# ELECTRONIC ECONOMIZERS FOR COIL POWER (FOR FAILSAFE CONTACTORS)

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## 1.0 INTRODUCTION

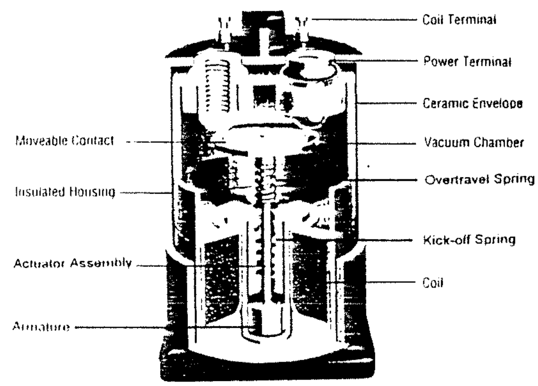
Power losses in the failsafe contactor during the steady state are caused by resistance in the contacts and coil. Since power contactors function as power throughput devices, the ideal contactor incurs no losses. Customer expectations are approaching ideal power switch limitations for applications including electric vehicle, battery packs, solar power systems, high performance military and aerospace equipment. Customers also demand small size and low weight. For power switching applications, the failsafe contactor is preferred since it always goes to (or stays in) the open position when coil power is removed. However, in the closed contacts position, coil power must be maintained in order to keep the contacts from opening.

Therefore, minimizing failsafe contactor coil power dissipation while the contacts are closed has preoccupied the invention of many contactor designers. The conventional approach to coil power conservation utilizes the cut-throat coil scheme, an effective, but mechanically sensitive and complex arrangement. The economizing schemes presented in this report are solid state electronic coil power controllers. *The circuits were designed not only to conserve coil power, but to enhance the mechanical performance and reduce the size of linear actuators for Kilovac's line of high voltage direct current aerospace contactors.* Kilovac's Czonka contactor, a 270 Vdc, 150A carry / 500A rupture rated device is used as a model to compare and demonstrate the electronic economizer schemes described here in. The electronic economizer circuits progress from a simple solid state version of the venerable mechanical cut-throat scheme to a completely closed loop electronic current source that compensates for coil temperature change and source voltage fluctuations. Figure 1.0 depicts a cut away illustration of the Czonka contactor. Within the contactor housing, space is allocated for the hybrid circuit implementation of the electronic economizers.

FIGURE 1.0

CZONKA CONTACTOR CUT-AWAY DRAWING

(2.5" x 2.5" x 4.5")




## 2.0 BACKGROUND

Contactors are designed to operate when subject to specified adverse operating conditions. The typical worst case scenario requires the contactor to operate when the coil voltage applied is at its low limit and the ambient temperature is at its high limit, which increases coil resistance. From a conventional contactor design standpoint, the result is typically a contactor designed to reliably, but barely, operate under worst case conditions. This however, results in excessive coil power dissipation under nominal conditions.

## 2.1 COIL POWER LOSS

The Czonka contactor without a coil economizer amply demonstrates the conventional contactor design dilemma alluded to in the previous section. The worst case operating condition specifies the continuous current test (150A rated current) at high altitude (80,000 feet) and high temperature ($85^{\circ}$C). The contactor must be able to operate and switch power when subject to this test criteria. From experimental data under these conditions, the coil can rise to $45^{\circ}$C above the ambient temperature. Given that the coil voltage can be as low as 23 Vdc (for the nominal 28Vdc system), the resulting magneto motive force (MMF), for the contactor's actuator coil is given in equation 2.1.1:

Eq. 2.1.1: $MMF = [(V_S)(N)]/R_C$ units =AT

$V_S$ = coil voltage
N = coil turns
$R_C$ = coil resistance

The MMF applied establishes the maximum work that a given actuator can do over its displacement, a fact that will be discussed in more detail later. For the moment, Eq. 2.1 shows that MMF of a given coil decreases with decreasing Vs and also decreases as Rc increases, Under worst case operating conditions, the effect of lower source voltage and higher coil resitance (due to high temperature) combine to drastically reduce coil MMF compared to the nominal case.

Furthermore, coil power is related to coil MMF by square law:

Eq. 2.1.2: $P_{coil} = [(MMF^2)R_C/N^2]$

OR $P_{coil} = V_S^2/R_C$

The result of Eqs. 2.1.1 and 2.1.2 is an unfortunate predicament. High power dissipation and coil MMF are manifest under nominal conditions when Vs is high and Rc is low. In contrast, under worst case conditions, the power dissipation is reduced since Vs is low and Rc is high, however, the MMF is reduced also. For the conventional contactor design, it's the high temperature, low source voltage combination that determines the effective work potential of the actuator. Excess work potential available because of high power and MMF under nominal conditions cannot be utlilized.

Table 1.0, line 1 summarizes the worst case condition described above. Line 2 indicates the factory nominal pickup voltage setting which allows operation when subject to worst case conditions. Line 3 demonstrates the typical field service conditions when the coil source voltage, resistance, and temperature are nominal. Power dissipation under nominal conditions is 15.1W, a 3 fold increase over the actual power that will close the contacts, as indicated in line 2. Addressing this coil power dissipation loss is the impetus for coil economizer schemes.

## 2.2 IRON CORE SATURATION

The dynamics of the typical electro-magnetic actuator favor the opportunity for coil power reduction subsequent to armature movement and positioning in the closed position. Figure 2.2 shows the Czonka mechanical spring design superimposed on the family of force vs travel curves of its solenoid actuator [1]. First, note that

TABLE 1.0
COIL MMF & POWER FOR VARIOUS CONDITIONS

| OPERATING CONDITION | COIL TEMP (°C) | COIL RESIST (OHMS) | COIL VOLT[1]. (VOLT) | COIL MMF (AT) | COIL PWR (W) |
|---|---|---|---|---|---|
| WORST CASE<br>CONTINUOUS CURRENT. HIGH TEMP & ALTITUDE | 130 | 76.0 | 23.0 | 785 | 7.0 |
| PICKUP SETTING<br>PICKUP SETTING ALLOWING WORST CASE OPER. | 25 | 54.6 | 16.5 | 787 | 5.2 |
| TYPICAL OPERATE<br>NOMINAL FIELD CONDITIONS ENCOUNTERED | 25 | 52.0 | 28.0 | 1400 | 15.1 |

NOTES: 1. NOMINAL COIL VOLTAGE = 28 Vdc

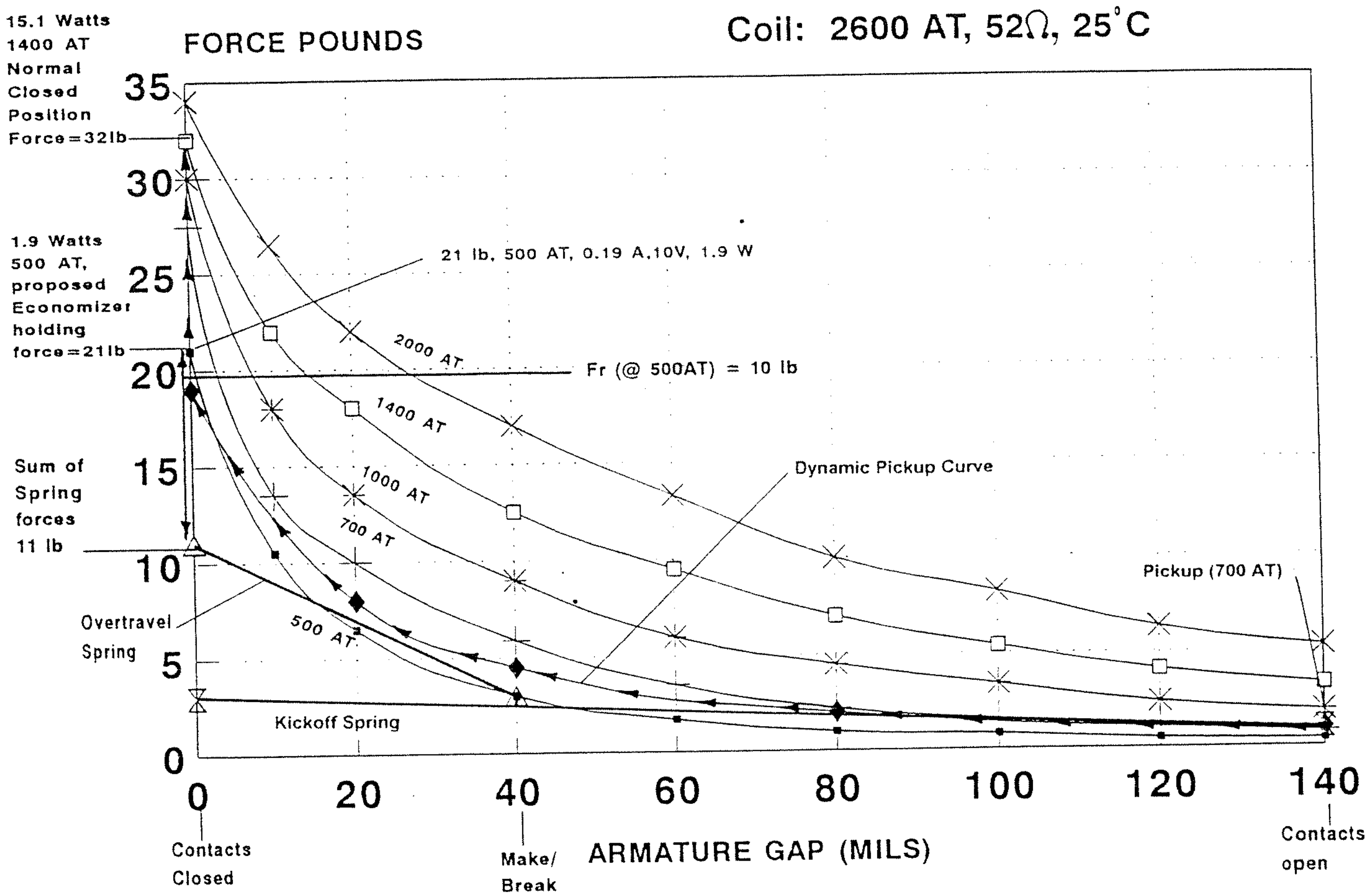
pickup is set at the open contacts position at the intersection of the 700 AT curve and the kick-off spring curve. This satisfies the pickup setting targeted in Table 1.0 The actuator closing under dynamic conditions, travels along the arrow path to the closed position. In the fully closed position, the force of the actuator far exceeds the opposing force of the spring loads once the coil current has reached the steady state. Convergence of the family of actuator force curves in the closed position is evidence of iron core saturation effects. Since the closed actuator's iron magnetic circuit is partially saturated with full voltage applied (28 Vdc applied to 2600 Turn, 52 Ohm coil yields MMF = 1400AT), a reduction in MMF, to say 500 AT, leaves plenty of reserve force ($F_r$), as indicated. Saturation effects in the closed contacts position is the key condition that coil economizing schemes exploit.

## 2.3 COIL POWER VS MMF

The essential contactor design is illustrated in Figure 2.2, the Force vs. Travel characteristic for the Czonka contactor. The contacts closed position on the left represents the contactor's ON state. Getting back to the OFF state (on the far right) requires springs that are designed such that their combined repulsion force falls beneath the pickup MMF curve, in this case the 700 AT. The area under a given MMF curve is the maximum work potential of the actuator going from the open to closed position [1]. The area under the spring curves is the energy stored on the springs that facilitates the cycle completion from closed to open when coil power is removed. For contactors, it is desirable to maximize stored spring energy so that the contact force is maximized (which favors low contact resistance) and to maximize overtravel (which compensates for contact erosion and provides the energy to break contact welds when hot switching). More system energy can be extracted only when a given actuator is operated at a higher MMF. However, increasing the MMF even moreso increases the coil power required. In a given coil, the number of turns is fixed, so MMF can only be

# FIGURE 2.2

# CZONKA ACTUATOR FORCE VERSUS TRAVEL CURVES [1]




increased by increasing the coil current (MMF = $N(I_0)$). But increasing coil current ($I_0$) impacts coil power dissipation by square law ( $P_{coil} = (I_0)^2 R_C$), a point amply demonstrated in Table 1.0:

## 2.4 ILLUSTRATING ECONOMIZING POTENTIAL

Utilizing Figure 2.2, let's say the designer wants to take advantage of the work potential available at 1400 AT instead of the existing design which operates at 700 AT. The increase in work potential can be evaluated by comparing the area under the force curves [1]. Numerical integration is employed here. The work potential over the 140 mil travel of the actuator at 700 AT is calculated to be 90 mJ requiring 3.8 W of steady state power dissipation using the coil specified in Table 1.0.

However, to compensate for the possibility of sagging source voltage at high temperature, and allowing for coil self heating, the nominal coil power at 25°C is actually 15.1 W. Now, the area under the 1400 AT force curve represents an energy potential of 172 mJ, nearly double that at 700 AT, however, the power dissipation is quadrupled to 15.1 W, a high price to pay. But even worse, to provide operation under worst case conditions for a nominal 1400 AT pickup, 30 to 50 W of power are required, in this case, enough power to damage the coil if sustained indefinitely, not to mention the load it puts on the user's coil driving voltage source. However, coil economizers allow the designer to take advantage of the actuator's work potential during the open to closed stroke. Once the magnetic circuit is closed, core saturation is exploited. The economizer then substantially reduces the coil current to establish a safe holding MMF. The coil current reduction results in radically reduced coil power dissipation in the steady state (Figure 2.2 proposes a coil power reduction from 15.1 W to 1.9 W for the existing Czonka contactor). The end result is a more effective, compact actuator with minimal power dissipation [2].

## 3.0 THE CONTACTOR ACTUATION CYCLE

Employing the axiom that a picture is worth 1000 words, the scheme and performance of each economizer circuit is illustrated with a schematic block diagram and an oscilloscope plot of the typical operating cycle from open to closed to open again. The operating cycle plots are particularly instructive in that they show the real time relation between coil current, armature position, and power contact state. In the appendix, the theory and design particulars for each economizer scheme is thoroughly discussed with references to its electronic circuit and timing diagrams. The more sophisticated electronic economizers also have oscilloscope plots which demonstrate compensation for source voltage sag and temperature, topics also discussed in depth in the appendix.

## 4.0 CONTACTOR CYCLE WITHOUT ECONOMIZER

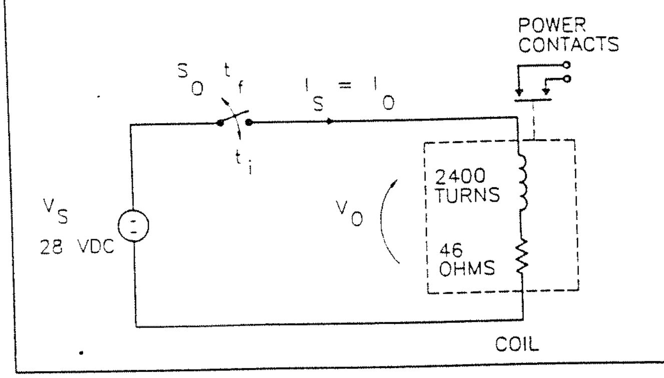
In order to prepare a basis for comparison, the contactor performance is first demonstrated with the non-economized, existing Czonka contactor operating directly from a 28 Vdc source. The electrical circuit is given in Figure 4.0. Energizing the coil by closing switch $S_0$ at time $t_i$ excites the coil, subsequently actuating the contactor from the open to closed position. Opening $S_0$ at time $t_f$ de-energizes the coil, opening the contacts.

### 4.1 OPERATING CYCLE

Figure 4.1 illustrates the typical operating cycle showing simultaneously the armature position, the state of the power contacts, and the coil current. 28 Vdc is applied at $t_i$. The coil current rises exponentially governed by the $L_C/R_C$ time constant of the coil. When the coil MMF reaches the pickup MMF (700 AT) the armature begins moving, generating a back EMF which increases with the velocity of the armature. Total armature displacement from open to closed (140 mils) occurs in about 5 ms. 40 mils from the closed position the power contacts make and continue to bounce for about 3 ms, long after the armature first contacts its fully closed position 1 ms after first make. Because the back EMF reduces the coil current during armature motion, when the armature reaches the closed position coil current $I_0$ is less than when the motion started, as indicated by the coil current dip during the pickup motion. The armature impacts the actuator's stator with enough kinetic energy and mechanical elasticity to cause the armature to recoil back, as is clearly indicated in the armature position dip. Armature recoil is an undesirable effect which is manifest when the stator's magnetic force acting to hold the armature is overwhelmed by the natural response of the armature/spring assembly impacting the stator with excessive kinetic energy and elasticity. Ramifications include increased actuator wear and frequently, longer contact bounce. It is worth noting that the armature recoil duration is marked by the second hump in the coil current response, making identification of this phenomenon easy.

FIGURE 4.0

SCHEMATIC, STANDARD CZONKA, NO ECONOMIZER




Total pickup time, including bounce, is 24 ms. Most of the delay is electrical. Actual steady state coil current is not achieved until more than 60 ms have elapsed. Subsequently coil power dissipation is 16 W, far in excess of what is required to hold the contacts closed, as described in section 2.2.

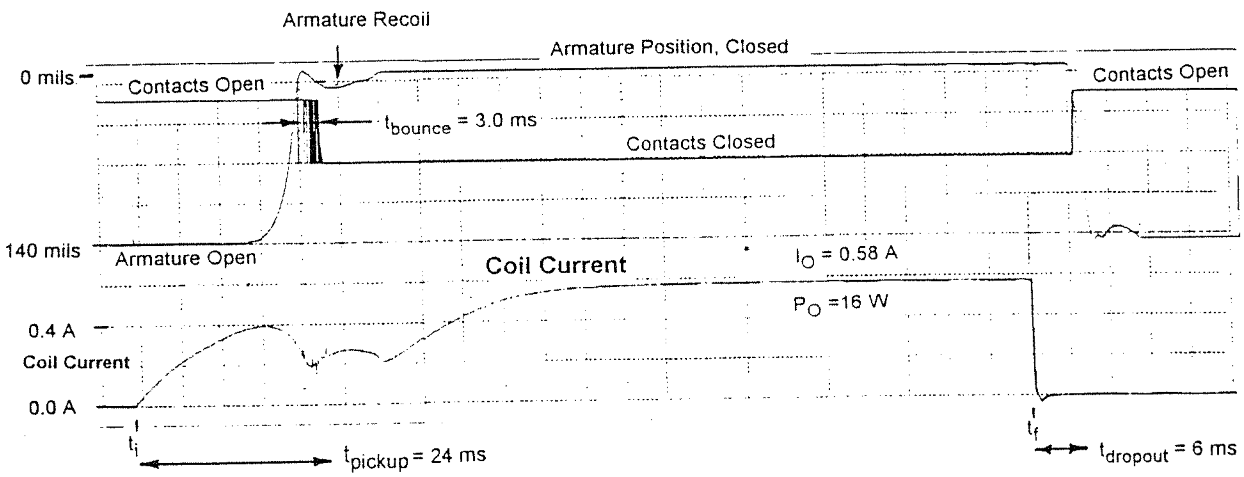
Completion of the cycle is initiated at $t_f$ when coil power is cut-off. Coil current rapidly decays in less than 1 ms facilitated by opening actuation switch $S_0$ (see figure 4.0) which provides a high impedence in series with the coil, reducing the coil current loop time constant. However, substantial mechanical motion is largely constrained for about 5 ms. The armature opening action is faster than the closing action because a majority of the work extracted during the closing cycle is stored in the kick-off and overtravel springs which release energy together to generate the opening motion. The opening motion transition is completed in 2.5 ms, with the contacts opening after 1 ms. (that is, 40 mils of travel as indicated in Figure 2.2). Total dropout time is 6 ms. Armature recoil occurs at the end of the cycle when the armature plunger impacts the bottom of its housing. Modest recoil from this position does not manifest any harmful consequences.

In summary, the standard Czonka contactor operating

FIGURE 4.1

TYPICAL OPERATING CYCLE WITHOUT ECONOMIZER

(HORIZONTAL SCALE: 5 ms / DIV)




cycle brings to light some interesting issues. First coil MMF is minimal during the pickup motion, contributing to armature recoil. Secondly, mechanical armature motion for both the opening and closing cycle is fast compared to the respective coil current response. Finally, the coil power in the steady state is clearly excessive, producing MMF that never gets a chance to produce work from the actuator because actuator motion is completed long before the coil current reaches the steady state.

## 5.0 TIMER WITH 2 COILS ECONOMIZER

The Timer with 2 Coils (T2C) economizer builds on the long established cut-throat coil economizer concept. Figure 5.0 shows the circuit schematic for the Czonka contactor employing the T2C economizer. The economizer is positioned for power control between the coil voltage source and the contactor coils. In this scheme, the standard Czonka coil is replaced by two parallel wound coils on the same bobbin as the original coil. The power coil (Pcoil) is employed only during the pickup interval, and is activated through solid state transistor switch $S_1$ for a preset interval which safely exceeds the maximum operate time. $S_1$ is activated by the controller only if the source voltage that is applied through $S_0$ is determined to be of sufficient magnitude. The holding coil (Hcoil) is always connected. Although it is unable to actuate the contactor by itself, it aids the Pcoil during pickup. After the contacts are closed and the Pcoil is shut off, the Hcoil remains on, supplying sufficient coil MMF to keep the contactor closed at significantly reduced power dissipation.

## 5.1 T2C, TYPICAL OPERATING CYCLE

Figure 5.1 shows the typical operating cycle for the Czonka contactor employing the Timer with 2 Coils economizer circuit. When 28 Vdc source voltage $V_S$ is applied to the economizer circuit at $t_i$, the control circuit allows both coils to operate in parallel, yielding an energetic pickup interval (2060 AT, 28 W). The operate time is reduced by 33% and the troubling armature recoil phenomenon is subdued by the added force generated by the increased MMF. The Pcoil remains on for an interval 5 times the normal operate time, a safety margin provided for high temperature, low source voltage conditions. At $t_{delta}$ (=100 ms) the Pcoil is timed out softly, leaving only the Hcoil in the circuit. MMF is reduced to 570 AT, and power supplied by Vs is reduced to 6.0 W during the remainder of the closed contacts portion of the cycle. When coil voltage is removed by opening control switch $S_0$ at time $t_f$, coil current rapidly decays resulting in fast, energetic dropout.

## 5.2 SUMMARY REMARKS, T2C ECONOMIZER

Functional simplicity is the benchmark established by the T2C economizer. It eliminates the mechanical complexity and sensitivity of auxiliary contacts required for the mechanical cut-throat coil power economizer from which it was derived. It maintains power to the Pcoil for the entire armature stroke, whereas the mechanical cut-throat scheme cuts off the Pcoil just before armature motion is completed, a contributing factor to its sensitivity, and often its delinquency. Coil power savings

FIGURE 5.1

TYPICAL OPERATING CYCLE, TIMER w 2 COILS

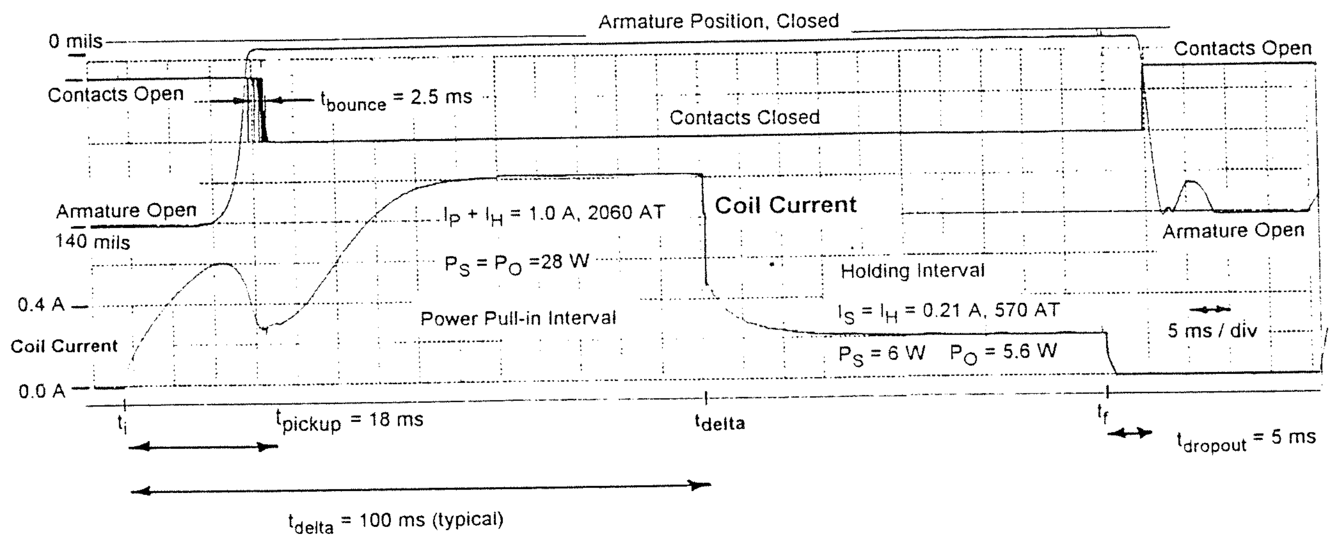
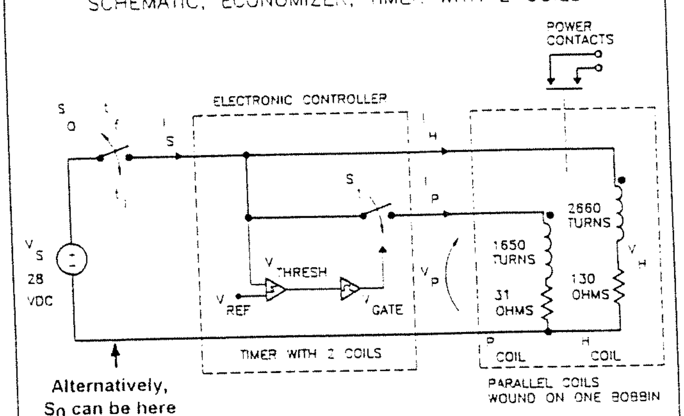



FIGURE 5.0

SCHEMATIC, ECONOMIZER, TIMER WITH 2 COILS




are substantial, combined with an enormous gain in actuator work output potential. Some complexity and cost are still manifest in the 2 coil design wound on a single bobbin. Also, because neither increased ambient temperature nor sagging coil voltage are compensated for, the MMF of the T2C holding coil must be, under nominal operating conditions, higher than what could be if the economizer had the means to compensate for changing conditions. The subsequent coil economizers demonstrate more sophistication, addressing these problems.

## 6.0 VOLTAGE CONTROLLED CHOPPER ECONOMIZER

A transistor functioning in the switch mode provides the foundation for the Voltáge Controlled Chopper (VCC). Figure 6.0 shows the schematic of the VCC controlled contactor. The transistor operating in the switch mode is represented by $S_1$. Make note of the simple coil with lower resistance (21 Ohms, 1600 Turns) than the coil used for the standard Czonka contactor without an economizer (52 Ohms, 2600 Turns). When $V_S$ is first applied through $S_0$, the controller verifies that $V_S$ is of sufficient magnitude, then it produces a gate which closes $S_1$ for an interval long enough to insure pickup. Energetic action is guaranteed by the low resistance coil. Subsequently, the controller begins switching $S_1$ on and off at a frequency far exceeding the roll off frequency of the coil, rationing pulses of energy that sustain coil current at a much lower holding level proportional to the switching duty cycle $[t_{on}/(t_{on}+t_{off})]$. Power conservation is achieved by the complementary effect of lower average source voltage and the resulting lower current. During $S_1$'s on time ($t_{on}$), power is supplied by $V_S$; during $S_1$'s off time ($t_{off}$), coil current is sustained through D5, a free wheeling diode, the energy being supplied by the magnetic field of the actuator. When the contactor is shut off via $S_0$, $S_2$ opens also, providing a high impedence to the coil, insuring rapid coil current decay and quick dropout time.

FIGURE 6.1

TYPICAL OPERATING CYCLE, VOLTAGE CONTROLLED CHOPPER

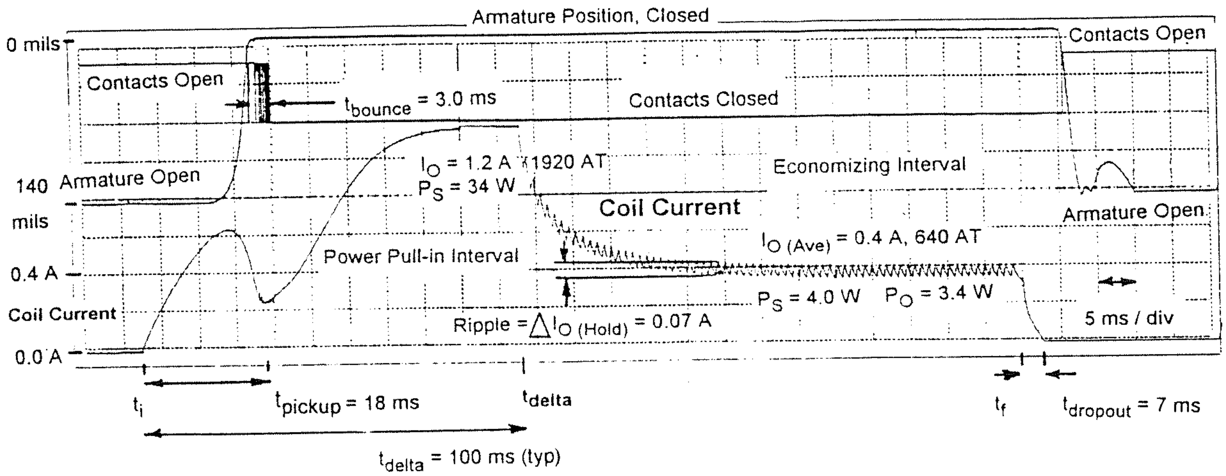
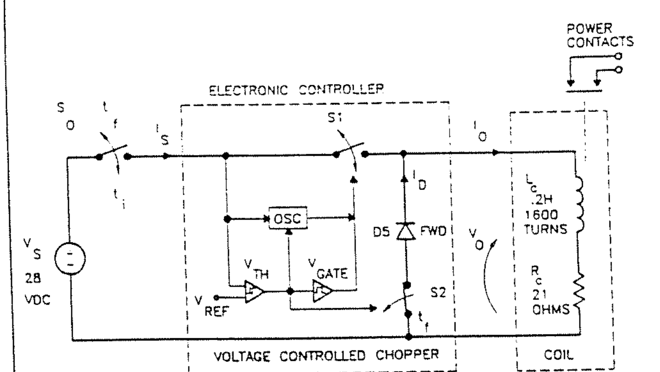



FIGURE 6.0

SCHEMATIC, ENCONOMIZER, VOLTAGE CONTROLLED CHOPPER



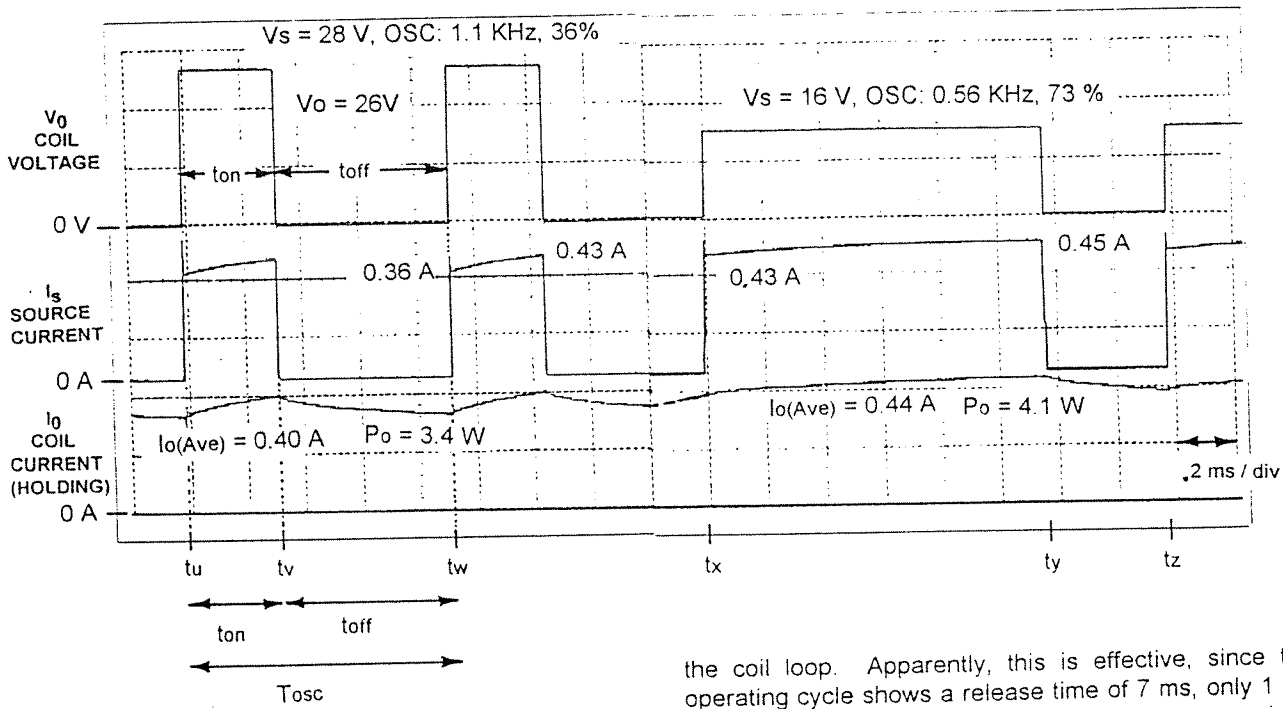

## 6.1 VCC, TYPICAL OPERATING CYCLE

At first glance, the operating cycle for the VCC economizer illustrated in Figure 6.1 looks similar to the cycle for the T2C timer shown in Figure 5.1. In fact, the VCC uses the same threshold detector and a similar gate generator so that the low resistance coil recieves full source voltage during the pickup interval, By the end of the pickup interval, coil MMF is 1920AT and the power supplied is 34W. After pickup, the controller switches into the economizer mode, at time $t_{delta}$, and starts chopping the source voltage, the results of which are readily apparent in the sawtooth shape of the coil current signal. In a few coil time constants ($T_{coil} = L_C/R_C$), the holding current decays to a steady holding level resulting in a holding MMF of 610 AT with coil power dissipation of only 3.4 W. The sawtooth current shape, an alternating current component, is the result of the chopping action of the source voltage, rising when source voltage is momentarily applied, falling during the interval when the $V_S$ is cut off and the collapsing actuator magnetic field sustains the coil current [6]. The holding current sawtooth variation is minor compared with its average value, so the actual holding MMF is essentially the average of the holding current multiplied by the coil turns. Although the holding current for the VCC is twice as high as that of the T2C economizer, holding power is much reduced because of the low average voltage supplied from the source through the chopper.

The VCC can supply more MMF for less power than the T2C, or for that matter, any conceivable cut-throat economizer, because the VCC uses the whole coil for economizing. Cut-throat systems dedicate only a fraction of the bobbin space for the holding coil. The rest of the space is idle while holding since it is occupied by the power coil which is only used during the pickup interval. The cut-throat holding coil, having less space and higher power, obviously heats up more, further affecting its holding MMF potential. Hence the secret to low holding power realized with the VCC economizer resides with its full utilization of coil bobbin space for both pickup and holding.

# FIGURE 6.3

COMPENSATION FOR SOURCE VOLTAGE SAG




But the VCC economizer has another crucial advantage. As its name implies - Voltage Controlled Chopper - it is designed to compensated for source voltage variations. Specifically, it increases its duty cycle when $V_S$ sags, thus maintaining essentially constant average voltage supply to the coil in the economizing mode. Hence a contactor with VCC economizing is subject to holding MMF variations caused only by temperature variations. The end result is that the safety margin built into the holding MMF can be further reduced. Excellent $V_S$ sag compensation is shown in Figure 6.3, an expanded oscilloscope plot simultaneously plotting coil voltage ($V_O$), source current ($I_S$), and coil current ($I_O$) as source voltage varies.. Here the VCC acting in the economizing mode keeps the coil current $I_O$ virtually constant as the source voltage $V_S$ sags from 28V to 16V by adjusting the duty cycle of the chopper.

The final act in the operating cycle, dropout, is normally increased with a chopper controller because coil current can decay slowly through the low impedance of the free-wheeling diode according to the long coil time constant. However, the VCC takes advantage of a simple $V_S$ sensing transistor, represented by $S_2$ in the schematic, to introduce a large impedence in series with the coil during dropout. This greatly reduces the time constant of the coil loop. Apparently, this is effective, since the operating cycle shows a release time of 7 ms, only 1 ms longer than the contactor without an economizer. Dropout voltage is set at 14 Vdc by the threshold detector described in the appendix.

## 6.2 SUMMARY REMARKS, VCC

Versatility makes a mark for the Voltage Controlled Chopper. It can readily retrofit into existing designs without changing the coil. For instance, the VCC has been operated with the original Czonka contactor and coil discussed in section 4. However, it would be prudent to take advantage of the actuator's work potential by using a "hotter" (lower resistance) coil as demonstated in this section. The VCC described here has a work potential equal to the T2C design, but dissipates significantly less power while achieving the same holding MMF. Compensation for sagging voltage is an outstanding feature which allows the holding MMF and power to be set at even lower levels. Some reserve MMF must be provided at nominal operating conditions to compensate for coil temperature rise due primarily to increased ambient temperature. The next, and last, economizer circuit presented in this report is a fully closed loop system, regulating coil current to an exact value regardless of drastic temperature changes and coil voltage sag.

FIGURE 7.1

TYPICAL OPERATING CYCLE, CURRENT CONTROLLED CHOPPER

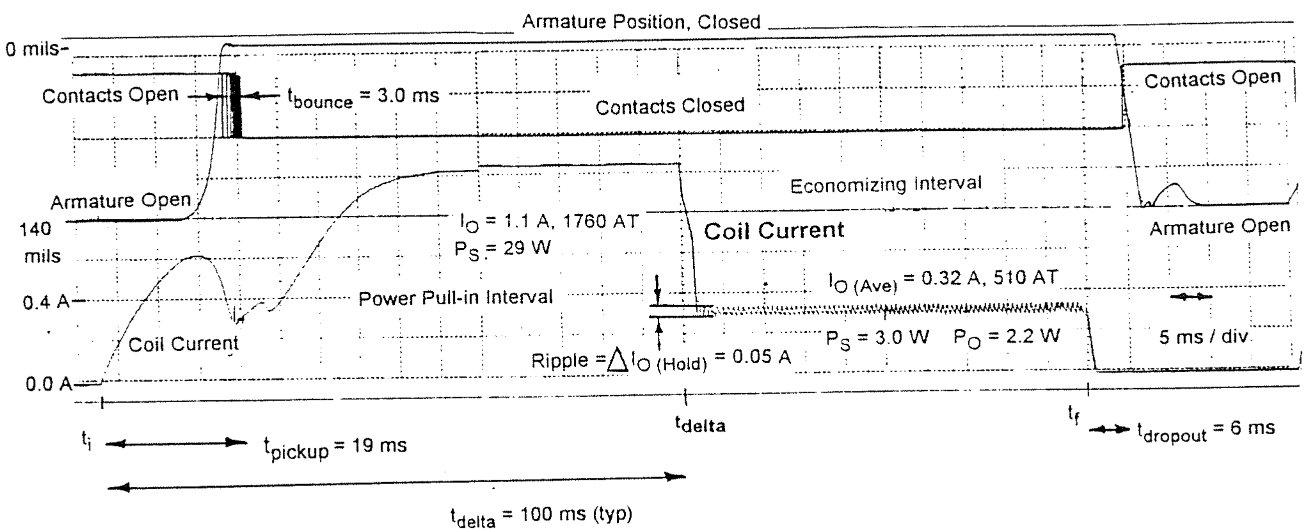
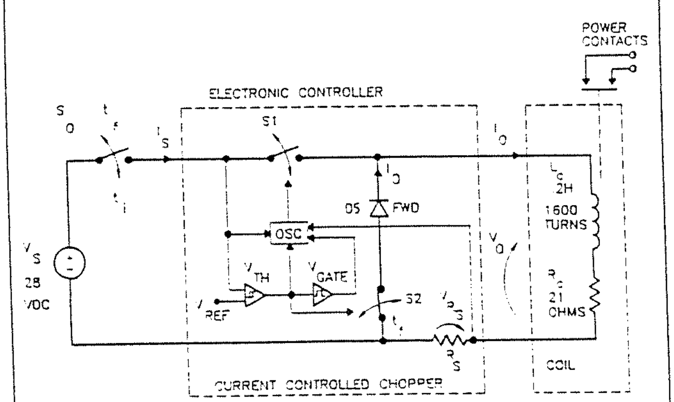



FIGURE 7.0

SCHEMATIC, ECONOMIZER, CURRENT CONTROLLED CHOPPER




## 7.0 CURRENT CONTROLLED CHOPPER ECONOMIZER

Switch mode power control with fully closed loop coil current regulation characterizes the function of the Current Controlled Chopper (CCC). Like the VCC economizer, its predecessor, it permits power pickup and steady state economizing with a single coil. However, a small current sense resistor $R_S$ (see Fig 7.0) provides current proportional feedback to the controller. During pickup, the controller operates identical to the VCC economizer. It monitors $V_S$, allowing pickup only if the source voltage is of sufficient magnitude. If so, $S_1$, the switching transistor, is turned on long enough to insure pickup. Subsequently, operation is handed off to the current controller which has a one track mind, that of maintaining constant, reduced, holding coil current. Switch mode coil current loops are identical to those presented in the VCC discussion given in Appendix B. The only difference in operation is the function of the power switching control oscillator. But first, take a look at the operation cycle, Figure 7.1.

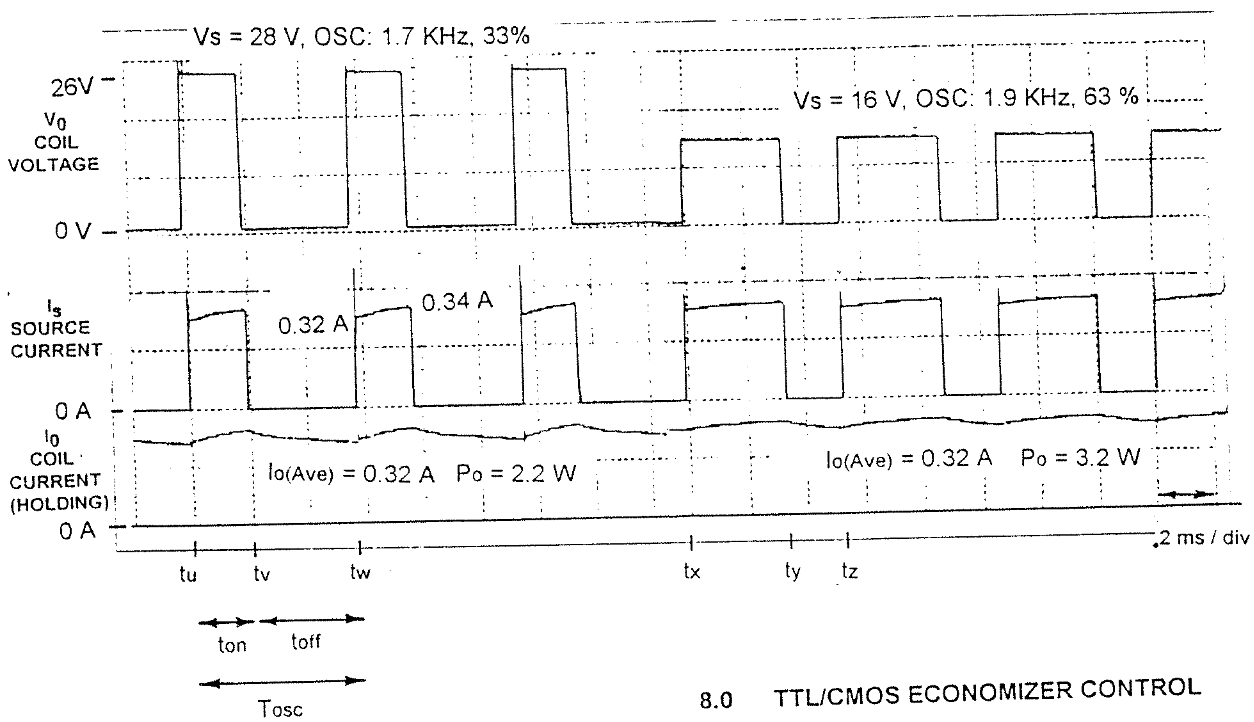
## 7.1 CCC, TYPICAL OPERATING CYCLE

At first glance, the operating cycle for the CCC economizer appears almost identical to the cycle for the VCC. Largely it is, however, an obvious difference is apparent right after the controller switches into the economizing mode at $t_{delta+}$. The coil current dives nearly vertically for its holding value, an action accomplished by the current controlled oscillator, upon being activated, reacting to what it sees as a serious over-current condition. This immediate, accurate compensation is indicative of absolute control afforded by the scheme.

Precise current control is not neglected at the expense of quick response. This assertion is amply illustrated in Figure 7.3 where coil current is maintained at exactly 0.32 A while the $V_S$ varies from 28 to 16 V. Furthermore, precise regulation is maintained even as the coil resistance changes with temperature since the current controlled oscillator regards only the current signal

# FIGURE 7.3

COMPENSATION FOR SOURCE VOLTAGE SAG
AND COIL TEMPERATURE RISE




relayed from $R_S$, a temperature compensated precision resistor.

Dropout is quick and energetic, courtesy of the fast dropout switch S2, a simple, but effective feature described for the VCC economizer.

## 7.2 SUMMARY REMARKS, CCC

Performance best describes the advantage of the Current Controlled Chopper. It's the only economizer capable of maintaining rock solid holding MMF regardless of coil temperature changes and source voltage variations. Because of this. the holding MMF can be established at a safe minimum without building in safety margins for high temperature and low source voltage. Although the CCC's predecessor, the VCC compensates for sagging voltage, its not capable of addressing coil temperature. The temperature problem is one not to be taken lightly, considering that most coils use copper wire with a temperature coefficient of resistivity of +39%/100°C. However, performance champion that it is , the CCC lacks the versatility inherent in the VCC design because the insertion of the sense resistor Rs requires that it be sized accordingly for each coil/contactor application.

## 8.0 TTL/CMOS ECONOMIZER CONTROL

In modern power distribution and control systems, for which Kilovac's Czonka contactors can be an integral part, computers perform command and control. Computers control power contactors by signaling relay coil driver amplifiers on or off via small signal digital logic. The coil driver transistor circuit takes the place of switch $S_0$ shown in the schematics diagrams of this paper. However, a simple buffer amplifier enhancement to the electronic economizers enables the contactor to be controlled directly from a TTL, CMOS, or open collector logic signal. This freeing the system designer from the mundane task of designing a relay driver, a task better left to the contactor designer whose intimate knowledge of actuator energies and transients assist in the development of a robust driver. In this case, the driver and economizer are one in the same. Appendix D discusses a simple buffer driver configured from a spare comparator available in the existing economizer designs, making the contactor with a econmizer directly controllable from a computer output.

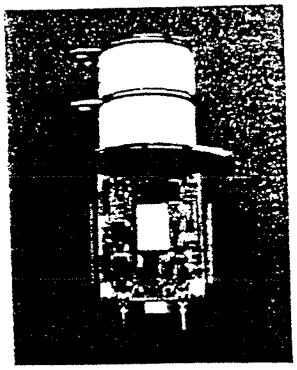
## 9.0 THE HYBRIDIZED ECONOMIZER CIRCUIT

Figure 9.0 shows a hybridized economizer circuit which, although different in function, is very similar in form to the economizer circuits described in this report. The

## FIGURE 9.0

## ECONOMIZER HYBRID CIRCUIT

(7/8" x 1" x 1/8")



NOTE: circuit shown implemented on Kilovac's K-44 Relay.

same comparator, circuit building blocks, and driver transistors are used in this adaptation. This shows that the hybridized economizer circuit is compact, easily accommodated within the Czonka contactor's housing.

### 10.0 ECONOMIZER PERFORMANCE COMPARISONS

Now that the presentation of three electronic economizer systems has been put forth, it behooves the designer to compare them on a level playing field. In the exercise which follows, all of the economizers are subject to the same environmental operating conditions.

In order to layout the designs for comparison, the worst case operating MMF must be determined with respect to the highest ambient temperature plus the additional increase in coil temperature due to self heating. Equation 10.0 describes a simple function for calculating Czonka's steady state coil temperature knowing the ambient temperature ($T_A$) and the coil power ($P_{coil}$). The formula is derived empirically from measured experimental data where the primary requirement is that the contactor is mounted to a heat sink which is also at $T_A$:

Eq. 10.0 $$T_{coil} = T_A + [4^oC/Watt][P_{coil}]$$

$T_{coil}$ = coil temperature in $^oC$
$T_A$ = ambient sink temperature in $^oC$
$P_{coil}$ = coil power in Watts.

Using Eq. 10.0, an iterative design process was conducted that, in the end, required an adjustment to the T2C economizer coil combination in order to provide more holding MMF because of the high temperature condition ($T_A$ = 85$^oC$) and the fact that the T2C cannot compensate for voltage sag like the chopper economizers do. In addition, it was determined that a more efficient coil could be had for the chopper economizers by filling the bobbin to capacity, as done for the other designs. Hence the chopper coil turns increased from 1600 to 1750 turns. The coil data is included in Table 10.0

Output parameters that largely determine efficacy for the failsafe actuator are work potential, (the area under the pickup MMF curve on the force vs travel characteristic) and power dissipation in the steady state after pickup [1]. These are precisely the characteristics that are vastly improved by employing electronic economizers. Table 10.0 compares the performance for each configuration. The column labeled "NONE" represents the standard Czonka contactor without an economizer. The test conditions are listed in Note 1 below Table 10.0.

### 10.1 NO ECONOMIZER

The Czonka contactor without an economizer performs well, but has room for enhanced performance currently limited by coil heating in the steady state which, as indicated in Table 10.0, rises to 45$^oC$ above ambient. Note also that work potential is far less and power dissipation is far higher than any of the economizers.

### 10.2 TIMER WITH 2 COILS

The Timer with 2 Coils (T2C) economizer was derived from the mechanical cut-throat concept to eliminate sensitive auxiliary contacts. The scheme also significantly increases the work potential of the actuator during pickup (Table. 10.0). While the T2C economizer eliminates the mechanical complexity of the cut-throat auxiliary contacts, it stops short of revealing performance improvements or any other simplifications not realizable with the plain mechanical cut-throat economizer, except that, like the other electronic economizers described below, it can be directly controlled from a small signal logic voltage (TTL or CMOS).

| TABLE 10.0 level field performance comparison[1] | CZONKA ECONOMIZER CONFIGURATION | | | |
|---|---|---|---|---|
| PARAMETER | NONE | T2C | VCC | CCC |
| COIL DATA<br>Turns (N)<br>Resist. 25°C (Ohm) | 2600<br>52 | 1300/2950<br>32/130 | 1750<br>21 | 1750<br>21 |
| POWER (WATTS)<br>Pickup: 28V, 25°C<br>Holding 23V, 85°C | 15.1<br>10.7 | 34<br>5.8 | 37<br>2.2 | 34<br>2.3 |
| WORK (mJ)<br>Pickup Potential<br>@ 23V, $T_A$ = 85°C | 107 | 171 | 168 | 163 |
| COMPENSATION for<br>Volt Source sag<br>Coil temp. change | NO<br>NO | NO<br>NO | YES<br>NO | YES<br>YES |
| TEMPERATURE<br>°C coil rise over $T_A$ | 43 | 23 | 9 | 9 |

NOTES:

1. Operating environment: = high altitude, continuous carry test: contactor mounted to a heat sink; ambient (including heat sink) temperature = 85°C; air pressure simulates 80,000 feet: contactor closed carrying rated current; contactor must pickup immediately after dropout with 23 VDC applied, where the nominal voltage is 28 VDC. Czonka (AP150X) contactor actuator used.

2. Economizer holding MMF set at 500 AT minimum for high temperature and low source voltage (23 V). The T2C economizer holding MMF will drop below 500 AT if Vs drops below 23 V. However, the VCC and CCC both compensate for voltage sag, and will maintain 500 AT until their preset dropout voltage of 14 V is reached.

## 10.3 VOLTAGE CONTROLLED CHOPPER

A giant leap forward is made with the Voltage Controlled Chopper (VCC), a switch mode power controller that automatically compensates for source voltage variations (sag being of particular interest here) in the economizing mode. The VCC uses only a single coil, a simplification and cost reduction not to be overlooked. Low coil power density is realized in the holding mode because the full bobbin/coil is utilized. Voltage compensation reduces the amount of reserve MMF, resulting in very low coil power dissipation in the holding mode, as indicated in Table 10.0. Notice also that the coil temperature rise above ambient is only 9°C, the result of low coil power dissipation. VCC economizing is extremely versatile. It can be directly retrofitted with existing coil/contactor assemblies, or it can be used in the work enhancement mode, as illustrated in Figure 10.0. The improvement in work potential, spring energies, overtravel, and holding power are obvious when compared to the standard contactor design given in Figure 2.2.

## 10.4 CURRENT CONTROLLED CHOPPER

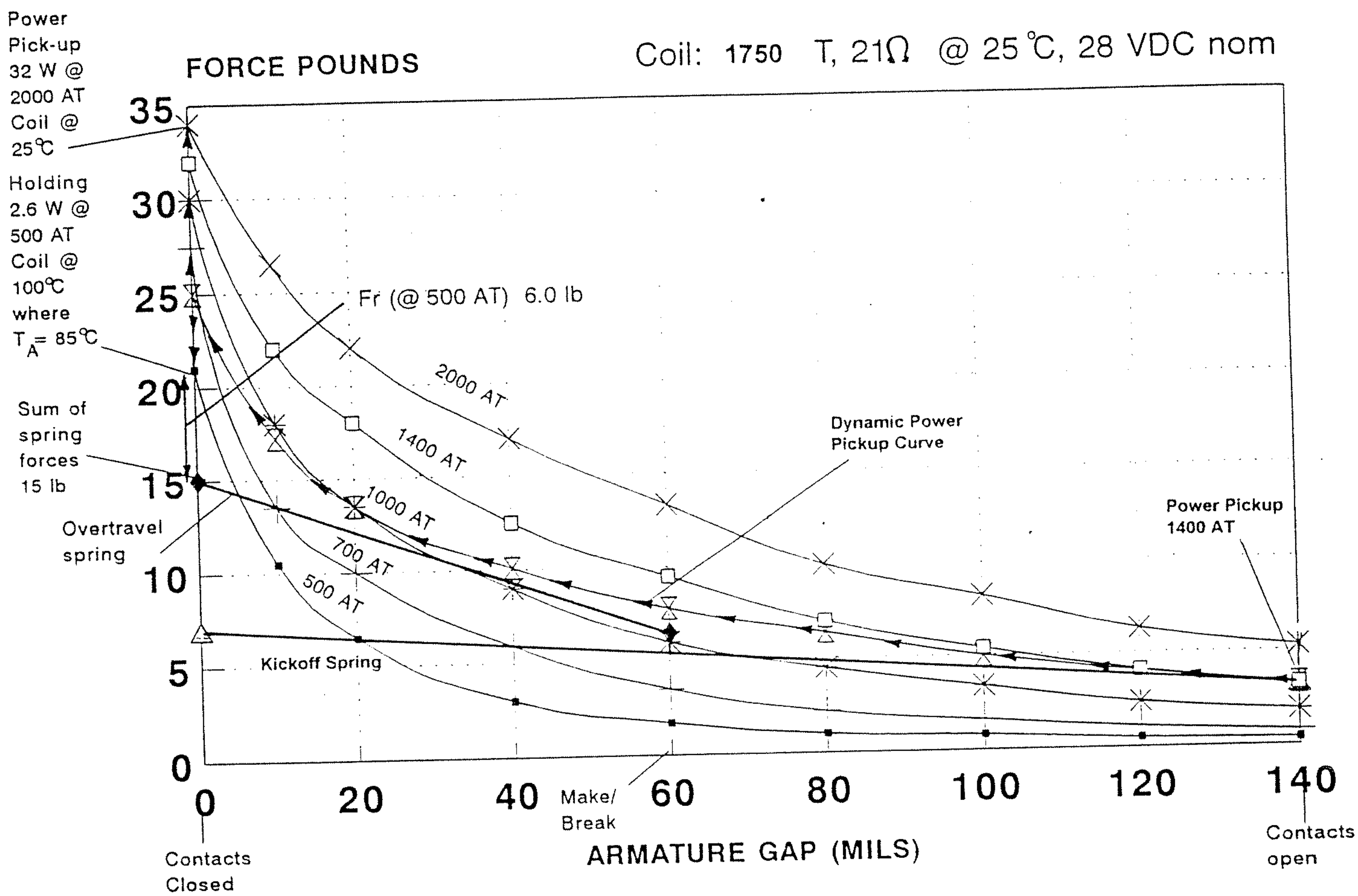
A further improvement in the switch mode controller is realized with the Current Controlled Chopper (CCC). This economizer works on the same principle as the VCC, except that it compensates for both source voltage variations and coil temperature by directly regulating the coil current. The CCC maintains exact coil current, thus precise MMF, in the holding mode. The CCC offers the best compensation for the widest range of adverse temperature conditions, including high and low temperature extremes. Table 10.0 indicates performance comparible to the VCC. But for low temperature extremes, power dissipation using the CCC actually decreases, a characteristic not found in the other schemes. For instance, power dissipation in the holding mode at -55°C is 1.4 W for the CCC versus 4.1 W for the VCC. However, the CCC suffers the requirement that a small precision resistor in series with the coil is needed to sense coil current. This makes it application specific in that a different current sensing resistor is necessary for each coil/actuator configuration. However, the CCC demonstrates its prowess by exactly controlling the parameter of interest, the coil holding MMF. For extreme ambient temperature variations, CCC economizing is the right choice.

## 11.0 CONCLUSIONS

Electronic economizers improve actuator performance in complementary ways. First, the economizers provide an energetic pickup interval. Hence a given actuator can do more work during the actuation cycle, significantly improving the force and energy available to provide essential contactor functions such as: high contact force; increased overtravel for electrical life; stiff springs for shock resistance; and energetic drqpout motion. Secondly, the economizer reduces coil power dissipation several fold after pickup, a benefit to the user who must supply coil power, not to mention the possibilities it suggests for the designer regarding reduced actuator size, weight, and heat dissipation problems. Thirdly, the chopper economizers compensate for source voltage and temperature variations. This combined with full utilization of a single coil allows the choppers to operate at holding power levels significantly lower than what's possible with the cut-throat schemes. Fourthly, the electronic economizers can be controlled directly from computer/digital logic signals, hence serving the dual function of a relay driver and an economizer. Finally, the electronic economizers eliminate all moving parts and the inherent sensitivity of the mechanical cut-throat

## FIGURE 10.0

# IMPROVED CZONKA ACTUATOR DESIGN USING VCC ECONOMIZER




mechanism.

This paper establishes the benefits, merits, and performance of three different, fully electronic economizer schemes. If the performance improvements alluded to here in could be realized by some mechanical means, or by way of a new magnetic material with wishful magnetic characteristics (unobtainium comes to mind) the relay industry would leap at the opportunity. This paper then, is a clarion call for electronic power control integration into the world of electro-mechanical contactors - a call long ago heeded in our big brother industry, electric motors. Hip-hip-economize!

## APPENDIX

### A.0 TOPICS

Theory and detailed description of the electronic economizer circuits is the subject of the appendices.

### A.1 T2C, ELECTRONIC CIRCUIT FUNCTION

All economizer circuits in this paper have control circuits based on the quad, LM339 voltage comparator integrated circuit [3]. This comparator operates from a single source (36 Vdc maximum) and features versatile open collector outputs. It's available in die form, a requirement for hybrid circuit implemention. External components determine the desired function of the individual comparators which are illustrated by triangles in the electronic circuits and are designated by the letter "A" followed by a single number (ex: A2). Solid state power transistors, which ultimately switch coil current, are designated by the letter "Q" followed by a single number (ex: Q1). For proprietary reasons, the values for external components which determine the comparator functions are not revealed. However, the operation of each economizer is thoroughly described including a review of the theory illustrated with timing diagrams.

It's important to note that all electronic economizers described in this report derive operating power from the source voltage ($V_S$) supplied through $S_0$, representing a coil power switch activated by the user. Hence the economizers see the same voltage supply as a contactor with a plain coil does. The circuits are designed specifically to operate whether a step or ramp voltage is supplied through $S_0$. In addition, the circuits will operate, as advertised, even if $S_0$ is located on the negative lead of the voltage source, rather than the indicated positive lead (for example, refer to Figure 5.0) In field applications $S_0$ is typically a transistor switch designed to apply essentially a step voltage. However, during factory production, quality assurance, and incoming inspection tests, it is standard practice to apply a ramp voltage to a contactor coil in order to set, test, or verify the pickup and dropout voltages, hence the requirement for ramp voltage operation.

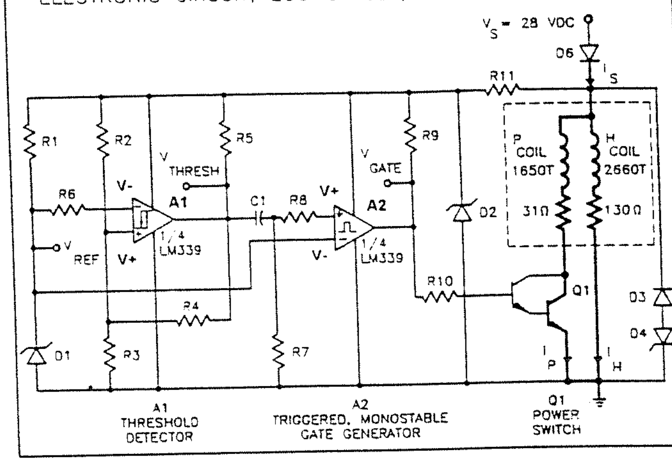
The simplest electronic economizer presented in this report, T2C circuit, is shown in Figure A.1. It bears striking resemblance to the well known mechanical cut-throat economizer system. The two main functional blocks found in the T2C circuit are also integrated into the more sophisticated economizers circuits described later.

## A.2 THRESHOLD VOLTAGE DETECTOR

The essential function of the T2C controller is to provide for current flow through the Pcoil for a sufficient time interval to allow the contacts to close when sufficient source voltage is supplied. It is the threshold detector A1 (see Figure A.1) which determines if the source voltage $V_S$ has achieved sufficient potential for pickup to occur. The threshold detector cycle described below is illustrated in Figure A.2 [4]. Suppose $V_S$ is applied in ramp form through $S_0$, starting at 0V at time $t_0$. Threshold detector A1 establishes a reference voltage ($V_{ref}$) at the inverting input (V-) by way of R1 and zener diode D1. But initially $V_S$ is less than the breakdown voltage of D1, hence D1 is a high impedance, thus $V_S$ is

FIGURE A.1

ELECTRONIC CIRCUIT, ECONOMIZER, TIMER WITH 2 COILS



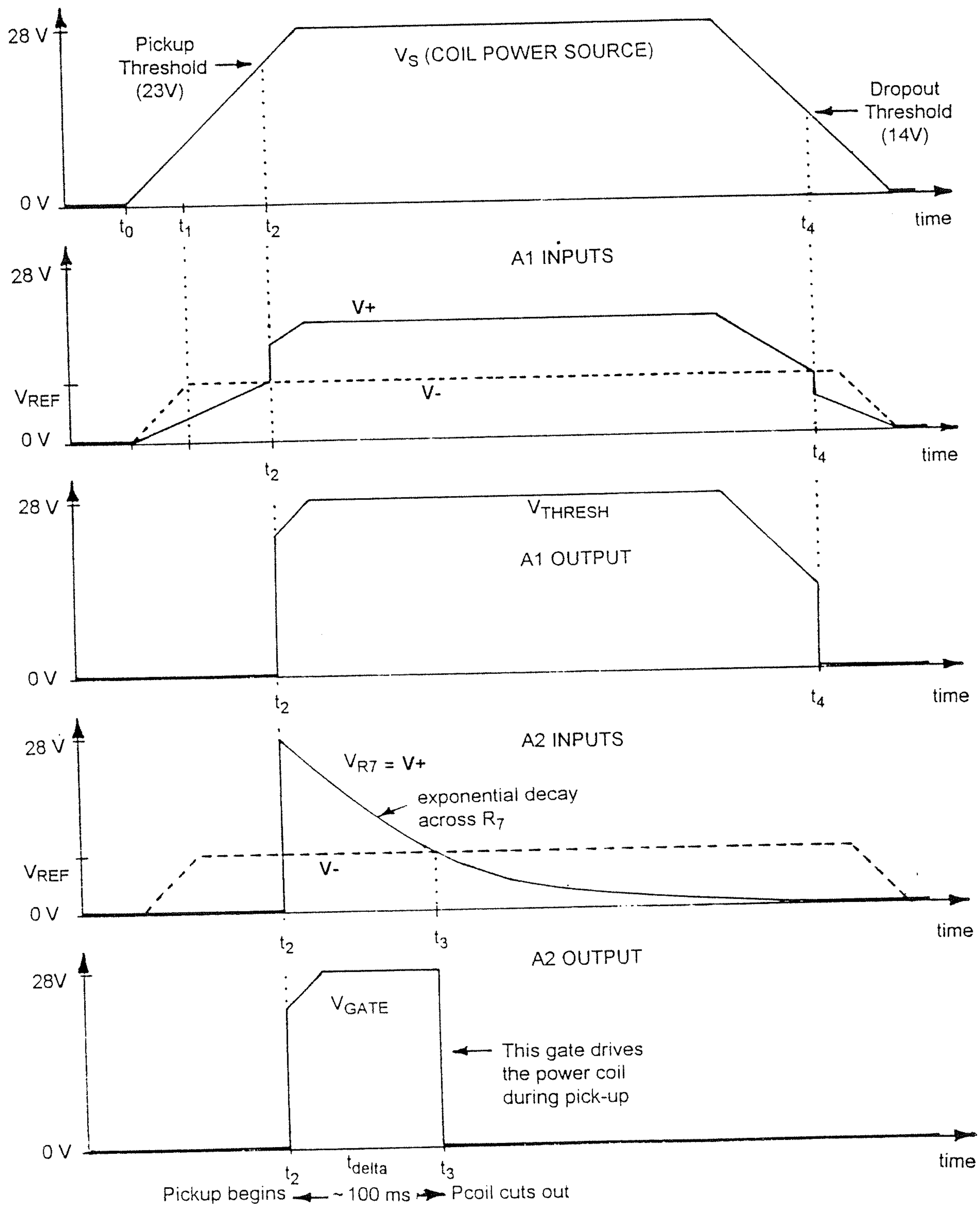

initially impressed at the inverting input of A1. At the non-inverting input (V+), $V_S$ is divided by R2, R3, and R4, impressing a lower voltage. Therefore, the inverting input prevails, keeping A1's open collector output transistor on, essentially grounding the output, thus the threshold voltage $V_{thresh}$ is initially low. The low state of $V_{thresh}$ prevents the gate generator A2 from producing its interval gate to the Pcoil driver Q1 while $V_S$ is too low to provide adequate pickup MMF. Eventually $V_S$ rises above the zener reference voltage of D1 at time $t_1$ and henceforth constant voltage $V_{ref}$ is established and impressed at the inverting input of A1. As $V_S$ continues to rise, so does the voltage at V+. This voltage is simply the division of $V_S$ by R2 in series with the parallel combination of R3 and R4. The diode and resistor values are calculated so that V+ just exceeds V- when $V_S$ reaches the desired pickup voltage (23Vdc for this nominal 28 Vdc system). At this time, $t_2$, the non-inverting input gains the upper hand causing the open collector transistor output of A1 to shut off, and the output voltage $V_{thresh}$ is instantly pulled up to $V_S$ through R5. This action triggers the gate generator which biases Q1 on, into saturation, providing full power to the Pcoil. As a sidenote, substantial positive feedback is supplied via R5 and R4 to the non-inverting input. This provides for wide hysteresis in the threshold detector cycle. What this means is that $V_S$ must be reduced to a voltage much lower than the pickup voltage in order to reset the threshold detector. Although this feature is not utilized by the T2C economizer, it is employed to preset the dropout voltage in the more sophisticated economizers discussed later. Hence the complete threshold detector cycle is given in Figure 5.3. The dropout threshold used later is 14 V, shown at time $t_4$.

## A.3 GATE GENERATOR

When the threshold voltage is pulled up nearly

# FIGURE A.2

THRESHOLD AND GATE GENERATION



instantaneously, it provides a trigger for the monostable gate generator A2. This gate generator single shots a rectangular output that drives Q1 into saturation, providing a path for current through the power coil for pickup [4]. The time duration for the gate is determined by the charging of capacitor C1 through R7, a decaying voltage impressed at the V+ input to gate generator A2. An illustration of this function is given in Figure A.2. The threshold detector output $V_{thresh}$ initially keeps the V+ input of the gate generator low; the V- input is higher, at $V_{ref}$. Therefore, the open collector output transistor of comparator A2 is on. This pulls down the gate voltage ($V_{gate}$), keeping Q1 off. When sufficient source voltage $V_S$ is detected at time $t_2$, $V_{thresh}$ steps high, pulled up through R5. $V_{thresh}$ is coupled to R7 through C1, instantly making the non-inverting input of the gate generator higher than the inverting input, hence the gate generator's output transistor cut off. This allows Q1 to be biased on through R9 and R10 initiating the pickup cycle of the contactor . The gate generator interval ends when the voltage developed across R7 through charging C1 decays below $V_{ref}$ at time $t_3$. Because R5 is small compared with R7, the voltage decay $V_{R7}$ indicated in Figure A.2 is governed primarily by the R7 x C1 time constant.

Eq. A.3.0 $\quad V_{R7(@\ t2+)} = V_{thresh}(e^{[-t/(R7\ C1)]})$

Knowing $V_{ref}$, $V_{thresh}$, and the required gate interval, $t_{delta}$, C1 and R7 are easily determined from Eq. A.3.0. The gate interval used for the Timer with 2 Coils economizer is about 100 ms, as evidenced by the duration of the power inrush current cycle in Figure 5.1.

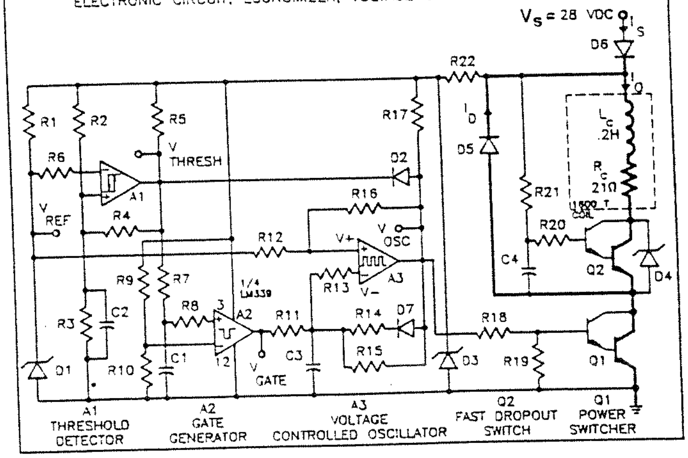
Three protection circuits are installed to protect the T2C economizer from transients, particularly the flyback voltage generated by the coils. Diodes D3 and D4 clamp the reverse voltage generated at dropout to a safe level, D4 absorbing most of the coil energy transient. Zener diode D2 works in conjunction with R11 to protect the control circuits A1 and A2 from any positive over-voltage and also clamps at one forward diode drop the reverse voltage. Diode D6 protects the entire controller from inadvertant misapplication of reverse polarity source voltage $V_S$.

## B.0 VCC, THEORY OF OPERATION

The pickup interval of the VCC economizer is straight forward, employing circuits concisely described in Appendix A for the T2C economizer. What is important to present here are the additional features that make the VCC tick. Figure B.1.0 shows the VCC electronic circuit. The addition of the voltage controlled oscillator (A3) is the heart of the VCC in the economizing mode. It is designed to operate at a nominal frequency much higher than the break (roll off) frequency of the coil so that energy can be pumped into the actuator's magnetic field

FIGURE B.1

ELECTRONIC CIRCUIT, ECONOMIZER, VOLTAGE CONTROLLED CHOPPER




during the $t_{on}$ interval, and alternately retrieved during the $t_{off}$ interval to maintaining fairly constant coil holding current. As an additional feature, the oscillator is designed to change its duty cycle as the source voltage $V_S$ varies, supplying constant average voltage to the coil (effective range is 36 to 14 Vdc, where 28 Vdc is nominal). In order to maintain steady holding current, as shown in Figure 6.1, the oscillator frequency is set according to Eq. B.0.0:

Eq. B.0.0 $\quad f_{osc} >> 2\pi/\tau_{coil}$

$f_{osc}$ = nominal oscillator frequency
$\tau_{coil} = L_C/R_C$

After satisfying Eq. B.0.0, the average holding current can be determined from Eq. B.0.1:

Eq. B.0.1 $\quad I_{O(ave.\ hold)} = [V_S/R_C][\text{Duty Cycle}]$

Coil power dissipated in the economizing mode is simply the average holding current multiplied by the source voltage and the oscillator duty cycle. This assertion can be clarified by refering to Figure 6.3. Here $V_S$ is only supplied during the $t_{on}$ interval. The source current during this time is the same as the average coil current. During the $t_{off}$ time, no source current is supplied, hence the Duty cycle factor $[t_{on}/(t_{on} + t_{off})]$ establishes the correct power supplied ($P_{O(hold)}$):

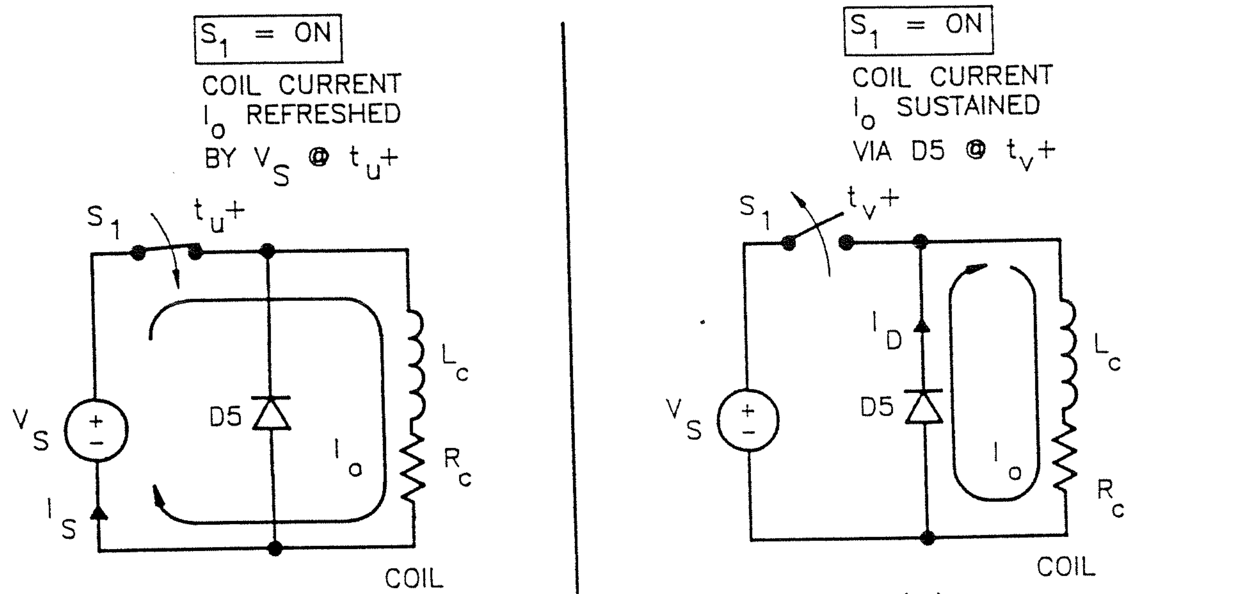
Eq. B.0.2 $\quad P_{O(hold)} = (I_{O(ave.\ hold)})(V_S)(\text{Duty Cycle})$

Substituting the terms for $I_O$ in Eq. B.0.1 into Eq. B.0.2 yields:

Eq. B.0.3 $\quad P_{O(hold)} = [V_S^2/R_{coil}][\text{Duty Cycle}]^2$

**FIGURE B.3**

CHOPPER MODE COIL CURRENT PATHS




$-L_c(dI_o/dt) + R_c(I_o) = 0$

Initial Condition: $I_{o_i} = [V_s/R_c][\text{Duty Cycle}]$

Solving separation of variables yields [5]:

$I_{o(tv+)} = [V_s/R_c][\text{Duty Cycle}]\ e^{[-t/(L_c/R_c)]}$

$V_s - L_c(dI_o/dt) - R_c(I_o) = 0$

Initial Condition: $I_{o_i} = [V_s/R_c][\text{Duty Cycle}]$

Solving by integrating factor yields [5]:

$I_{o(tu+)} = [V_s/R_c]\{1-(1-\text{Duty Cycle})\ e^{[-t/(L_c/R_c)]}\}$

The first term is the steady state coil power during the pickup interval. The second term shows that coil power while holding in the economizing mode is reduced by the square of the duty cycle. This characterizes the mechanism for coil power conservation utilizing a single coil and a chopper circuit.

The circuits that refresh and sustain coil current in the economizing mode are shown at the bottom of Figure B.3. First consider the $t_{on}$ interval. When $S_1$ turns on at $t_{u+}$ to refresh the holding current, the current rises according to:

Eq. B.0.4 $\quad I_{0(tu+)} = (V_s/R_c)\{1-(1-\text{Duty Cycle})e^{-t/(Lc/Rc)}\}$

In Eq. B.0.4, the initial holding current is accounted for by the Duty Cycle factor, etc., from Eq. B.0.1. When $S_1$ turns off at $t_{v+}$, the coil current is sustained through the free wheeling diode D5 with the coil supplying the back EMF generated by the actuator's collapsing magnetic field [6]:

Eq. B.0.5 $\quad I_{0(tv+)} = (V_s/R_c)[\text{Duty Cycle}]e^{-t/(Lc/Rc)}$

Again, the coil current above is completely defined by the circuit parameters and the duty cycle of the oscillator. When the oscillator is set at a sufficiently high frequency according to Eq. B.0.1, then the output coil current $I_0$ in the holding mode is constrained to minimal fluctuations as illustrated in the actual oscilloscope plots of Figures 6.1 and 6.3.

The nominal duty cycle of the economizer oscillator can be determined from Eq. B.0.1 once the designer has determined the required holding MMF:

Eq. B.0.6 $\quad \text{Duty Cycle} = [MMF_{hold}(R_c)]/[V_s(N)]$

$MMF_{holding}$: determine from force vs travel
N = coil turns

$R_C$ = coil resistance
$V_S$ = source voltage

Once the duty cycle has been determined, the nominal operating frequency of the oscillator can be estimated based on the maximum holding current fluctuation desired. Fluctuation of the holding current is the ripple current divided by the average holding current ($I_{0(ave)}$), the ripple being the magnitude of the sawtooth shape of the current signal shown in Figure 6.1. The sawtooth is actually an exponential current rise and fall with time, but its quite linear within its operating region where it's bound far below the assymptotes it is seeking. Bearing this in mind, the rate of change of current in the coil at the beginning of rise or fall can be estimated by the derivative of the first order exponential as the function is intitiated. Thus, taking the derivative of Eq. B.0.5 and setting t = 0 yields the initial (and maximum) rate of change of holding current [7]:

Eq. B.0.7 $\quad {}^{d}/_{dt}[I_0]_{(t=0)} = [-V_S/L_C][\text{Duty Cycle}]$

Having established this helps to develop a simple equation for the required oscillator frequency based on a desired ripple/holding ratio ($\Delta I_0/I_0$) called the fluctuation. The ripple is estimated from Eq. B.0.7 to be ${}^{d}/_{dt}[I_0][t_{off}]$, this being the function Eq. B.0.5's initial rise over run. The holding value is $I_{0(holding)}$ which is equal to $[V_S/R_C][\text{Duty Cycle}]$. Knowing also that the off time $t_{off} = T_{osc}[1\text{-Duty Cycle}]$, where $T_{osc}$ is the oscillator cycle time, the oscillator frequency that meets, but does not exceed, the specified fluctuation is determined to be:

Eq. B.0.8 $\quad f_{osc(min)}=[\text{Fluctuation}][R_C/L_C][1\text{-DutyCycle}]$

$$\text{Fluctuation} = [\Delta I_0] / [I_{0(holding)}]$$

Hence the designer chooses the operating frequency of the oscillator based on the coil characteristic, the pre-determined duty cycle, and a specified holding current fluctuation. A word of caution here. Coil inductance $L_C$ is not a constant, but a dynamic parameter in an iron core actuator. It's best to use the inductance determined at the holding current with the actuator closed using a low frequency impedance bridge to get a relatively accurate measure of the inductance at the actual economizing operating point with the armature in the closed position. Otherwise, it's best to underestimate the inductance in order to keep the fluctuation below the target value. Once both the oscillator duty cycle and frequency have been determined, the fundamental VCC design work is done.

Remember however, that the VCC oscillator is designed to compensate for variations in source voltage, since high temperature and sagging voltage can combine to dropout a contactor in the holding mode. What follows is a description of the oscillator configuration, its fundamental operating principle, and finally how it compensates for $V_S$ variations.

## B.1 OSCILLATOR VOLTAGE COMPENSATION

Voltage compensation is provided by the oscillator in order to supply the coil with a constant average voltage during the holding mode. The design exercise which accomplishes this somewhat involved, however, the fundamental principle of operation can be grasped by studying Figure B.2.0, the timing diagram for the oscillator. In the description that follows, the circuit diagram, Figure B.1.0 is also a necessary reference.

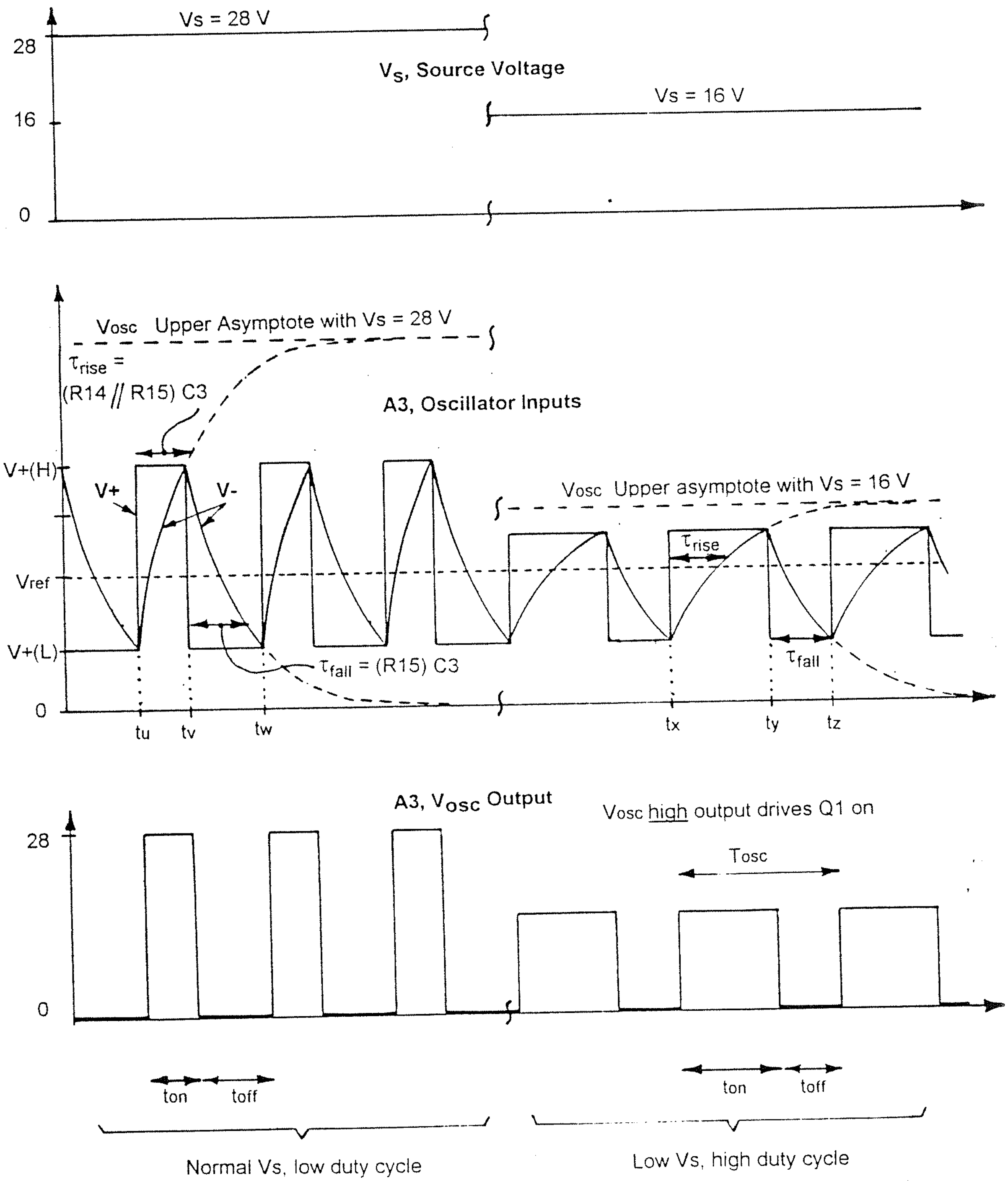
The oscillator is free running (self sustaining ) [4]. Evaluating the nominal case first - the holding mode with $V_S$ = 28 Vdc applied. If the oscillator output $V_{osc}$ has just gone high, then the non-inverting input V+ of A3, the oscillator, shifts high to V+(H) as shown at time $t_u$. With $V_{osc}$ high, capacitor C3 increases its charge through the parallel combination of R14 and R15, hence the voltage at the non-inverting input V- increases exponentially toward the assymtote $V_{osc}$ governed by the (R14 II R15)C3 time constant labeled $\tau_{rise}$. V+ remains constant at V+(H). At time $t_v$, V- exceeds V+(H) driving $V_{osc}$ low, completing the $t_{on}$ interval. Rapid transition is insured by substantial positive feedback driving V+ low, as indicated. With $V_{osc}$ low, capacitor C3 begins discharging into the low potential sink $V_{osc}$. However, it can only discharge through R15, since diode D7 blocks the path through R14. The effect being that C3 has different charge and discharge paths. Thus diode D7 forms a pass/blocking circuit regulating the duty cycle of the oscillator. At time $t_w$, V-, decaying exponentially toward the ground potential assymptote (this time governed by the slower [(R15)C3] time constant $\tau_{fall}$), is discharged below V+(L), driving $V_{osc}$ high, ending the $t_{off}$ interval, and completing the nominal cycle description.

The operating frequency $f_{osc}$ is the inverse of the cycle time $T_{cycle}$. It can be entirely determined by the selection of the R14, R15, and C3.

The mechanism which adjusts the duty cycle as $V_S$ varies is a complex one. However, Figure B.2 illustrates the operation on the right side of the timing diagram starting at $t_x$. At this point $V_S$ has drooped from 28 to 16 V. But oscillator input V+(H) does not drop in the same proportion because it is partially coupled to $V_{ref}$, a constant. This brings the $V_{osc}$ assymptote closer to the V+(H) level, hence V- takes more time to rise to the level of V+(H). The vertically shifted down position of $\tau_{rise}$ clearly illustrates this. The end result is a longer $t_{on}$ time, ending at $t_y$. Complementing longer $t_{on}$ when $V_S$ sags is shorter $t_{off}$ time, starting at $t_y$. C3, discharging

# FIGURE B.2

VOLTAGE CONTROLLED OSCILLATOR TIMING DIAGRAM



through R15 toward ground potential, finds itself starting at a lower potential. But V+(L) does not shifted down, being wholey determined by constant $V_{ref}$. Hence V- reaches V+(L) in shorter time. The compensation scheme is designed to provide fairly constant average voltage to the coil over the range 36 V to 14 V, with 28 V being the nominal condition. Success is amply demonstrated in Figure 6.3.

## B.2 FAST DROPOUT SWITCH

In Figure B.1.0, transistor Q2 is curiously positioned between the coil and Q1, the power switcher. During pickup and holding, Q2 is fully on, serving no particular purpose. However, when the source voltage $V_S$ is removed, Q2 senses this, quickly shutting off, leaving the reverse biased zener diode D4 in the coil discharge loop in series with the free wheeling diode D5. D4's dynamic resistance immediately and substantially raises the discharge time constant of the coil through D4. This makes for rapid coil current decay, necessary for quick contactor dropout. Figure 6.1 shows the dropout time at 7 ms, only 1 ms longer than when the contactor is operated without an economizer. However, if Q2 were not present, dropout time would require several coil time constants since contactors normally dropout at a very low percentage of nominal voltage, typically 10%, meaning coil current must decay to about 10% of nominal, requiring 2 to 3 coil time constants. Using Eq. B.0.5, with the coil parameter values shown in figure 6.0, the coil current requires 20 to 30 ms to decay to dropout without Q2 and D4 installed. This delay is unacceptable for many applications.

The same protection scheme found in the T2C economizer, protecting the controller from transients, is incorporated in the VCC economizer.

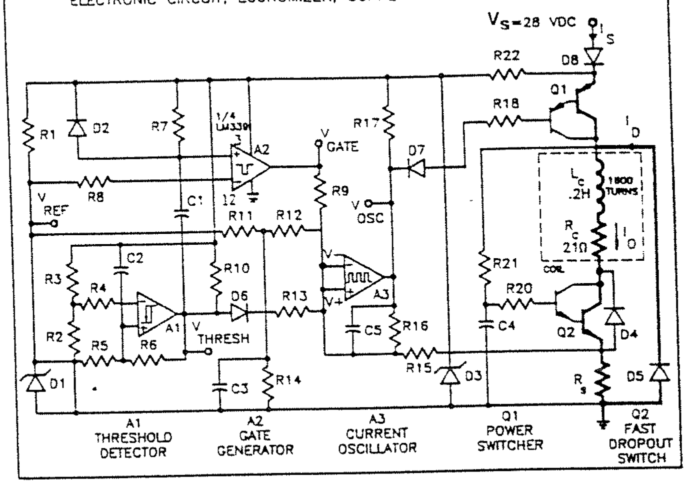
## C.0 CCC, THEORY OF OPERATION

Since only the holding current control is different in the CCC compared to with the VCC, it's the exclusive topic of the theory of operation. A3, an open collector comparator (shown in Figure C.1) is configured, but not obviously so, as a forced oscillator. It's forced to oscillate as its current sensing input V+ reacts to small voltage fluctuations in the sense resistor Rs which are proportional to current rise and fall in the coil. The coil current itself rises and falls with power supplied and cutoff from $V_S$ via Q1, which is invariable controlled by the oscillator. Hence the loop is closed for current control.

V- maintains an exact reference derived by a voltage divider from $V_{ref}$. On the other hand, A3's V+ input tracks, except for a small amount of feedback, the

FIGURE C.1

ELECTRONIC CIRCUIT, ECONOMIZER, CURRENT CONTROLLED CHOPPER




voltage $V_{Rs}$ developed across the current sense resistor Rs. Without any current control, $V_{Rs}$ would rise, in several coil time constants, to $V_S(Rs/(Rs + Rc))$, where Rc is the coil resistance. Setting reference V- anywhere below the maximum achievable by V+ will force current control because the oscillator will begin switching $V_S$, the source voltage, on and off via Q1, hence limiting the coil current. The current limit realized is dependent on the duty cycle of the oscillator. The oscillator duty cycle can be precisely established from equation C.0.0:

Eq. C.0.0 $\quad$ Duty Cycle = $(V-)/V_{Rs(\text{without current cntrl})}$

$$(V-) = V_{ref}\,(R14/(R14 + R11)$$
$$V_{Rs(\text{without current cntrl})} = Vs(Rs/(Rs + Rc))$$

Substituting the circuit parameters for V- and $V_{Rs}$ yields the description of the duty cycle of the oscillator for all operating conditions:

Eq. C.0.1 $$\text{Duty Cycle} = \frac{Vref}{V_S}\cdot\frac{(R14)}{(R14 + R11)}\cdot\frac{(Rs + Rc)}{(Rs)}$$

In Eq. C.0.1, notice that the duty cycle increases as the coil resistance Rc increases, and decreases as $V_S$ increases, both representing compensation in the right direction. Having the duty cycle leads to determination of the coil current $I_O$ in the holding mode:

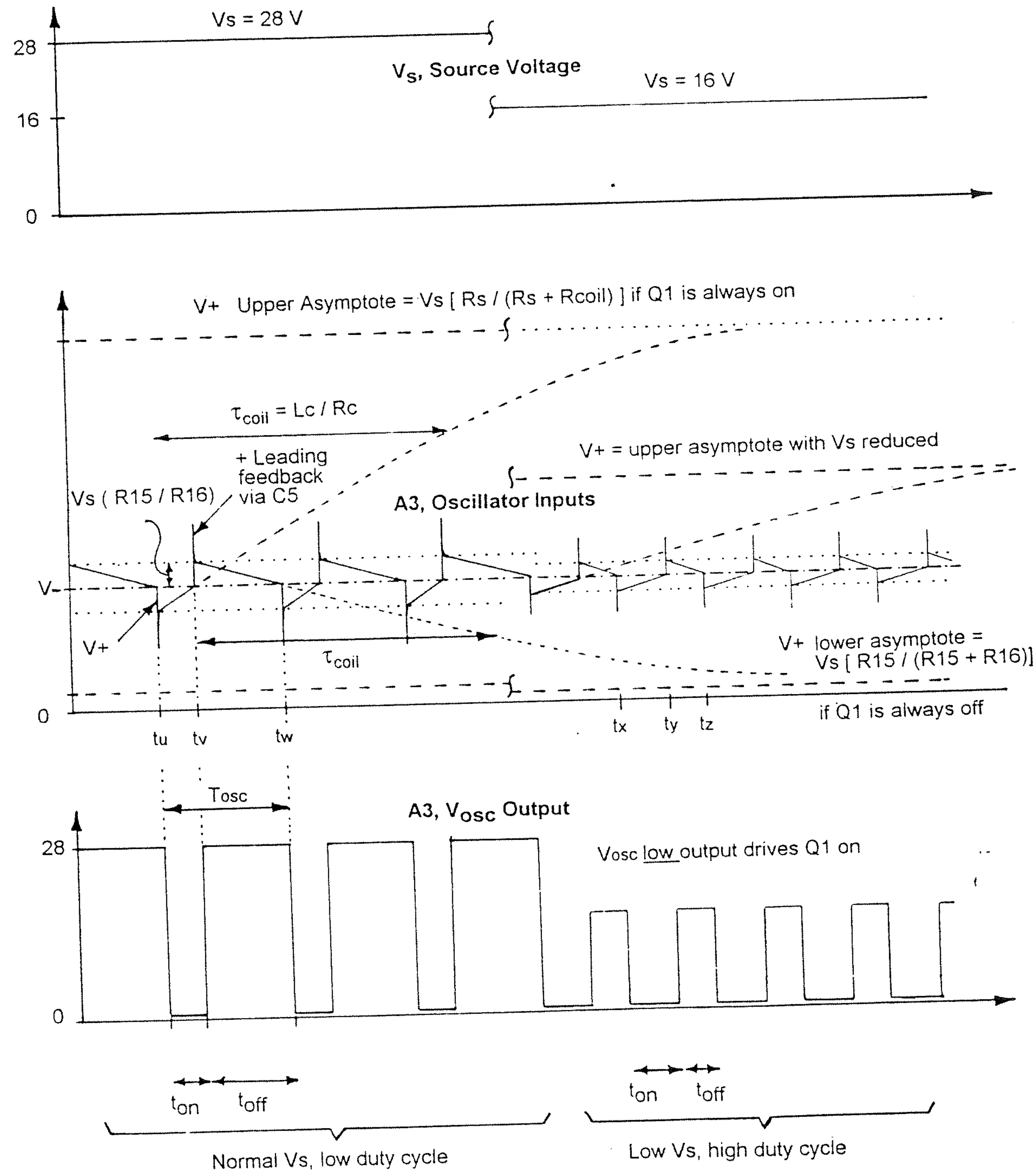
Eq. C.0.2 $\quad I_{O(\text{holding})} = (V_S/Rc)(\text{Duty Cycle})$

Substituting Eq. C.0.1 into Eq. C.0.2 yields a reduced, handy equation for determining the holding coil current providing that the coil resistance is much greater than the sense resistor (Rc >> Rs):

Eq. C.0.3. $\quad I_{O(\text{hold})} = (V_{ref} / Rs)\,(R14 / (R14 + R11))$

# FIGURE C.2

CURRENT CONTROLLED OSCILLATOR TIMING DIAGRAM



$I_0$(hold) = (V-) / (Rs) see Eq. C.0.0

condition: Rc >> Rs

Clearly, from Eq. C.0.3, the holding current $I_0$ is independent of both the source voltage $V_s$ and the coil resistance Rc (which changes with temperature), hence achieving the desired result. Having established Eq. C.0. concludes the development of a closed loop current source feedback mechanism capable of supplying practically constant current

## C.1 CURRENT CONTROLLED OSCILLATOR ACTION

A3's oscillator action, the effect of which yields the constant holding current, is not obvious from the electronic circuit (Figure C.1), However, the timing diagram given in Figure C.2 helps visualize the action. Remember that the current being sensed by the oscillator via voltage $V_{Rs}$ is a small signal compared with the voltage $V_s$ being controlled.

In this discussion oscillator A3 is operating in the holding mode, maintaining constant average current to the coil by controlling the duty cycle via power switcher Q1, a PNP darlington. Suppose V+ is lower than V-, as indicated at time $t_u$, Figure C.2. This means $V_{osc}$ output is low, A3's open collector output having been driven hard into saturation. Hence Q1 is saturated on, so coil current again begins to rise, the effect of which is impressed at V+ via Rs. Subsequently, V+ rises exponentially with the coil current toward the upper asymptote (Figure C.2). At $t_{V+}$, V+ exceeds V- triggering A3 to shut off, pulling up $V_{osc}$ output via R17. The speed of the switching action is increased by positive feeback, leading through C5 and sustained through R16. The sustained feedback shifts V+ above V- by the ratio $[V_s]$ [R15/(R15 + R16)], where R16 >> R15. $V_{osc}$, having been pulled high, cuts off Q1 ending the $t_{on}$ interval. Subsequently, at $t_{V+}$, coil current begins to decay through D5. Coil current decays according to its time constant and V+ receives the analog of this signal through R15 via Rs. At time $t_{W+}$ non-inverting input V+ recedes below V-, causing A3's open collector to drive into saturation, pulling $V_{osc}$ low, turning on Q1, hence ending the $t_{off}$ interval. Note that pulling $V_{osc}$ low is again aided by leading positive feedback through C5 and sustained through R16.

The operating frequency of the oscillator, as well as its duty cycle varies with changing conditions in order to maintain constant average current in the coil. Of course, coil current fluctuates somewhat as the switching transistor Q1 turns on and off. In Eq. C.0.3, note that the average holding current is $I_{0(ave.\ hold)}$ = [(V-)/Rs]. Fluctuation about the average is caused by the amount of positive feedback impressed from $V_{osc}$ output to V+ input when the oscillator switches. This can be deduced from the transition range of V+ indicated by the dotted lines above and below V- in Figure C.2. The amount of feedback is the voltage measured from either dotted line to V-. Employing circuit analysis, an accurrate estimate of the sustained positive feedback (not counting the advance through C5 which is a very short transient) is determined to be:

Eq. C.1.0 $V_{feedback} = V_s\,[R15 / (R15 + R16)]$

$V_{feedback} \approx V_s[R15/R16]$, for R16>>R15

In order for the oscillator to change state, the sustained feedback must be overcome by a change in the coil current signal relayed by Rs to V+. Hence the change in sense resistor voltage $V_{Rs}$ must attain the sustained feedback level in order to force the oscillator to toggle:

Eq. C.1.1 $\Delta(V_{Rs}) = V_{feedback}$

The change in coil current is the change in $V_{Rs}$ divided by Rs. Hence:

Eq. C.1.2 $\Delta I_{0(holding)} = \Delta(V_{Rs}) / Rs$

Substituting Eq. C.1.0 into Eq. C.1.2 yields:

Eq. C.1.3 $\Delta I_{0(holding)} = [V_s/Rs][R15/(R15+R16)]$

Dividing Eq. C.1.3 by Eq. C.0.2 yields an equation for the fluctuation, $\Delta I_0/I_0$.

Eq. C.1.4 $$\text{Fluctuation} = \frac{(Rc)}{Rs[\text{Duty Cycle}]}\,\frac{(R15)}{[R15 + R16]}$$

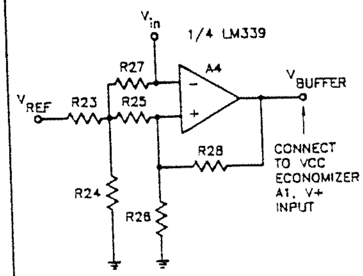
$$\text{Fluctuation} = \Delta I_0/I_0$$

The designer can establish the proper feedback to maintain a desired holding current fluctuation by selecting R15 and R16 in accordance with Eq. C.1.4. An excellent illustration showing a decrease in coil current fluctuation when $V_s$ decreases (hence duty cylce increases) is illustrated in Figure 7.3. It's a pleasant surprise to get better current regulation with sagging source voltage.

As a final note. the designer does not need to set the frequency of the CCC oscillator other than to establish the feedback that will produce the desired maximum holding current fluctuation using Eq. C.1.4. However, trying to minimize the fluctuation too much is futile, since it will contribute to switching transition losses (through transistor Q1's active region) by operating at too high frequency. Nominal 15% Fluctuation, as shown in Fig. 7.1, seems reasonable.

FIGURE D.0

BUFFER AMPLIFIER FOR SMALL SIGNAL (TTL, CMOS) CONTROL OF VCC ECONOMIZER




INPUT/OUTPUT TRUTH TABLE

| $V_{in}$ (TTL or CMOS) | $V_{source}$ (HIGH ≥ 23V) | CONTACTOR/ ECONOMIZER |
|---|---|---|
| LOW | LOW | OFF |
| LOW | HIGH | ON |
| HIGH | LOW | OFF |
| HIGH | HIGH | OFF |

## D.0 TTL/CMOS BUFFER AMPLIFIER

As described in section 8 in the main body of this paper, using a spare comparator configured as a buffer switch makes the economizer directly controllable from small signal logic, in essence giving the economizer the dual role of a relay coil driver and an economizer. Figure D.0 shows the spare comparator of the VCC economizer configured as a buffer controlled by small signal logic control input $V_{in}$. When the buffer is used, the economizer is tied to the $V_s$ buss. The output of the buffer gets connected to the threshold detector A1's V+ input disabling it, hence keeping the economizer off, unless $V_{in}$ is asserted. The truth table in Figure D.0 shows the overall economizer logic function with small signal $V_{in}$ control. A logic low asserted at $V_{in}$ shuts off the buffer A4, effectively taking it out of the circuit, enabling the threshold detector to signal the economizer driver to turn on the contactor, provided the source voltage $V_s$ is of sufficient magnitude.

The logic low level has been chosen as the asserted state because it allows control to be asserted from either low logic voltage, an open collector output, or a plain mechanical switch. In short, grounding $V_{in}$ asserts control to enable the contactor through the economizer. The resistors about A4 are designed to keep the economizer off if $V_{in}$ is removed (open ciruit) or is high (TTL/CMOS legal high), to establish the correct logic state as Vs ramps up and down, and to protect $V_{in}$ from high $V_s$ transients. With $V_{in}$ not present (open), $V_{ref}$ impresses a fractional voltage at V- input via voltage divider R23 and R24. V+ is kept always at an even lower fraction of $V_{ref}$ via network R23, R24, R25, and R26. Hence V- is higher than V+ as long as $V_{in}$ is not present, making $V_{buffer}$ output low, keeping the economizer off. If $V_{in}$ is asserted low, then V+ is higher, shutting off the buffer, allowing the threshold detector to monitor $V_s$, signaling power throughput to the coil if $V_s$ is determined to be of sufficient magnitude. Resitor R28 provides a bit of positive feedback for switching efficacy.

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