC circuits achieve maximum power transfer under matched impedance conditions even though inductance and/or capacitance may be present in either the load or the source. That subject is beyond the scope of this text.

Example 3.13 Teenage Freddie, with hearing already impaired by overexposure to loud rock music, concludes that his 120-W stereo amplifier has lost some of its "oomph". Having just completed a brief introduction to some DC circuit analysis in his high school physics class, he decides that he needs additional speakers to again enjoy the pleasures of rapturous noise.

He concludes that if he adds one speaker in parallel with each of the two speakers (one on each stereo channel), the additional current resulting from the reduced resistance of two speakers in parallel will boost the sound level by the desired amount.

He purchases two new speakers identical to the originals and makes his set up. But, instead of getting more sound out, he senses there is less. Furthermore, his amplifier now smells as if it is overheating. In desperation, Freddie comes to you, his beneficent uncle, for consultation. Please explain to Freddie what is wrong, why his approach will not work, and advise him on future actions.

Solution 3.13. A look at the amplifier specifications indicates a total continuous output power of 120 W, or 60 W per channel into an 8-Ω speaker on each channel. Because high-powered audio amplifiers are always designed for maximum power transfer, you conclude that the output impedance of the amplifier is 8 Ω as well. At full power out,

$$V^2/8 = 60, \text{ that is,}$$
$$V = [(8)(60)]^{1/2}$$
$$= 21.9 \text{ V},$$

the voltage across the speaker at full output power, Figure 3.35. Because you know that the amplifier is impedance matched, you immediately conclude that the open-circuit voltage of the amplifier is 43.8 V. This is because with equal source and speaker resistance, the voltage drop

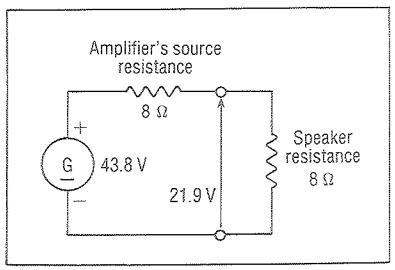


Fig. 3.35. Simplified schematic and values for the audio amplifier of Example 3.13 when operated at maximum power.

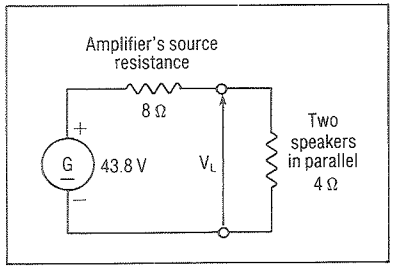


Fig. 3.36. When two 8-Ω speakers are connected in parallel, the net load is only 4 Ω.

across the load (speaker) must equal the voltage drop across the source resistance, or 43.8 V at the source. Redrawing the circuit with one 8-Ω speaker replaced by the 4-Ω equivalent of two speakers in parallel, Figure 3.36, the new current can be calculated.

$$I = 43.8/(8 + 4)$$
$$= 3.65 \text{ A}.$$

You inform Freddie that his conclusion about more current was correct because the current with the original 8-Ω speaker would have been

$$I = 43.8/(8 + 8)$$
$$= 2.74 \text{ A}.$$

However, a power calculation reveals the reason for reduced sound with the higher current. With the single 8-Ω speaker,

$$P = (I)^2(R_L)$$
$$= (2.74)^2(8)$$
$$= 60 \text{ watts},$$

which we knew all along. However, when the 4-Ω system is evaluated,

$$P = (I)^2(R_L)$$
$$= (3.65)^2(4)$$
$$= 53.3 \text{ W},$$

so the power level is lower even though the current is higher. As for the overheating of the amplifier, you now turn your attention to the power consumed by the amplifier's source resistance. It was originally designed to dissipate exactly the same amount of power that the load was to consume, namely, 60 watts. Under the 4-Ω load, however

$$P = (I)^2(R_s)$$
$$= (3.65)^2(8)$$
$$= 106.6 \text{ W}.$$

The output transistor(s) must consume nearly twice the power for which they were designed, leading to excessive self-heating and accounting for the burning odor. Having made these calculations, you now explain to your nephew that the problem lies in the music itself, that rock music is incapable of generating more than 60 watts, and therefore, his goal of boosted output is not achievable no matter how many speakers he connects to his stereo amplifier. Instead you counsel him to pursue a career as a librarian — advice he heeds. The ensuing years of quietude allow restoration of a good portion of his hearing.

Maximum power transfer is a useful design goal for audio power amplifiers but it is not the goal of all electronic devices. For example, a high-performance, regulated-DC power supply may carry specifications of 15-V regulated, with a source resistance of 0.01 Ω. Quick calculation shows that a load resistance of 0.01 Ω connected across the power supply results in a current of 750 A. While the rated output current may be only 10 A, this power supply clearly will be damaged if operated at its maximum power-transfer point.

Likewise, hydraulic systems do not always operate at the point of maximum power transfer. This is generally the case in pump-controlled circuits in which pump displacement and speed regulate the flow. Just as in electrical circuits, the point of maximum power transfer will occur when the delivered flow is one-half the fully unloaded flow. The internal leakage path under that condition has to absorb one-half the pump's output. For a tight pump, ie, one with high volumetric efficiency, the resulting pressure will probably be so high that it will lead to the pump's destruction well short of the maximum power point.

When using proportional or servovalves to control flow, the hydraulic power supply usually is configured to provide constant pressure, not positive displacement. This control scheme allows the variable restriction valve to control flow to the load. In such systems, maximum power transfer is achieved at viable pressures and flows and can be a system design goal.

Consider the conditions which transfer maximum power to a load when the hydraulic supply contains a throttling valve, Figure 3.37. This simplified equivalent circuit uses a constant pressure generator to develop fixed pressure P_s in psig. This pressure is connect through throttling orifice K_s to an arbitrary load. For analysis, begin with the assumption that the valve is fully open and it therefore can be represented by a fix[illegible] rifice. That is usually one of the design parameters of the system: th[illegible] ve is sized and selected on the basis of its fully open capacity.

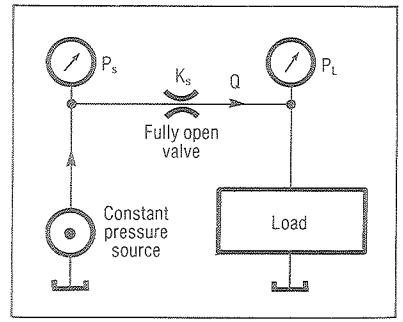


Fig. 3.37. This schematic, typical of the hydraulic essentials of servosystems, represents a valve-controlled load using a constant-pressure source, which is a well-regulated pressure-compensated pump.

That condition is assumed in this development. Begin with the pressure-drop loop equation for the circuit of Figure 3.37:

$$P_s = \Delta P_{across\ K_s} + P_L, \tag{3.93}$$

or

$$P_s = Q^2/K_s^2 + P_L. \tag{3.94}$$

To form a power equation, multiply both sides of Equation (3.94) by the flow, Q:

$$(Q)(P_s) = (Q^3/K_s^2) + (Q)(P_L). \tag{3.95}$$

from which we recognize that $(Q)(P_L)$ is the power delivered to the load. That is

$$W_L = (Q)(P_s) - Q^3/K_s^2, \tag{3.96}$$

which is the desired form. To find conditions for maximum load power, differentiate load power with respect to flow and set the result to zero:

$$d(W_L)/d(Q) = (P_s - 3)(Q)^2/(K_s)^2 = 0. \tag{3.97}$$

Understanding that

$$(Q)^2/(K_s)^2 = \Delta P_{across\ valve\ Ks}, \tag{3.98}$$

that is substituted into Equation (3.97) so that

$$(P_s - 3)(\Delta P_s) = 0, \tag{3.99}$$
$$\Delta P_s = P_s/3. \tag{3.100}$$

That is, the drop across the valve must be one-third the supply pressure so as to deliver maximum power to the load. Conversely, the load pressure must be two-thirds of the supply pressure in order to receive maximum power.

Electrical power transfer requires equal load and source resistances. An analogous statement would be possible for a hydraulic system except for two practical reasons:

- the hydraulics industry, lamentably, has never accepted the notion of resistance and/or impedance, although the adoption of standardized definitions would be beneficial, and
- the load on a hydraulic power unit is not usually a simple restrictive device such as an orifice. Instead, the load is an energy-conversion device such as a cylinder or motor which couples power to yet another device, the ultimate load. Therefore, conditions for maximum power transfer will remain in pressure terms, as in Equation (3.100).

Example 3.14. It is necessary to design a hydraulic power unit with valve control which will result in maximum power transfer to the load. The load is known only to require 1850 psi while absorbing a flow of 188 in^3/sec. If the valve is a flow-rated 1000-psi servovalve what is the flow rating of the valve in gpm?

Solution 3.14. Because we desire to design for maximum power transfer,

$$\begin{aligned} P_s &= 3(P_L)/2 \\ &= (3)(1850)/2 \\ &= 2775 \text{ psig.} \end{aligned}$$

Valve coefficient K_v can now be found:

$$\begin{aligned} K_v &= (Q_{\text{at the design point}})/[P_s - (P_{L,\text{ at the design point}})]^{1/2} \\ &= 188/(2775 - 1850)^{1/2} \\ &= 6.18 \text{ in}^3/\text{sec}/(\text{psi})^{1/2}. \end{aligned}$$

The rated flow of this valve can be found from the orifice flow equation and evaluated using the conditions under which the valve is flow-rated, ie, 1000 psid:

$$\begin{aligned} Q_{vr} &= K_v(1000)^{1/2} \\ &= (6.18)(31.62) \\ &= 195 \text{ in}^3/\text{sec} \\ &= 50.76 \text{ gpm.} \end{aligned}$$

CHAPTER FOUR
Capacitance and Inductance

A capacitor is formed anytime two conductors (usually plates) are separated by an insulator. The insulation used in capacitors is called a dielectric, Figure 4.1. If one conductor accumulates electron or ion charges relative to the other, the charges cannot neutralize one another because of the insulated separation.

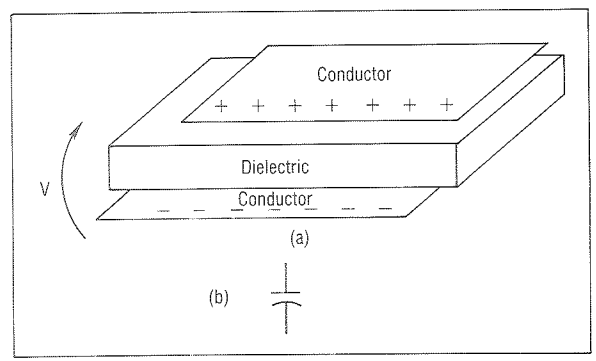


Fig. 4.1. Capacitors are comprised of two conductor plates separated by an insulating dielectric, (a). *Capacitor symbol,* (b).

A voltage difference therefore exists between the two conducting plates and the capacitor is said to have some degree of charge. Should a conductor be connected between them, the charges will move to neutralize one another and discharge the capacitor. The charge-holding ability of a capacitor is called its *capacitance*.

The hydraulic analogy to the capacitor is a volume or accumulator. Just as an accumulator is a mechanical bucket that holds molecules of oil, the capacitor is an electronic bucket that holds electrons. The analogy can continue: as additional molecules of oil are packed into the accumulator, it pushes back with increasing pressure because of its gas precharge; more effort is required to push the next batch of molecules into the accumulator. The accumulator becomes charged as the packing con-

tinues, Figure 4.2.

The electronic analogy: if an electron is stripped off the upper plate of a capacitor and deposited on its lower plate, the upper plate loses a net charge of one electron that is gained by the lower plate. When attempting to strip another electron from the upper plate, the positive

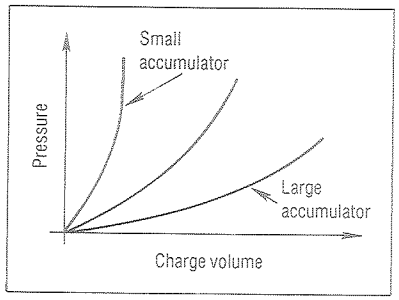


Fig. 4.2. Curves indicate how size of accumulator affects pressure as oil charge volume changes.

charge already existing there resists the stripping effort. Further, the lower, negatively charged plate tries to push the new electron away as it is deposited there. As this stripping or charging process continues, it requires more and more effort to strip and deposit each new charge. This effort is measured in volts.

Capacitance is a measure of the amount the voltage builds with each succeeding new charge transferred from one plate to the other. The unit of capacitance is the farad but because this unit is too large to be practical, capacitance usually is measured in microfarads and picofarads:

$$1 \text{ farad} = 1{,}000{,}000\ \mu f = 10^6 \mu f,$$

and

$$1 \text{ farad} = 1{,}000{,}000{,}000{,}000 \text{ pf} = 10^{12} \text{pf}.$$

A large capacitor will hold a large number of charges for a given volt-

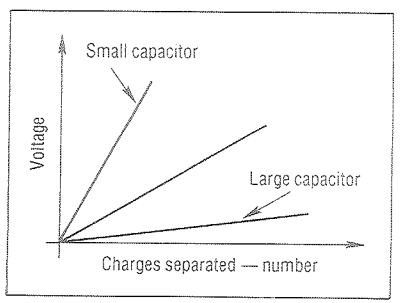


Fig. 4.3. Analagous to accumulator charges indicated in Figure 4.2, these curves indicate how voltage changes as number of separated charges vary in large and small capacitors.

age while a small capacitor requires only a small charge before it builds to the same voltage, Figure 4.3.

In a more practical situation, the charging of an accumulator is done with the aid of a pump, Figure 4.4. As the pump transfers molecules of oil from the reservoir to the accumulator, the pressure builds. The speed

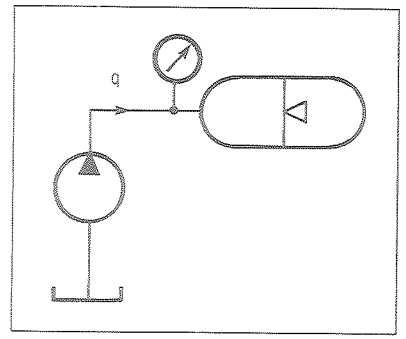


Fig. 4.4. Simplified hydraulic circuit with flow, q, which charges accumulator.

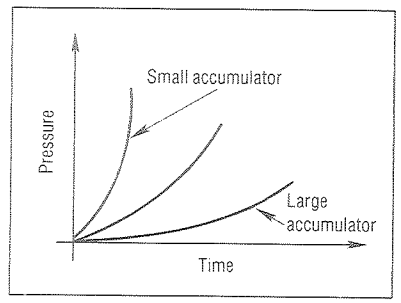


Fig. 4.5 Curves indicate time vs. pressure for various sizes of accumulators.

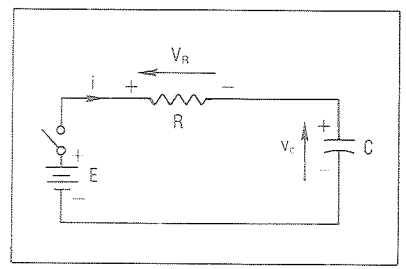


Fig. 4.6. Simple illustrative electrical circuit with capacitance C.

with which accumulator pressure builds depends upon the rate at which oil is pumped or charged into the accumulator and its size, that is, the volume or "capacitance" of the accumulator, Figure 4.5.

An analogous situation exists in an electrical circuit with a cap or, Figure 4.6. When the switch is closed in this circuit, the energy present

Corner horsepower helps select hydraulic motors

Selection of hydraulic motors for vehicle propulsion drives generally requires data such as the rolling radius of the drive wheel or the pitch radius of the drive sprocket and the overall gear ratios. Often this information is unknown or not yet determined in the earliest stages of design. However, the designer may need to investigate the type, displacement, and — of course — cost of the hydraulic motors before progressing farther.

If this is the case, a theoretical value called *vehicle corner horsepower* (VCHP) can help designers select the smallest and most economical motors that meet the vehicle performance specifications. VCHP is calculated by this formula:

$$(\text{VCHP}) = TV/375,$$

where

T is maximum required vehicle tractive effort, ft lb, and

V is maximum required speed, mph.

This formula is derived from the basic definition of one horsepower as 33,000 ft lb/min.

Here's a VCHP example: a vehicle with a gross weight of 15,000 lb must be able to climb a 40% grade while fully loaded and have a maximum travel speed of 10 mph on level ground. These two operating parameters will not occur simultaneously. (Available engine power will limit maximum speed on the grade.)

The 40% grade (21.8° slope) requires a tractive effort of 6321 ft lb, assuming a 0.05 rolling resistance. Therefore:

$$(\text{VCHP}) = (6321)(10)/375 = 169$$

To determine the smallest motor that will meet the performance requirements — regardless of rolling or pitch radii, or gear ratios — look for a motor or combination of motors that have a *motor corner horsepower* (MCHP) greater than the calculated VCHP. The MCHP is calculated from this formula:

$$(\text{MCHP}) = DPNn/440{,}000,$$

where

D is motor displacement, cir

P is maximum available pressure, psi

N is maximum allowable continuous motor speed, rpm, and

n is number of driving motors.

Note that MCHP is *not necessarily* the actual power capacity of the motor, but rather a theoretical value based on the motor's maximum output torque at the available pressure and maximum shaft speed. The MCHP formula also considers factors that protect the motor against overspeed and allow for mechanical inefficiencies.

These calculations now allow technical review of motors that are candidates for an application and comparison of the costs of those that will meet the operating specifications. Wheel and sprocket sizes, along with gear ratios, can be finalized later in the development of the machine. Note: the continuous horsepower rating of any motor should not be exceeded during any phase of equipment operation.

This material was provided by Ultra Fluid Technologies, Inc., Columbus, Ohio, a manufacturer of hydraulic wheel motors. Ultra has computerized these corner horsepower calculation procedures as well as more detailed specification steps for traction drives. Contact them at (614) 759-9000 for more information.

Continued on page 111

Basic Electronics for Hydraulic Motion Control

by Jack L. Johnson, PE

Chapter 1 — Essential ideas about calculus

Chapter 2 — Electrical meters and measurement

Chapter 3 — Basic electrical circuit analysis

Chapter 4 — Capacitance and inductance

Chapter 5 — Alternating current circuit analysis

Chapter 6 — Diodes, rectifiers, and power supplies

Chapter 7 — Transistors, operational amplifiers, and other signal processing

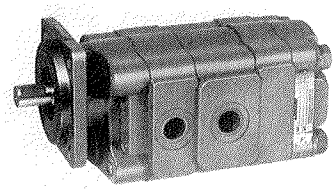
Chapter 8 — Sensing for measurement and control

Chapter 9 — Electrohydraulic devices

Chapter 10 — Examples of electrohydraulic control systems

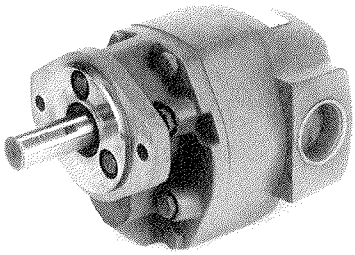
Another part of the new book, BASIC ELECTRONICS FOR HYDRAULIC MOTION CONTROL continues on the next page. HYDRAULICS & PNEUMATICS will publish the serialization of this work every other month until its completion, estimated for the latter part of 1991. The bound text will be available after that time.

Rugged construction

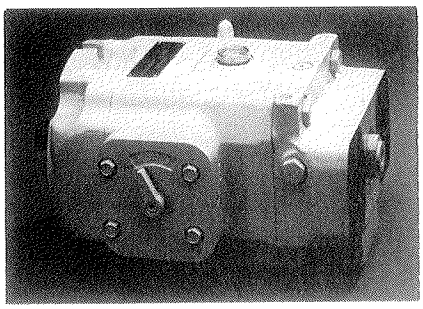


. . . of high-strength cast iron and alloy steel combines with extended-length roller bearings in heavy-duty HDM 7600 gear motors. Five available gear widths generate hp range from 43 to 133 at 2000 rpm and approximately 3000 psi. Standard mounting: 4-bolt C.
Permco 211

Integral check valves



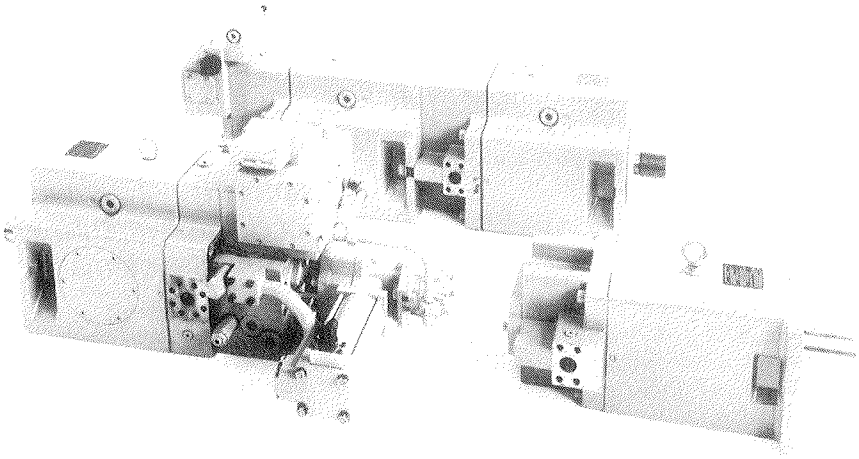
. . . permit bi-directional rotation and eliminate need for external case drains on DM Series gear motors for applications requiring moderate starting torque and moderate- to high-speed efficiency; 13-model series covers theoretical torque range from 1.05 through 61.8 lb-in./100 psi. Will turn as slowly as 300 rpm at low torque.
Delta Power Hydraulic 212



Electrohydraulic

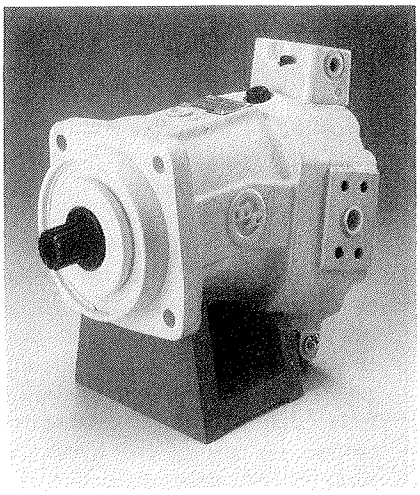
. . . or hydraulic strokers provide for remote control of displacement in Gold Cup Series 6 axial-piston motors for bi-directional operation in open or closed loops. Two speed is another control option. Maximum pressure: 6000 psi. Maximum speed: 3000 rpm. Maximum hp: 255.
Hagglunds Denison 213

Open- and closed-circuit



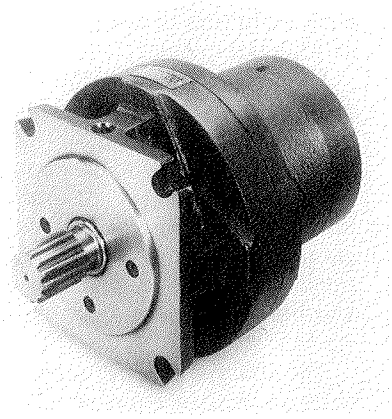
. . . swash-plate, axial-piston motors can be flange- or foot-mounted. Five sizes in each type. Rated pressure: 3600 psi (smallest), 4550 psi (others). Single-direction speed range: 150 to 1800 rpm. Output torques from 150 to 2345 lb-ft.
Flender Corp. 214

Bent-axis



. . . variable-displacement Model AA6VM piston motors use spherical control plate to improve high-pressure volumetric efficiency. For open- or closed-loop circuits. Displacement may be changed under full load; speed ratio of 4.85:1 is possible. Displacement range (over 5 sizes): 1.71 to 12.20 cir. Continuous pressure rating: 5800 psi.
The Rexroth Corp.
Industrial Hydraulics 215

Large radial bearings



. . . absorb piston reaction forces and provide balanced loading in MF Series piston motors for systems with constant starting, stopping, and sudden reversals. Forged-bronze barrels and hardened-steel pistons. Rated to 4775 lb-in. at 5000 psi; intermittent pressure rating is 8000 psi; rated speeds to 2800 rpm.
Dynex/Rivett Inc. 216

with the wire conductor that carries the current. Inductance even exists in a straight piece of wire but because its value is so very small, it is inconsequential in slow systems such as electrohydraulics. When the wire is wrapped in a coil to form an inductor, the flux linkage is enhanced and the inductive properties become significant.

If the current through a coil is changing, the amount of flux linking with the coil also changes and during the change, a voltage is *induced* which opposes the current change. The ± signs in Figure 4.13 indicate the polarity of this induced voltage. Note that the polarity wants to *push back* against the incoming current and impede its growth.

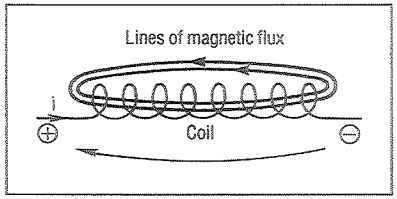


Fig. 4.13. Inductor coil shows elements of inductance and polarity of subsequent induced voltage. Circular magnetic flux, Φ, is increasing.

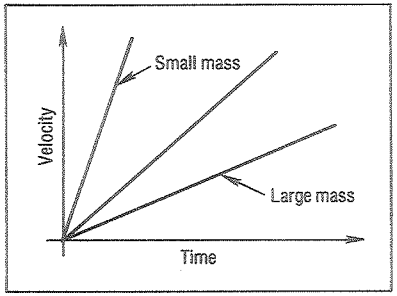


Fig. 4.14. Graph indicates accelerations of various sizes of mass with constant force applied to mass. Friction is ignored.

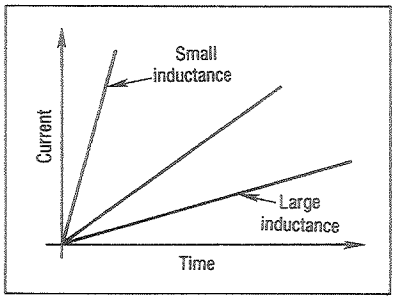


Fig. 4.15. Graph plots current increases vs. size of inductance with constant voltage applied to coil.

The mechanical analogy to inductance is mass or inertia. That is, inductance of an electrical coil resists changes in current similarly to the way mass and inertia resist changes in velocity. When a constant force is

applied to a mass and no friction is present, such as in situations encountered in the weightlessness of space, there is uniform acceleration and velocity increases constantly, Figure 4.14. In analogous fashion, a constant voltage applied to a resistanceless coil (a practical impossibility even in space), will produce a continuously rising current, Figure 4.15.

In practice, a coil must have some resistance because, after all, it is wound with real wire. Furthermore, Ohm's Law cannot be violated; it says that maximum current i can never exceed E/R, where E is the applied voltage and R is the total series resistance, Figure 4.16. Therefore, in real coils, the current does not rise without limit. Instead, it rises and asymptotically approaches E/R, Figure 4.17.

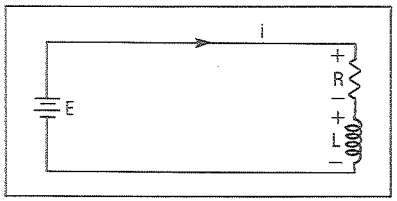


Fig. 4.16. Illustrative inductance circuit. Maximum current cannot exceed E/R.

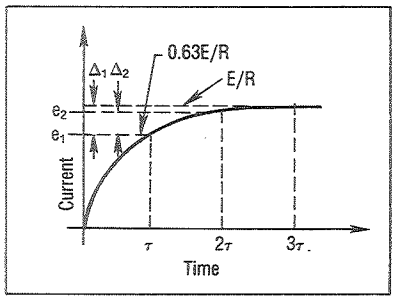


Fig. 4.17. Inductor current builds exponentially according to time constant.

The unit of inductance is the henry and its algebraic and schematic symbol is L. Note in Figure 4.17 that current build-up is exponential as is voltage build-up in a capacitor. The time constant in an inductive circuit is

$$\tau = L/R, \tag{4.6}$$

where τ remains in seconds when L is in henries and R is in ohms.

The exponential rise of inductance is brought about because of the voltage drop across resistance iR. When first excited there is no current, a state the inductor would like to maintain; consequently there is no iR drop and full source voltage E is felt across the coil. This results in a current rise however gradual. As the current rises, some voltage is lost across

resistor iR; hence, less voltage is available at the inductor. The rate of current rise begins to decrease and the end result is an exponential current increase.

Actually, the coil current and the flux that it created represent energy stored in the flux field. When electric power is removed from a coil, flux field energy must decay and dissipate. As the magnetic field collapses, it induces a voltage in its parent coil that attempts to keep coil current going. The peak voltage depends upon the electrical resistance presented to the inductor at the instant the power source was disconnected. The peak instantaneous voltage can be calculated when the resistance is known.

Example 4.3. If the switch of Figure 4.18 is closed for a long time and then suddenly opened, what will be the voltage across dissipating resistor R_D?

Fig. 4.18. Circuit of concern in Example 4.3.

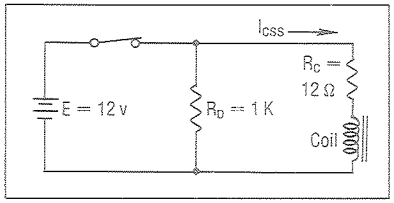
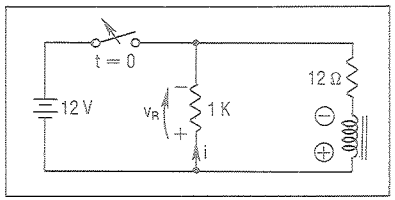


Fig. 4.19. State of circuit of Example 4.3 at instant switch is opened.



Solution 4.3. After the switch has been closed for a long time, the coil current will rise to its steady-state value:

$$i_{CSS} = E/R_C$$
$$= 12V/12$$
$$= 1\,A,$$

with circuit state at the instant the switch is opened indicated in Figure 4.19. At the instant the switch is opened, the inductor maintains the 1 A which must go through the 1000 Ω resistance because the switch opening killed the path through the battery. Now,

$$V_R = -IR_D$$
$$= -1(1000)$$

$$= -1000\,V.$$

Summary of inductance:

- inductors introduce the time factor as a variable because there is a delay in *current* increase when the coil becomes engergized. This is in contrast with, but similar to, capacitors which cause delays in *voltage* increase
- charging and discharging of inductors is exponential, that is for charging

$$i = (E/R)(1 - \epsilon)^{-Rt/L}. \tag{4.7}$$

For discharging,

$$i = Io\epsilon^{-Rt/L} \tag{4.8}$$

- the inductive time constant is

$$\tau = L/R \tag{4.9}$$

in seconds

- when an inductor first starts charging, it acts like an open circuit
- when an inductor reaches steady-state, it acts like a short circuit, and
- **disrupting or opening an inductive circuit which is carrying current can result in extremely high induced voltages.**

The following magazine pages of **Basic Electronics for Hydraulic Motion Control** are the initial pages of Appendix A. The various appendices in their entirety will be included in the back of the bound volume. Parts of them will appear in HYDRAULICS & PNEUMATICS from time to time.

Appendix A*

Glossary

AC coupled — The ability to pass electrical signals only if they are above a minimum frequency.

Active region — That region in the metering characteristics curve of a valve which lies between the dead zone and the saturation region, Figure A.1.

Amplifier — A device which has a power input port and at least one signal- or control-input port. Resulting controlled power output can exceed the control input power, Figure A.2.

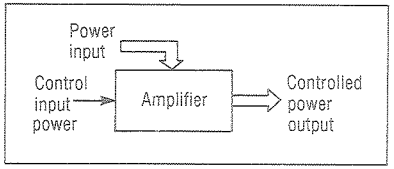


Fig. A.2. Block diagram of amplifier inputs, output.

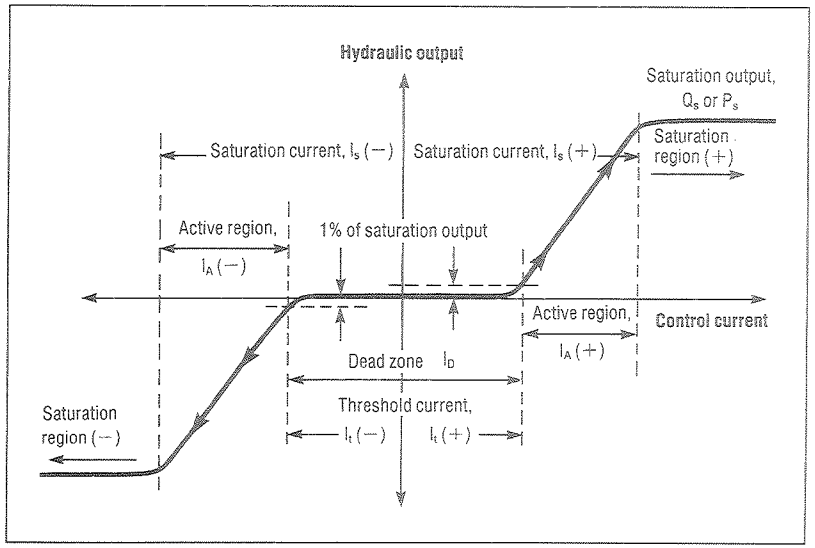


Fig. A.1. Generalized metering characteristics curve for proportional electrohydraulic interface device (PEHID).

Amplifier, operational — An electronic package consisting of several transistors and capacitors arranged to produce an output which is an amplified replica of the input. Configuring the package with user-selected input and output impedances, operational amplifiers can be used to add, subtract, integrate, and differentiate, as well as provide electronic compensation and bandpass frequency filtration. Figure A.3. Synonym: op-amp.

Analog — A representation of information by the amplitude of a physical variable.

Bandwidth — That band of frequencies which lies below selected points on the frequency response curve, and based on specified criteria. Two common criteria are the minus three decibel roll-off and the 90° phase lag frequency. Note that the frequency where the amplitude (gain) in dB has rolled off by three is the same as a 30% reduction in amplitude in the units

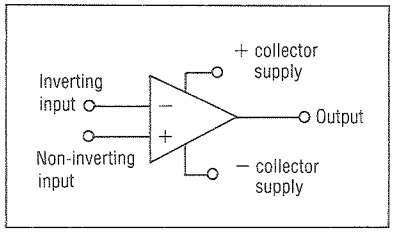


Fig. A.3. Operational amplifier symbol.

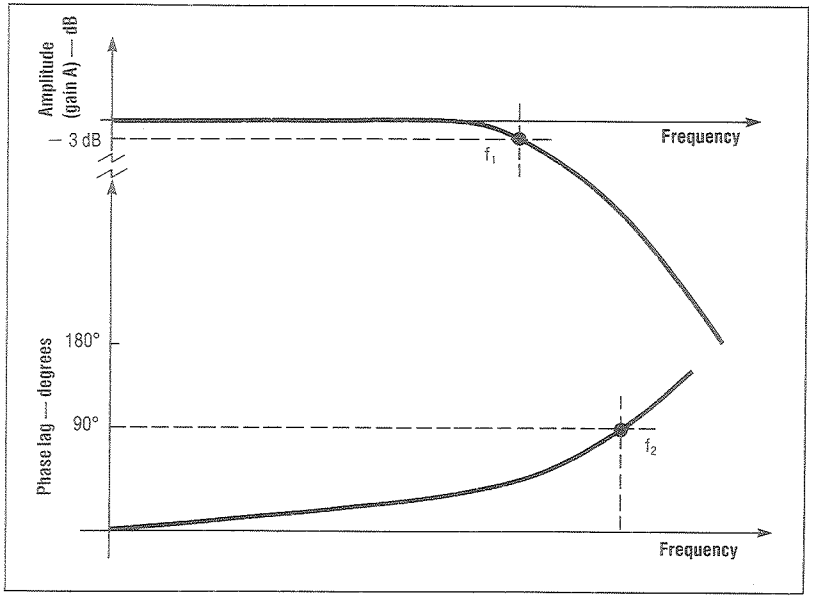


Fig. A.4. Gain and phase curves for proportional electrohydraulic interface device (PEHID); f_1 represents frequency at −3 dB bandwidth, and f_2 represents frequency at 90° phase lag bandwidth. Published bandwidth depends upon which of these two criteria a manufacturer chooses.

Table A.1 — Binary code			
3-bit binary number			Decimal equivalent
bit 2	bit 1	bit 0	
0	0	0	0
0	0	1	1
0	1	0	2
0	1	1	3
1	0	0	4
1	0	1	5
1	1	0	6
1	1	1	7

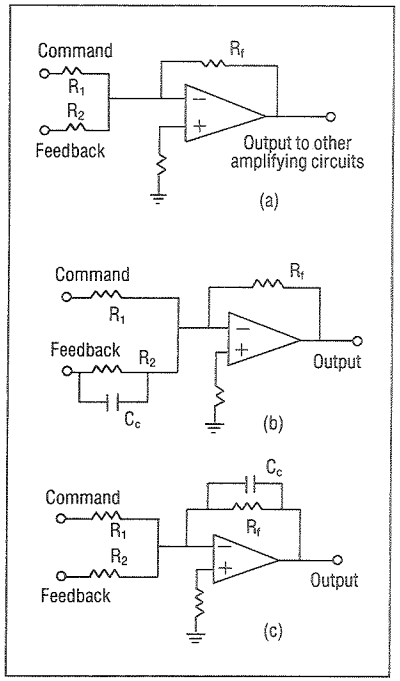


Fig. A.5. Electronically uncompensated operational amplifier circuit, (a)*; operational amplifier circuit with lead compensation of the feedback signal,* (b)*; operational amplifier circuit with lag compensation of the error signal,* (c)*. Other compensation methods are possible.*

of measure, Figure A.4. See Frequency response.

Bel — A dimensionless unit that expresses the ratio of two values of power. It is the logarithm to the base 10 of the power ratio. The more commonly used decibel (dB) is 10 times the logarithm to the base 10 of the power ratio. A bel is 10 decibel. $x = \log_{10} y$; $y = 10^x$; $a^0 = 1$; $0\ \text{dB} = 10^0 = 1$.

Binary code — A digital coding scheme using combinations of ones and zeros, ons and offs, trues and falses, etc., to represent quantities, Table A.1. See Gray code.

Center-lap conditions — A consideration in the design and manufacture of hydraulic valves describing the amount of spool movement needed for the pressure and tank ports to begin communicating with their respective work ports. Valves can be over, under, or critically lapped. See Dead zone and Figure A.1.

Closed loop — A commonly used term to distinguish closed control loops rather than the positional loop used to set position of the main hydraulic valve spool. This is not to be confused with the closed hydraulic circuit of a hydrostatic transmission. See Inner loop.

Command — That signal which tells a system what output level to seek. Synonym: set point.

Compensation, electronic — A process whereby an electronic circuit is especially tailored to improve the dynamic response of the overall electrohydraulic system, Figure A.5.

Compensator, unloading — A specific pressure-compensated flow control valve which also relieves a fixed-displacement pump at a low pressure when a mating directional control valve is centered, Figure A.6.

Contamination tolerance — A measure of the ability of a proportional electrohydraulic interface device (PEHID) to function within specific limits when operated with a fluid containing contaminants of a specified kind and size.

Control, closed-loop — A control concept using sensors to monitor performance or status of a machine or process output. The sensors send or feed information back to the input for automatic corrective action, Figure A.7.

Control, feedback — See Control, closed-loop.

Control, man-in-the-loop — See Control, open-loop.

Control, open-loop — A control concept in which a human observes the status or performance of a process or machine. The human makes control decisions and corrections to the system when its status or performance is unacceptable, Figure A.8. Synonym: man-in-the-loop. See Control, closed-loop.

Control, PID — A proportional, integral, and derivative control scheme that integrates or differentiates the error in a servo mechanism or scales it proportionally with a constant. The scheme is the forerunner of the state-variable controller.

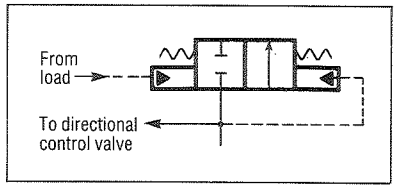


Fig. A.6. Hydraulic unloading compensator circuit.

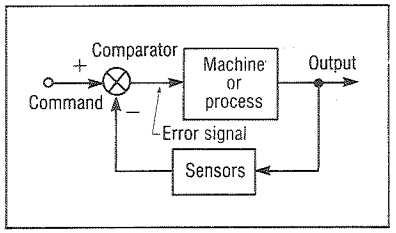


Fig. A.7. Block diagram of closed-loop control.

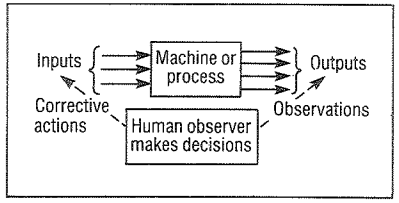


Fig. A.8. Block diagram indicates how observer makes decisions to establish closed control loop.

Control, ramp — A special electronic conditioning circuit which, when given a step input, increases or decreases the output linearly (as the case may be) until the output reaches the value of the input. Two control concepts can be implemented: constant slope, variable time to reach input level; and constant time lag, variable slope, Figure A.9.

Controller — That portion of a closed-loop control system which receives command and feedback

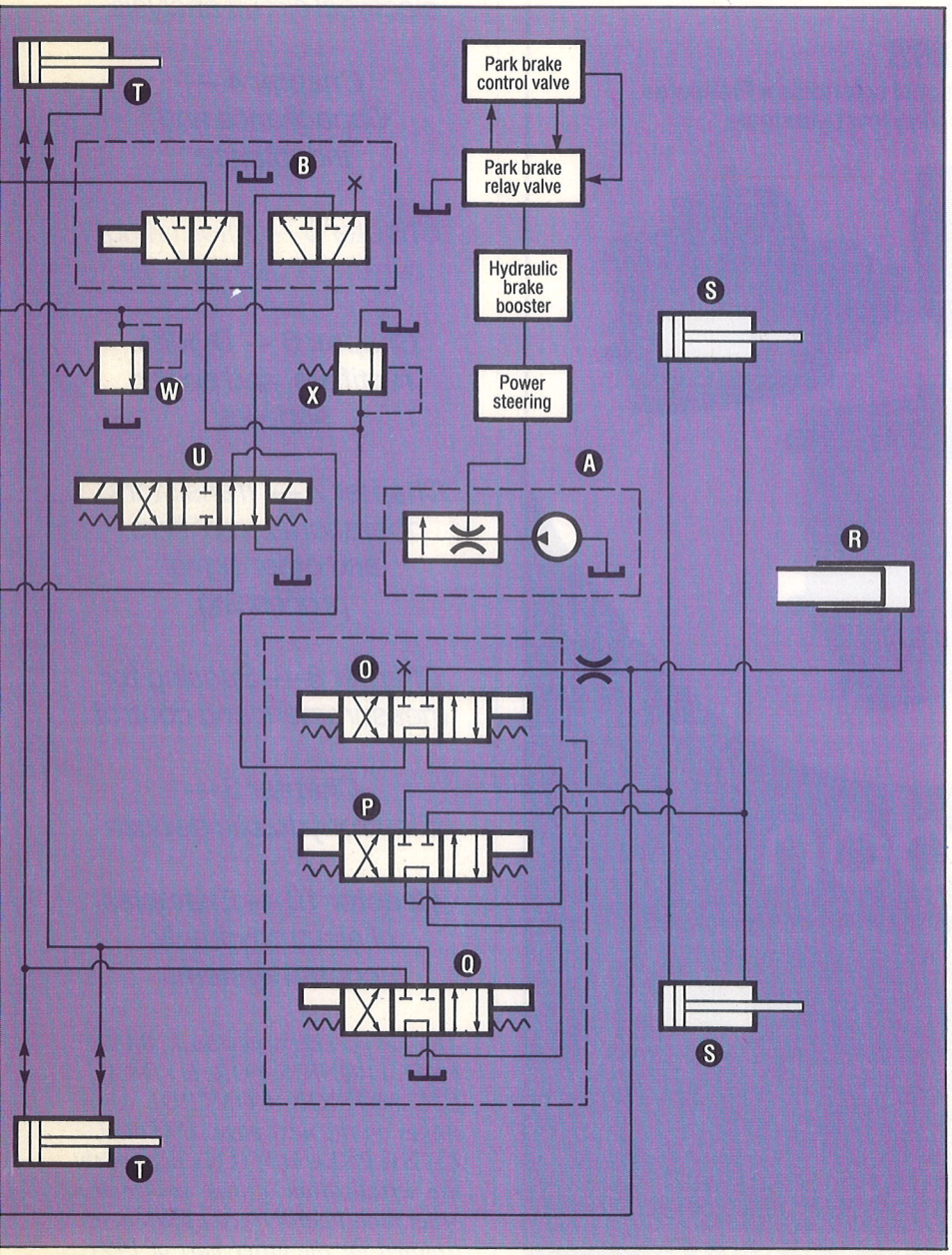
the rolling-rack cylinder to return. This permits the rolling rack to move rearward as a new tier of bales is added to the load rack. Rolling-rack relief valve *Z* lets the rolling rack roll to the rear when the load rack is raised to unload.

Air check valves

The cylinders that actuate the first and second tables are fitted with air check valves, relief valves, and breathers. The air check system slightly pressurizes air in the head end of the cylinder that starts the table on its downward cycle. This pressure reduces the length of time it takes the table to return to its home position. Because the double-acting cylinders actually function as single-acting, breathers were installed in the cylinder head ends to keep contaminants out during cylinder retraction.

Although the check valves resemble automotive tire valves, we determined that a tire valve core would not function properly. Should the check valve fail or become contaminated, the table could stick in the up position or drift down slowly.

A porous bronze breather in each check valve prevents chaff or dust from inadvertently entering the cylinder. The breather can be cleaned by rinsing it in solvent, then blowing it dry with compressed air. A relief valve, set at 150 psi, vents air if pressure in the chamber exceeds the setting of the relief valve spring. HP



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CHAPTER FIVE
Alternating Current Circuits

Alternating current (AC) has evolved as the electrical power transmission method of choice throughout the world. The main reasons for this are because:

- AC can be easily transformed (stepped up or down) with nearly 100% efficiency
- transformation efficiency leads to greater transmission line efficiency, and
- machines that produce alternating current are simpler and less costly than their direct current counterparts.

The basic AC generating machine is an alternator, Figure 5.1. It produces a voltage which is different at every instant of time and undergoes reversals in polarity twice each cycle. Output voltage, v_o, varies with time, and its amplitude depends on:

- the rotational frequency, f, or speed at which the alternator coils rotate
- the flux density, ϕ, or strength of the magnetic field, and

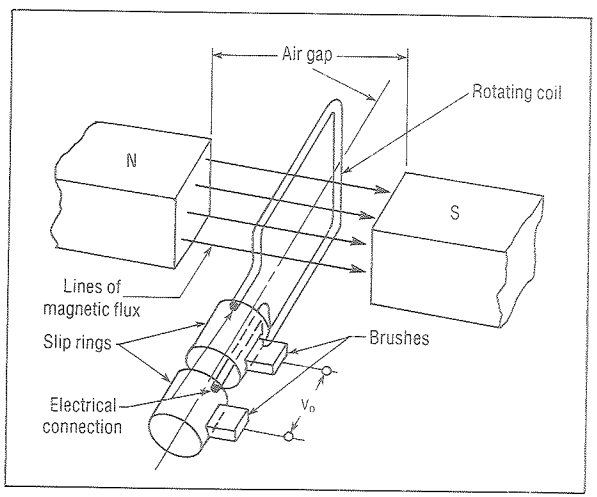

Fig. 5.1. Simplified cutaway drawing of an alternator indicates the magnets, the rotating coil at 0° position in the air gap, magnetic lines of flux, ϕ, and the brushes which deliver the generated voltage to the circuit.

- the number of turns of wire used to make each rotating coil.

Because coil movement is parallel to the flux lines in Figure 5.1, output voltage is zero. When the coil has turned to the horizontal or 90° position, the coil then is passing through the maximum number of flux lines/unit of time, and the output voltage instantaneously is maximum. At the 180° position, voltage again is instantaneously zero. As rotation continues past 180°, output undergoes a sign reversal and begins increasing negatively.

The resulting voltage wave curve in a properly designed alternator is a sine wave, Figure 5.2, that follows the mathematical function from trigonometry, sin Θ. This wave has a maximum value of +1 and a minimum value of −1. Note that when the coil rotates at a constant

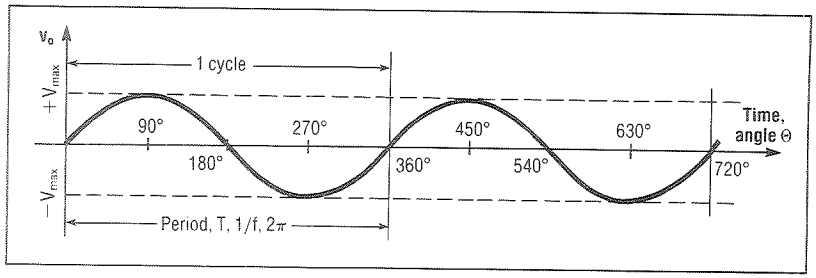

Fig. 5.2. The sine wave shape delivered by an alternator indicates its time-dependence/time-angle relationship and the magnitude of its output voltages. In a sense, the wave shape represents the number of magnetic flux lines being cut at any particular instant.

speed, angle theta, Θ, Figure 5.2, is a linear function of time. That is

$$\Theta^\circ = Kt, \tag{5.1}$$

where constant K is the rotary speed in degrees/second when degrees are used as the measure of the angle. Because radians are a more mathematically pure angular measure, most literature prefers their use. Using radians, Equation (5.1) becomes

$$\Theta^r = 2\pi ft, \tag{5.2}$$

where f is the angular frequency or rotational speed in hertz, Hz, or cycles/second. For convenience, $2\pi f$ is called the angular frequency in radians/second, and usually is indicated with a lower case Greek omega, ω:

$$\omega = 2\pi f. \tag{5.3}$$

Continuing, the frequency in Hz is the reciprocal of the period of the

wave shape, T:

$$T(seconds/cycle) = 1/[f(cycles/second)]. \quad (5.4)$$

Now, it is possible to express one equation which describes the sinusoidal voltage, Figure 5.2, for all time and in terms that usually are known or very easily determined:

$$V = V_{max}\sin(2\pi ft), \quad (5.5)$$

or

$$V = V_{max}\sin(2\pi t)/T, \quad (5.6)$$

or

$$V = V_{max}\sin(\omega t). \quad (5.7)$$

Degrees and radians are measures of rotational angles just as feet and yards are measures of distance; the last unit is just longer than the first. The degree divides a circle into 360 parts, while the radian divides it into 2π parts. This simple ratio converts radians to degrees and back:

$$\Theta^r/\Theta^\circ = (2\pi)^r/360^\circ = (\pi)^r/180^\circ \cong 0.0175 \cong 1^r/57.3^\circ. \quad (5.8)$$

To be sure, dealing with the instantaneous value of AC voltages is cumbersome. Fortunately, if only the *peak amplitude* and *frequency* of sinusoidal AC voltages are known, everything else can be determined immediately. When dealing with fixed or single-frequency systems, only the amplitude is important.

Happily, AC circuits can be engineered using methods similar to those used with DC circuits, although the mathematics admittedly are more complex. Actually, the branch of mathematics which applies to AC circuits is called *complex* algebra. This is not because the mathematics is so complicated, but because it deals with *complex numbers*, which have real and imaginary parts.

All AC circuits can be analyzed using the peak amplitude of the sine wave voltage, but a more convenient value, called the *Root Mean Square* or *RMS*, is used. It is derived from AC or DC voltages which will provide heating equivalence. Specifically, and by definition:

$$V_{RMS} = [average\ value\ (v)^2]^{1/2}.$$

This is based upon the equation:

$$power = v^2/R.$$

Look at the sinusoidal voltage and its squared value, Figure 5.3. Now

$$V_{RMS} = [average(v)^2]^{1/2} \quad (5.9)$$
$$= (V_{max}^2/2)^{1/2}$$
$$= V_{max}/(2)^{1/2} = V_{max}/1.414 = 0.707\ V_{max}.$$

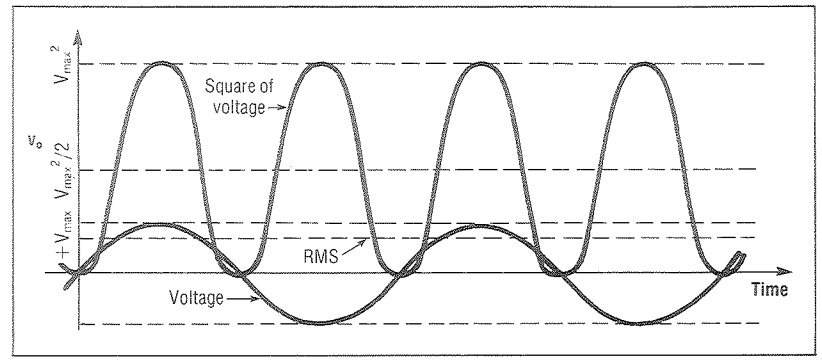

Fig. 5.3. Comparison of the maximum voltage, its square, and the RMS value.

When the voltage in a home is said to be 115 volts, this is really an RMS value. Understand that

$$V_{max}\ line = (V_{RMS}\ line)/0.707 = 115/0.707 = 163\ V,$$

the peak value of house voltage.

AC circuit analysis deals with current and voltage in circuits built from Resistors, Inductors, and Capacitors **(R/L/C)**. When a sinusoidal voltage is applied to an R/L/C circuit, the resulting current also is sinusoidal. The problem then becomes one of determining the current, given values for voltage and the R/L/C.

This concept can be extended to circuits of any required complexity. That is, sinusoidal voltages result in sinusoidal currents and sinusoidal currents result in sinusoidal voltages. In all remaining sections of this book, the following notations will be observed:

- **lower case letters will imply instantaneous, or time-varying values, and**
- **upper case letters will imply constant, DC, or RMS values.**

Current and voltage in resistive circuits

Ohm's Law applies to AC circuits as well as DC circuits.

$$i = e/R = (E_{max})[\sin(\omega t)]/R, \tag{5.10}$$

and so, because we recognize that the maximum current is the coefficient on the $\sin(\omega t)$,

$$I_{max} = E_{max}/R. \tag{5.11}$$

The current and voltage in a resistive circuit are said to be in phase with each other, because they both pass through their respective peaks and valleys at exactly the same time, Figure 5.4.

Current and voltage in capacitive circuits

The basic law governing current and voltage says that the current in a

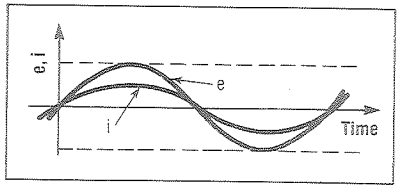

Fig. 5.4. Curves indicate how AC voltage and current remain in phase with each other.

capacitor depends upon the rate at which its voltage changes. The faster the voltage changes, the higher the current; and the larger the capacitance, C, the higher the current.

Mathematically,

$$i_c = C \textit{ times the rate of voltage change.}$$

$$i_c = C(\Delta V)/\Delta t. \tag{5.12}$$

Understand that the actual voltage level does not affect the current, only the rate at which the voltage changes.

Example 5.1. Consider the following, non-sinusoidal, time-varying voltage being impressed across a capacitor, Figure 5.5(a). What will the current waveform be?

Solution 5.1. Because capacitive current depends on the time rate of change of voltage, the current waveshape tracks the steepness of the voltage waveshape, Figure 5.5(b).

Example 5.2. Now consider what happens when the voltage is sinusoidal, Figure 5.6(a). Again use the fact that current depends upon how fast the voltage changes.

Solution 5.2. Voltage across the capacitor is given as being a sine wave. Therefore the current through the capacitor is a cosine wave, Figure 5.6(b). Now,

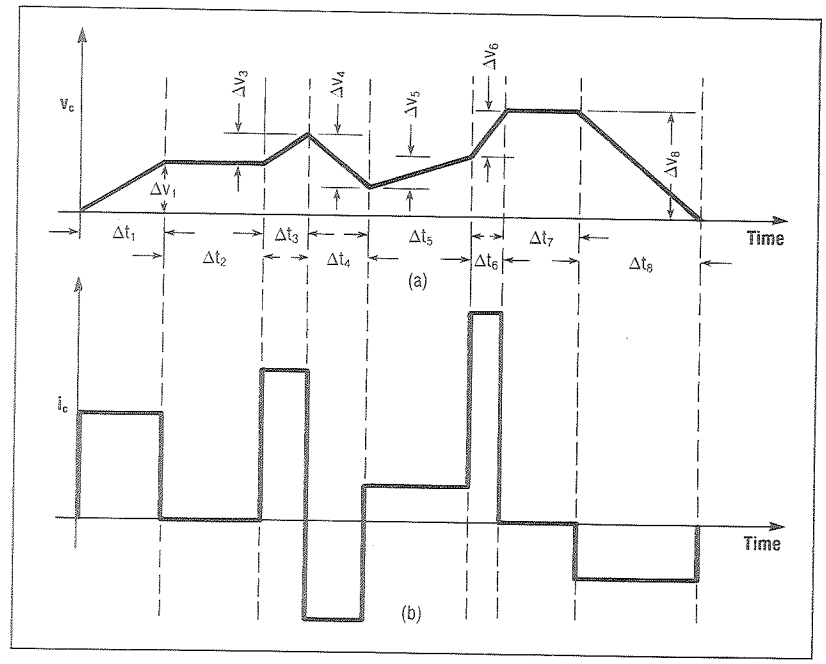

Fig. 5.5. In those time intervals where the voltage, (a), changes most rapidly, the current, (b), is greatest. Where the voltage decreases, the current is negative.

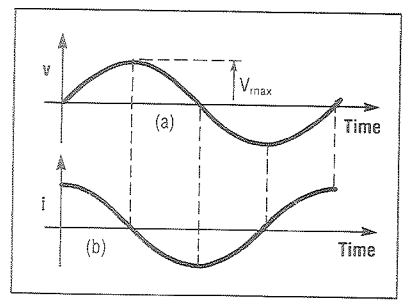

Fig. 5.6. The current is a sinusoidal cosine wave, (b), and as such, leads the voltage, (a), by 90°.

$$i = I_{max}\cos(\omega t)$$
$$= I_{max}\sin(\omega t - 90),$$

where it is necessary to determine I_{max} now that the phase shift has been found.

It can be shown that the rate of change of voltage from a sinusoidal source is directly proportional to the angular frequency and the peak

value of voltage. That is:

$$I_{max} = 2\pi f V_{max} C. \tag{5.13}$$

Capacitive reactance, X_C, is in ohms. This is a new term and is defined defined as:

$$X_C = 1/(2\pi f C). \tag{5.14}$$

Now,

$$I_{max} = V_{max}/X_C. \tag{5.15}$$

See how much this looks like Ohm's Law.

When both sides of Equation (5.15) are multiplied by 0.707, RMS current can be related to RMS voltage:

$$0.707 I_{max} = 0.707 V_{max}/X_C.$$

$$I_{RMS} = V_{RMS}/X_C. \tag{5.16}$$

Example 5.3. A 0.01-μf capacitor is connected directly across a 120 V AC line. What will the RMS current be? Sketch the current and voltage waveforms.

Solution 5.3. Because the line voltage is 120 V_{RMS}, the peak voltage is 120(1.414) which rounds to 170 volts. Now, the instantaneous voltage is

$$v_c = 170\sin(377t),$$

where 377 is the angular frequency of the 60 Hz line in rad/sec.

$$I_{RMS} = E_{RMS}/X_C,$$
$$X_C = 1/2\pi f C$$
$$= 1/[(6.28)(0.01 \times 10^{-6})(60)]$$
$$= 265{,}000\ \Omega.$$

$$I_{RMS} = 120/265{,}000$$

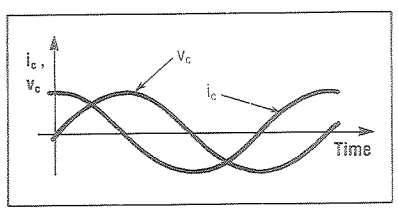

Fig. 5.7. Curves for Example 5.3. The curent appears to be ahead of the voltage in a capacitive circuit. Therefore, we say that the current leads the voltage.

$$= 452\ \mu A.$$

Therefore, the peak current is 1.414(452 μA), or 639×10^{-6} A. Thus, instantaneous current, i_C, is $639 \times 10^{-6}\sin(377t - 90°)$. Figure 5.7 shows the current and voltage waveforms.

Current and voltage in inductor circuits

The basic law governing current and voltage in an inductor should be compared to the law for current and voltage in capacitors. The voltage across an inductor depends on the rate at which its current changes. The faster the current changes, the higher the voltage.

Mathematically,

$$v_L = L(\Delta i/\Delta t), \tag{5.17}$$

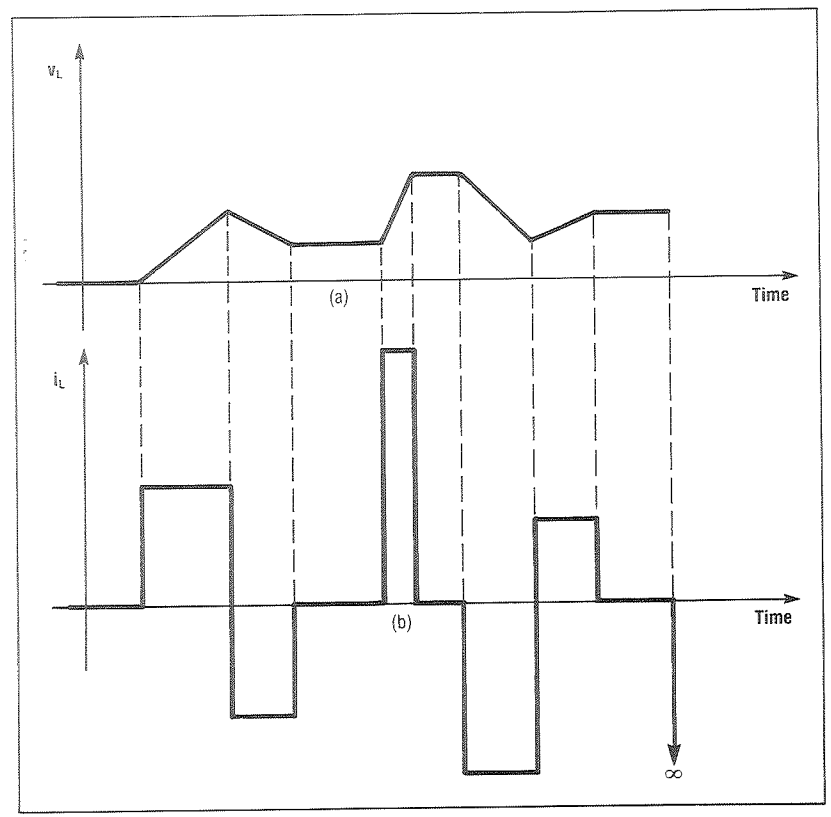

Fig. 5.8. Curves for Example 5.4. Inductor voltage is curve (b).

where inductance, L, is measured in henries. Understand that the magnitude of current i does not affect the voltage, but only the rate at which the current changes during the time interval.

Example 5.4. Consider the non-sinusoidal, time-varying current through an inductor, Figure 5.8(a). What will the voltage waveform be?

Solution 5.4. Voltage across an inductor depends upon the rate at which the current changes. Note, then, that a vertical (instantaneous) change in current requires an **infinite** voltage, an impossibility, Figure 5.8(b).

Example 5.5. Now consider the case where the current is a sine wave, Figure 5.9(a). Recall that $i_L = I_{max}\sin(\omega t)$.

Solution 5.5. Inductor voltage depends upon the rate at which its current changes. Therefore, when the current is a sine wave, the voltage must be a cosine wave and therefore **lead** the current by 90° as indicated by the curve in Figure 5.9(b). Now,

$$\begin{aligned} v_L &= V_{max}\cos\omega t \\ &= V_{max}\sin(\omega t - 90°). \end{aligned}$$

It is now necessary to determine the peak voltage, V_{max}. The rate of change of current is directly proportional to the angular frequency at the maximum rate of change, and the maximum voltage is also directly proportional to the inductance, measured in henries. That is:

$$V_{max,\,inductor} = 2\pi f L I_{max}. \tag{5.18}$$

It now is convenient to introduce *inductive reactance*:

$$X_L = 2\pi f L, \tag{5.19}$$

and

$$V_{max} = X_L I_{max}. \tag{5.20}$$

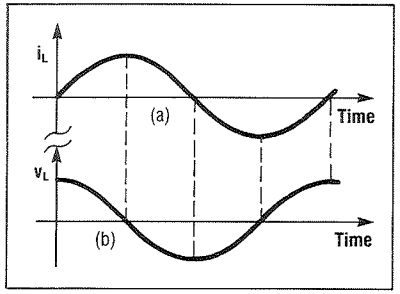

Fig. 5.9. Curves for Example 5.5. As indicated, the voltage (cosine) function, (b), leads the current (sine) curve, (a), by 90°.

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By multiplying both sides by 0.707, RMS values can be used:

$$V_{RMS} = X_L I_{RMS}. \tag{5.21}$$

Example 5.6. What RMS voltage is required to cause a 300-mA current in a 0.5 henry inductor at 250 Hz? Sketch the wave form.

Solution 5.6. Because the current is a sine wave of 250 Hz, $\omega = 1570$ rad/sec, and the frequency of the current and voltage must be the same, $\omega_I = \omega_V$.

$$\begin{aligned} X_L &= 2\pi fL \\ &= 6.28(250)0.5 \\ &= 785\ \Omega. \end{aligned}$$

$$\begin{aligned} V_{RMS} &= X_L I_{RMS} \\ &= 785(0.3) \\ &= 235.5\ \text{V}. \end{aligned}$$

$$\begin{aligned} i_L &= [0.3\sin(1570t)]/0.707 \\ &= 0.424\sin(1570t). \end{aligned}$$

By inspection, we see that

$$I_{L,\,max} = 0.424\ A.$$

$$\begin{aligned} v_L &= [235\cos(1570t)]/0.707 \\ &= 332.4\cos(1570t). \end{aligned}$$

Also by inspection, we see that

$$V_{L,\,max} = 332.4\ \text{V}.$$

The waveform can be sketched knowing the peak amplitude and frequency of the current and voltage, Figure 5.10.

Example 5.7. A 115 V AC voltage is connected to a 0.05 henry coil; the frequency is 2.5 kHz. What will the current be? Will the current lead or lag

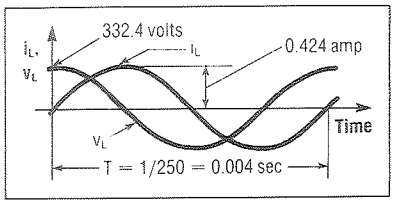
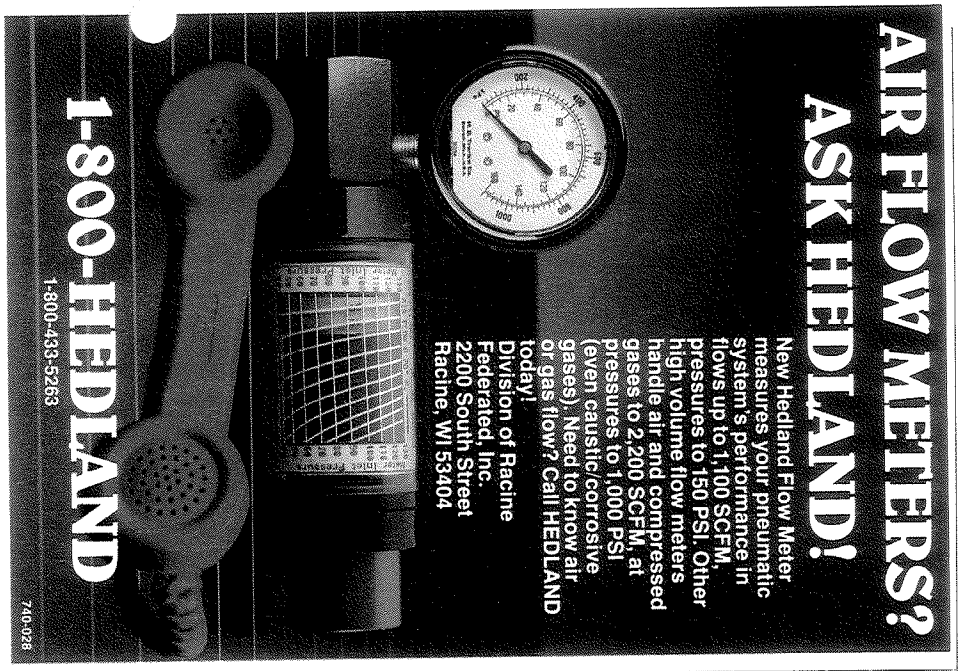


Fig. 5.10. Curves for Example 5.6. The voltage, dependent on the rate at which the current changes, leads the current by 90°. Therefore, the voltage is a cosine wave.



Circle 114

Circle 115

the voltage?

Solution 5.7. First, calculate the inductive reactance:

$$X_L = 2\pi fL$$
$$= 6.28(2500)0.05$$
$$= 78.5\ \Omega.$$

Now, calculate the RMS current:

$$I_L = V_L/X_L$$
$$= 115/78.5$$
$$= 1.46\ \text{A}.$$

The current will **lag** to the voltage, which is the same as saying the voltage will **lead** the current as shown in Figure 5.9.

The complex operator and impedance

Current and voltage in inductive and capacitive circuits are related by a variation of Ohm's Law for AC circuits:

$$I = V_C/X_C \tag{5.22}$$

for capacitive circuits, and

$$I = V_L/X_L \tag{5.23}$$

for inductive circuits.

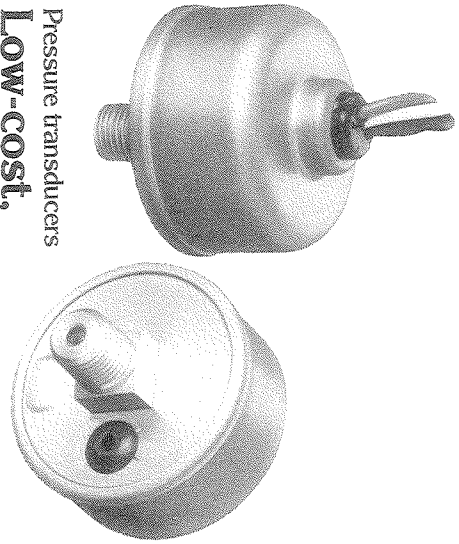
Now, if the voltage or current and the inductive or capacitive reactance is known, the other parameter can be calculated. **But remember that there are 90° phase shifts between current and voltage and that the shift directions are opposite in inductive as opposed to capacitive circuits.**

A mnemonic crutch was created to help remember these phase shifts: ELI THE ICE MAN. This stands for:

- **E** (voltage) is before **I** in inductive circuits. (**E** leads **I** in **L** circuits), and
- **I** (current) is before **E** in capacitive circuits. (**I** leads **E** in **C** circuits).

It would be convenient if there was a way to handle the phase shift *automatically*, or in some way that it would take care of itself. Fortunately, there is a branch of algebra that deals with this problem with mathematical exactness. It is called *complex algebra* and deals with quantities which have real (resistors) and imaginary (reactive) parts.

The existence of a 90° phase shift will be denoted in formulas with j, the complex operator. That is, a 90° phase shift in the wave shapes can be handled by using imaginary numbers.



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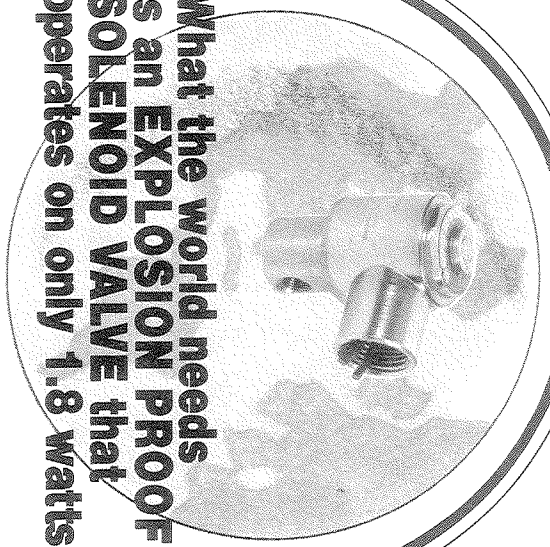

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$$\textit{Complex operator} = j = (-1)^{1/2}. \tag{5.24}$$

Math books use lower case i to symbolize complex numbers, but in electrical circuit analysis, i already is used for current, so j is preferred. Given this, **$-j$ indicates a phase lag of 90° and $+j$ denotes a phase lead of 90°.**

The equations for current and voltage now can be expressed in their complex forms:

$$V_C = -j(X_C)I_C \tag{5.25}$$

for capacitive circuits, and

$$V_L = +j(X_L)I_L, \tag{5.26}$$

for inductive circuits.

The interpretation is that in capacitive circuits, voltage *lags* the current by 90°. The $-jX_C$ in the capacitive Equation (5.25) is a reminder of this. Similarly, the $+jX_L$ in the inductive Equation (5.26) may be used as a reminder that voltage *leads* the current by 90°.

The concept of *impedance* is helpful when developing a complete Ohm's Law for AC circuits. Impedance is an all-encompassing term which permits dealing with the most complicated combinations of R, L, and C in circuits. Impedance allows use of all the circuit theorems, because impedance in AC circuits is similar to resistance in DC circuits. That is, if resistance is a measure of the degree to which current meets opposition in DC circuits, then impedance is a measure of the degree to which R, L, and C impede current in AC circuits.

The rules of complex algebra govern how current, voltage, and impedance are quantified to keep track of phase shifts in AC circuits, phase shifts which nearly always are something other than 0° or 90°. Commit the following definitions to memory for use with problems concerning AC circuits.

Impedance of a resistor:

$$\overline{Z}_R = R. \tag{5.27}$$

Impedance of a capacitor:

$$\begin{aligned}\overline{Z}_C &= -jX_C = X_C \text{ at an angle of } -90° \\ &= -j1/2\pi fC \\ &= 1/2\pi fC \text{ at an angle of } -90°.\end{aligned} \tag{5.28}$$

Impedance of an inductor:

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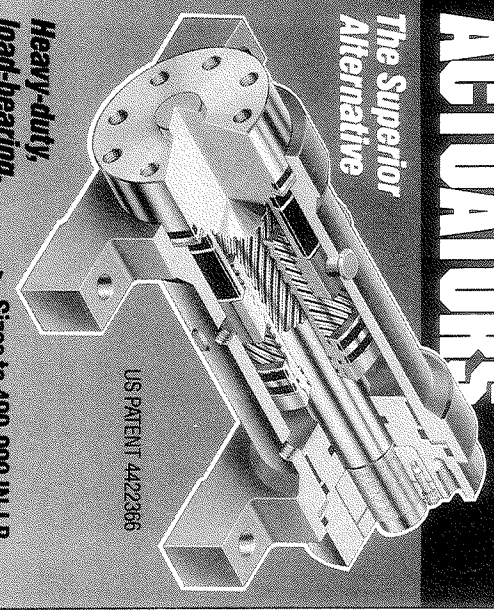
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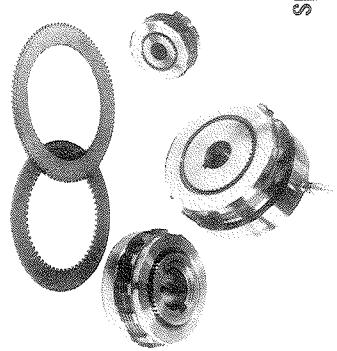
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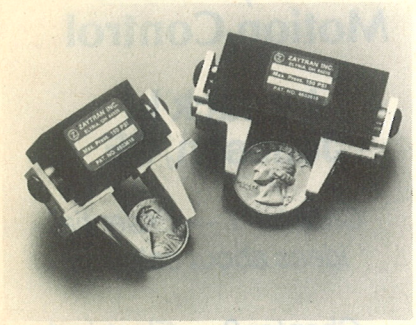


Compact gripper has two synchronous parallel slides that move in unison to provide true parallel jaw motion and constant holding force in any position.

ator *B* rotates 90° to align open gripper *D* with the machine spindle — as shown in the horizontal view.

Actuator *A* extends again, placing the jaws of gripper *D* around the finished piece in the spindle. Gripper *D* closes on the finished part and actuator *A* retracts to withdraw it from the spindle. After actuator *A* rotates 180°, it extends to locate the raw slug held by gripper *C* in the spindle. Then gripper *C* releases its piece, actuator *A* retracts to withdraw both grippers, and actuator *B* rotates 90° to return the device to its original orientation. The sequence then repeats.

Following through this series of motions and actions, it's easy to see how a relatively complex program of movement can be attained be properly sequencing standard pneumatic linear and rotary actuators. In this application, the combination actuator simplifies assembly and keeps the device more compact.

Jeffrey Schneid, vice president, Zaytran Inc., Elyria, Ohio, described this application.

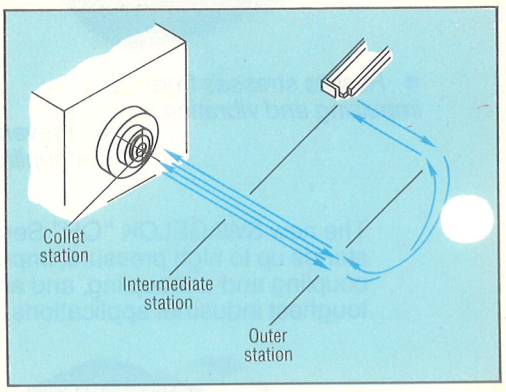
Simple robot handles robot parts

The ultimate in robot design might be a device sophisticated enough to make parts to reproduce itself. This pick-and-place robot takes a small but valuable step in that direction.

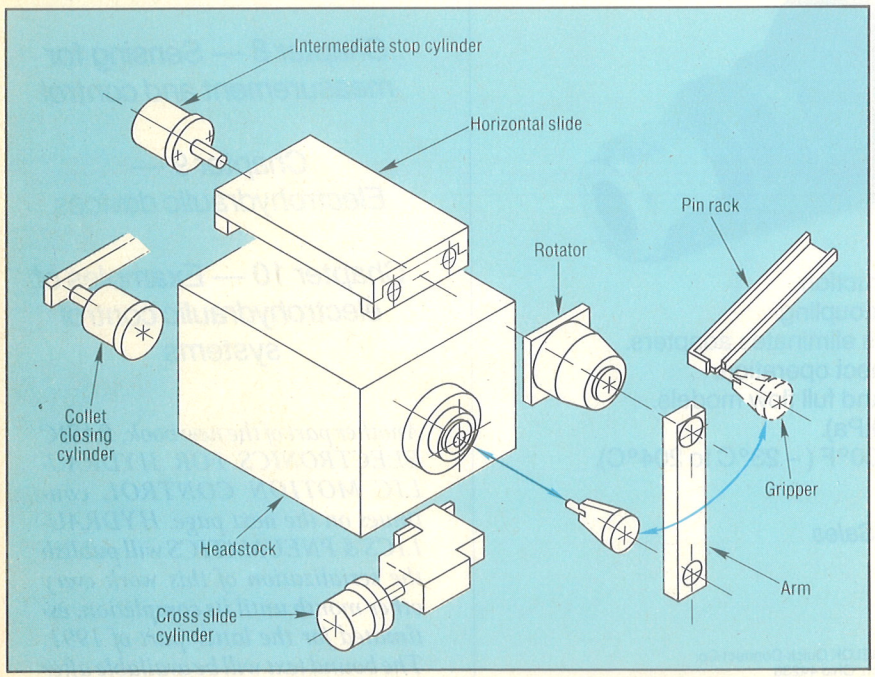
We need to cut retaining-ring grooves in a wide assortment of pins with varying diameters and lengths. Quantities do not justify processing on automatic screw machines so we had been running them on a small turret lathe. This required a full-time operator on an extremely boring job — one that wouldn't even challenge a raw apprentice.

To alleviate this situation, we wanted to automate the process — with sufficient versatility to produce small batches of pins for just-in-time delivery within our shop. As usual, we also needed to keep cost low.

We invested a few man-days in planning, collecting the necessary components, and assembling and installing our machine-loader robot. The system includes a controller, eight directional control valves, and four of our own integrated robotic components. All robot components are standard industrial products and their total cost was less than $3000. We also modified the lathe by adding an air cylinder to the collet closer and replacing the lead screw on the cross slide with another air cylinder.



Robot sequences gripper movement to three locations.



Pneumatic gripper, rotator, and cylinders combine in pin-feeding installation.

Here's the robot sequence:

1. Grab pin from the rack at the intermediate station and move linearly to the outer station.

2. Rotate down to the lathe centerline.

3. Move linearly to the collet.

4. Move back to the outer station and park there while the lathe cuts the groove.

5. Return to the collet and retrieve the machined pin.

6. Move to the outer station, releasing and dropping the pin en route.

Continued on page 64

$$\bar{Z}_L = +jX_L = X_L \text{ at an angle of } +90^\circ \quad (5.29)$$
$$= +j2\pi fL$$
$$= 2\pi fL \text{ at an angle of } +90^\circ.$$

The bar above the Z is a reminder that it is a *complex* quantity and contains phase-angle information. Note that the phase angle associated with R is 0 and with capacitive impedance is 90°.

Here is Ohm's Law for AC circuits:

$$\bar{I} = \bar{E}/\bar{Z}, \quad (5.30)$$

where the $\bar{Z}$ term, generally, is not confined to any specific R, L, or C element.

Basic concepts of complex algebra

Complex algebra deals with quantities which add together at right angles rather than in a straight line. The right angle addition is denoted by complex operator j, Figure 5.11. There are two equivalent mathematical forms using:

- rectangular coordinates,

$$R \pm jX, \quad (5.31)$$

and

$$|\bar{Z}|\cos\phi \pm j|\bar{Z}|\sin\phi, \quad (5.32)$$

and

- polar coordinates,

$$(R^2 + X^2)^{1/2} \text{ at an angle of } \phi = |\bar{Z}| \text{ at an angle of } \phi \quad (5.33)$$

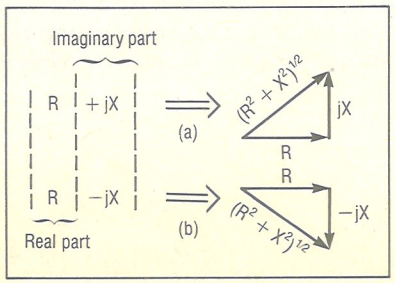


Fig. 5.11. Complex operators, +jX and −jX, indicate the addition of quantities at right angles to each other rather than in staight lines. Since $\tan\phi = X/R$, $\phi = \tan^{-1}X/R$ *for triangle (a), and* $= \tan^{-1}-X/R$ *for triangle (b).*

and

$$\phi = \tan^{-1} \pm X/R. \quad (5.34)$$

The addition of complex numbers is easier to carry out in rectangular form:

$$(R_1 + jX_1) + (R_2 + jX_2) + \ldots + (R_n + jX_n)$$
$$= (R_1 + R_2 + \ldots R_n) + j(X_1 + X_2 + \ldots + X_n).$$

Multiplication and division of complex numbers is easier to do in polar form:

$$A \text{ of angle } \phi \times B \text{ of angle } \theta = A \times B \text{ of angles } \phi + \theta.$$

$$(A \text{ of angle } \phi)/(B \text{ of angle})\,\theta = A/B \text{ of angles } \phi - \theta.$$

Current and voltage in R/L/C circuits

When resistive and reactive components are combined into a single circuit, the net phase angle between applied voltage and total current generally will not be 90°, but somewhere between 0° and 90°.

Example 5.8. Consider the series circuit, Figure 5.12, containing a resistance of 30 Ω, an inductive reactance of 40 Ω, and carrying a current of 1 A RMS.

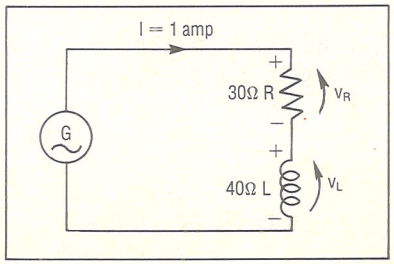


Fig. 5.12. Circuit illustrates Example 5.8.

Solution 5.8. To determine the value of applied voltage E, the impedance concept can be used. But first look at the problem from a sinusoidal wave shape point of view.

$$V_{R\,max} = I_{max}R$$
$$= I_{RMS}(R)/0.707$$
$$= (1)(30)/0.707$$
$$= 42.43 \text{ V}.$$

$$V_{L\,max} = I_{max}X_L$$
$$= I_{RMS}(X_L)/0.707$$
$$= 1(40)/0.707$$
$$= 56.58\text{ V}.$$

It is known that the current and voltage are exactly in phase for the resistor and that the voltage across the inductor **leads** the current by 90°. Assuming that the current is a sine wave, the resistor voltage, v_R, is a sine wave as well, Figure 5.13.

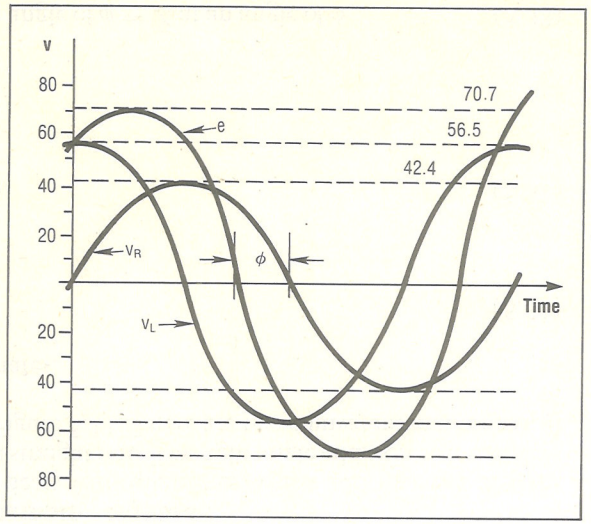


Fig. 5.13. Waveshapes for Example 5.8.

Kirchoff's Voltage Law applies at every instant of time, and so total voltage E must be the instantaneous sum of the resistor voltage and the inductor voltage, that is

$$\bar{E} = v_R + v_L. \tag{5.35}$$

The totally applied voltage curve, labeled e, Figure 5.13, was determined by graphically adding resistor voltage v_R to inductor voltage v_L. From this crude construction, it can be estimated that

$$\bar{E} = v_R + v_L,$$
$$\cong 70\sin(\omega t - 50°).$$

In more precise terms:

$$= 42.43\sin(\omega t) + 56.58\cos(\omega t).$$

There is a trigonometric identity of the form:

$$A\sin(X) + B\cos(X) = (A^2 + B^2)^{1/2}\sin(X - \phi), \tag{5.36}$$

where

$$\phi = \tan^{-1}B/A \tag{5.37}$$
$$= \tan^{-1}56.58/42.43$$
$$= 53.13°.$$

Now

$$42.43\sin(\omega t) + 56.58\cos(\omega t)$$
$$= [(42.43)^2 + (56.58)^2]^{1/2}\sin(\omega t - \phi),$$

so

$$e = 70.7\sin(\omega t - 53.13°),$$

the final results. Compare this with the graphical estimate reached earlier.

Note that the peak applied voltage is 70.7 volts, which means that the RMS voltage, $(0.707)E_{max}$, is 50 volts. Now, it can be said that the applied voltage of 50 volts RMS leads the current of 1 amp RMS by 53.13°.

Further understand that the same conclusion can be reached if the

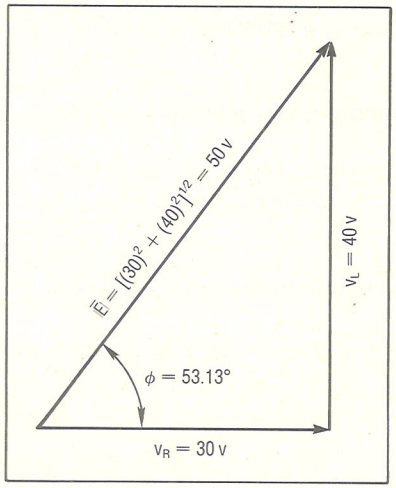


Fig. 5.14. The addition of complex voltages, that is 30 + j40, implies a right triangle with a hypotenuse of 50 volts at an angle of 53.13°. The angles in the triangular interpretation correspond exactly with the phase angles that would be seen if they were observed on an oscilloscope.

RMS values of resistor voltage and inductor voltage are treated as legs of a right triangle, Figure 5.14. This is much simpler than having to add sine and cosine waves and sketch complicated wave shapes.

In the general case, if we recognize that the resistor voltage is IR and the inductive voltage is IX_L, the two voltages add at right angles. Thus, a right triangle, Figure 5.15, can be sketched:

$$|\bar{E}| = [(IR)^2 + (IX_L)^2]^{1/2}, \tag{5.38}$$

and

$$\phi = \tan^{-1} X_L/R. \tag{5.39}$$

Observe that the hypotenuse of the voltage triangle, $|\bar{E}|$, contains a common current term that can be factored out:

$$|\bar{E}| = [(IR)^2 + (IX_L)^2]^{1/2}$$

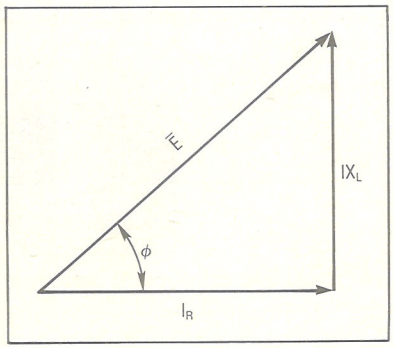


Fig. 5.15. The voltage across the inductor, IX_L, and the voltage across the resistor, IR, add at right angles, that is, $E = IR + jIX_L$, which forms this right triangle.

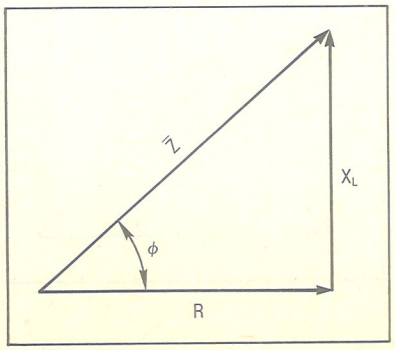


Fig. 5.16. The concept of impedance, $\bar{Z}$, develops when factoring the current out of Equation (5.37). The result is a right triangle formed by resistance R along the real axis and inductive reactance, X_L, in the imaginary direction.

$$= [I^2(R^2 + X_L^2)]^{1/2}$$
$$= |\bar{I}|(R^2 + X_L^2)^{1/2}. \tag{5.40}$$

Now R and X_L are legs of the impedance right triangle, Figure 5.16, where the hypotenuse

$$|\bar{Z}| = (R^2 + X_L^2)^{1/2}, \tag{5.41}$$

and Equation (5.39) remains applicable.

Or given in the rectangular coordinates of complex algebra notation:

$$\bar{Z} = R + jX_L, \tag{5.42}$$

where R is the real part and jX_L is the imaginary part and the notation implies a right triangle. $\bar{Z}$ is called the complex impedance of an R/L circuit and this last equation contains the value of the impedance needed to solve R/L circuit problems including phase and magnitude.

Now for an R/L circuit, Ohm's Law is:

$$\bar{E} = \bar{I}\bar{Z}$$
$$= \bar{I}(R + jX_L), \tag{5.43}$$

where it must be recalled that

$$X_L = 2\pi fL.$$

The circuit, of course, must have R in series with X_L, Figure 5.17, where

$$\bar{E} = \bar{I}(R + jX_L).$$

The idea can be extended to R/C circuits as well, remembering that the complex operator carries a negative sign, Figure 5.18. That is, R and $-jX_c$ are legs of a right triangle where the hypotenuse

$$|\bar{Z}| = (R^2 + X_c^2)^{1/2}, \tag{5.44}$$

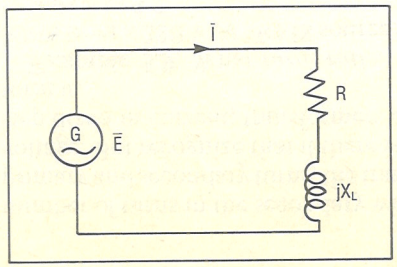


Fig. 5.17. Series R/L circuit.

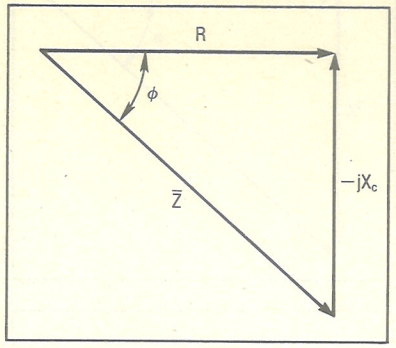


Fig. 5.18. Impedance triangle for a series R/C circuit.

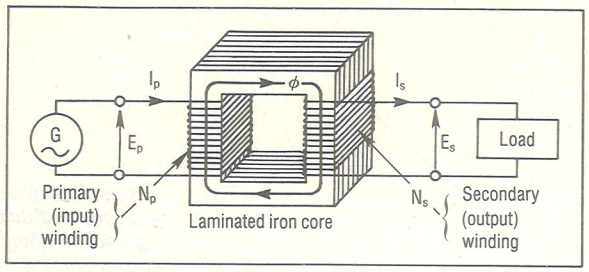


Fig. 5.19 Simplified construction diagram of an iron-core transformer with a single winding primary and a single winding secondary.

and

$$\phi = \tan^{-1} - X_C/R. \tag{5.45}$$

Transformers

Transformers consist of two coils whose only linkage is the magnetic flux flowing through their common iron core, Figure 5.19. Primary voltage E_p, (RMS value of an alternating source) and its associated primary AC current I cause a flux ϕ in the iron core which links to the secondary winding. Because the flux is changing, there is a voltage induced into the secondary winding. If the secondary is connected to a load, secondary current I_p results. The voltage and current relationships (given without proof) are:

$$E_p = E_s(N_p)/N_s \tag{5.46}$$

and

$$I_s = I_p(N_p)/N_s, \tag{5.47}$$

whe N_p is the number of turns in the primary winding and N_s is the

number of turns in the secondary winding. By controlling the number of primary and secondary turns, the transformer can step up or step down the voltage. But recognize that if there is a step up in voltage, there must be a step down in current; transformers do not create power, they only transform it.

Example 5.9. What *turns ratio*, N_p/N_s is needed to supply 24 V AC RMS from a 220 V AC RMS source?

Solution 5.7.

$$\begin{aligned} N_p &= E_p(N_s)/E_s \\ &= 220/24 \\ &= 9.17 \text{ turns/turn.} \end{aligned}$$

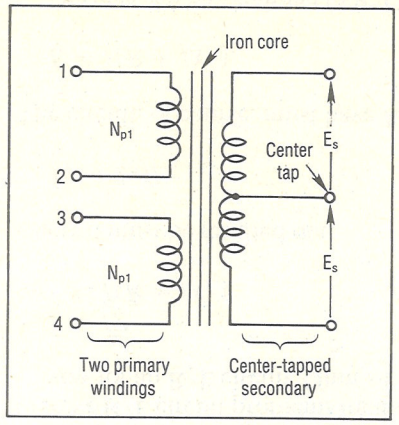


Fig. 5.20. Schematic diagram of a dual primary, center-tapped secondary transformer.

Commercial transformers come in a large variety of current and voltage ratings and in an equal variety of winding configurations and numbers. Two primary windings, Figure 5.20, are provided so the user can connect the windings in series for 230-V operation, or in parallel for 115-V operation. In either case the same secondary voltage is maintained.

This example is only for illustration. Each transformer must be approached individually. Some manufacturers print the required connection scheme on the transformer nameplate for quick reference.

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Chapter Six
Diodes, rectifiers, and power supplies