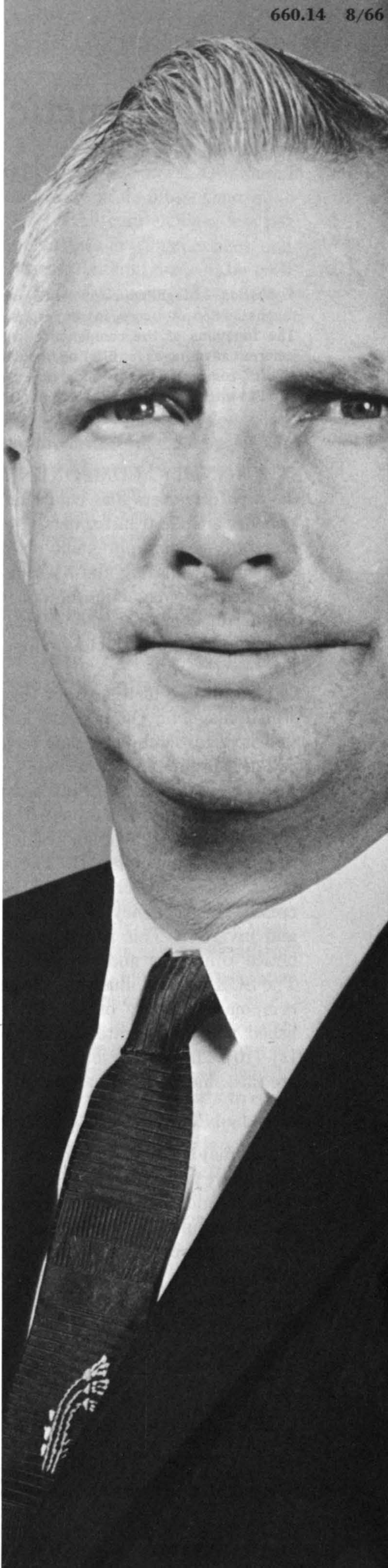

Basic Magnetic Functions in Converters and Inverters Including New Soft Commutation

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Basic Magnetic Functions in Converters and Inverters Including New Soft Commutation

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***Abstract*—Magnetic components, operating on the principle of magnetization of a core, in converters and inverters are discussed. The functions of the components in switching circuits and their inherent advantages for filtering, insulation, and isolation are shown. "Soft" commutation, for suppression of silicon controlled rectifier circuit switching losses, is explained.**

INTRODUCTION

MAGNETIC COMPONENTS are an important part of inverters and converters. These magnetic components include transformers, filter reactors, commutating reactors, surge suppression reactors, and control circuit elements. Insulating and filtering are important functions provided by magnetic components. Semiconductors are wonderful components, but they do not provide circuit insulation. Semiconductors, alone, are not practical filters for power flow.

The purpose of this paper is to illustrate the functions which magnetic components are providing in converter and inverter circuits. A new technique of "soft" commutation is presented to illustrate new advanced functions of magnetic components. Soft commutation uses the commutating circuit to suppress the switching losses of the silicon controlled rectifier (SCR). The need for suppression reactors is removed. The use of magnetic components and capacitors, in soft commutation, greatly increases the frequency capability of the SCR for converters and inverters. This paper limits the illustration of magnetics to inverter and converter circuits using SCR units. The SCR circuits illustrate the functions of the magnetic components. Many other SCR circuits have been published which illustrate the use of magnetic components [1]-[10]. The basic functions of these magnetic components are the same as shown in this paper.

FUNCTION OF MAGNETIC COMPONENTS

The major magnetic components in inverters and converters are transformers, filters, and commutating reactors (Figs. 1 and 2). Magnetic components are also used in control circuits. Magnetic control circuits are used in the gate firing circuit or in the commutation circuit, as shown in Fig. 2. The functions of the magnetic control circuits are the same as those of magnetic amplifiers which have previously been described [11],[12] and they are not repeated here.

Transformers

The functions of transformers in solid-state conversion systems are the same as those in 60- and 400-c/s systems. Transformers are used to change voltage and provide insulation of power. The transformers often operate over a wide range of frequencies in contrast to fixed frequency power distribution systems of 60 or 400 c/s. Transformers in some conversion systems operate down to a few cycles per second. In other systems, the transformers operate at 10 kc/s or at greater frequencies.

In low frequency systems (under 3 kc/s), the transformers use laminated cores. At high frequencies (over 5 kc/s), powdered cores are usually preferred. The "tradeoff" between efficiency (core losses), cost, size, weight, construction factors, etc., determines the exact choice of core materials.

The size and weight of the transformer decreases as frequency increases. The cost does not decrease appreciably as frequency increases to 3 kc/s. Above 5 kc/s, the cost of the transformer decreases as frequency increases. But the increase of frequency above 5 kc/s is limited by derating of the SCR, and it is finally limited by the commutating time of the SCR. Derating of the SCR depends upon the conversion circuit and is greatly reduced (Fig. 3) by using soft commutation (discussed later in this paper).

The lamination thickness in the core of the transformer must be reduced as frequency is increased (10 c/s to 3 kc/s). In general, the cost per pound of core material increases inversely with the thickness of the lamination. Above 5 kc/s, powdered cores are usually used, and the cost per pound of core does not increase appreciably as frequency increases.

The cost of a transformer for a given conversion system depends upon the many trade-offs of design. The trade-offs include size, weight, efficiency, manufacturing techniques, environmental requirements, etc. A typical range of transformer cost is $1 to $20/kW. Cost per kilowatt decreases as power and frequency increase. One kW at 60 c/s is approximately $20/kW, and 50 kW at 10 kc/s is approximately $1/kW.

The cost, size, and weight are functions of the core material. Typical core materials are as follows:

1) Silicon–iron for 10 to 500 c/s.
2) Silicon–iron or 50 percent nickel-50 percent iron for 500 c/s to 3 kc/s.
3) 79 percent Nickel, 17 percent iron, 4 percent molybdenum for 2 to 8 kc/s.
4) Powdered iron type cores for 5 to 50 kc/s.

Other material and different frequency ranges are some-

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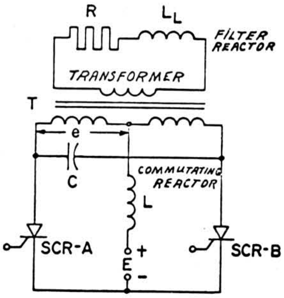

Fig. 1. Parallel inverter.

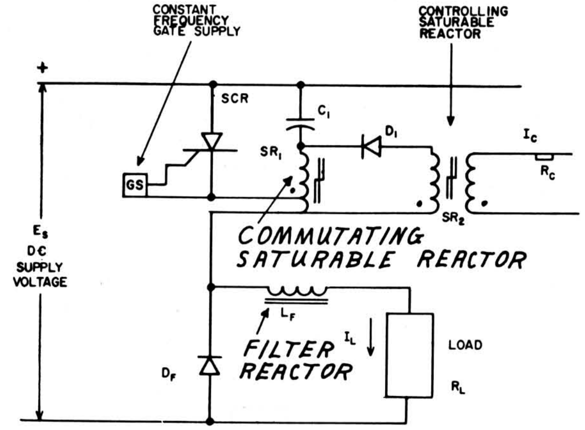

Fig. 2. Time ratio control (TRC) power converter with saturable reactor control.

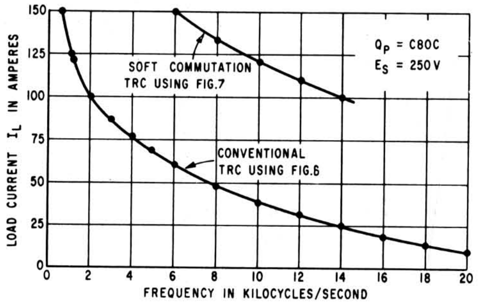

Fig. 3. Comparison of soft commutation and conventional commutation for constant required commutating time (implying constant junction temperature).

times used, depending upon the trade-off factors of the design. For example, silicon–iron can be used at 5 kc/s for less cost than the other core materials discussed previously. At 5 kc/s, the core losses of silicon–iron are 5 percent (or more) of the power handled by the transformer. If the power losses are not disturbing, the core of the transformer can be cooled by circulating oil, and low cost is achieved.

The transformer functions in solid-state conversion systems are the same as those of most power systems. The flexibility of design parameters in conversion systems usually permits a much larger choice of transformer design factors than most other power systems.

Filters

The functions of filters in solid-state conversion systems are to change square wave to sine wave or to smooth direct current. The filter reactors combined with capacitors provide the filter elements. The filter reactors use magnetic cores to minimize the size, weight, and cost. The choice of core material is the same as that for transformers, when ac filters provide sine wave power. Laminated cores are used at higher frequency in dc filters than in ac filters. In dc filters, the flux of the core changes less per cycle than the flux of ac filters. With low flux changes, and consequent less core loss, thicker laminations can be used in dc filters than in ac filters. Otherwise, filter design choices are similar to transformers discussed previously.

Commutating Reactors

The commutating reactors serve a major function for commutating solid-state conversion systems. The commutating circuit provides the function of turning off the SCR (stopping conduction) at the desired time of the operating cycle of the conversion system. The commutating capacitor C of Figs. 1, 2, 4, and 5 provides the energy to commutate the SCR. The commutating reactor serves the functions of orientating the capacitor voltage, limiting current in the capacitor, and often determining the length of time for commutating the SCR. In some conversion circuits, the commutating reactor also determines the length of time the SCR is on (conducting current).

The basic functions of the commutating reactor are illustrated in Fig. 4. There are many other commutating circuits using reactors [1]–[10]. Figure 4 is chosen for its simple illustration of the basic functions of the commutating reactors.

Consider the operation of Fig. 4. Prior to starting operation of the circuit, supply voltage E_S is applied. With SCR_1 off, commutating capacitor C_C is charged until capacitor voltage $e_C = E_S$. Capacitor C_C is charged through the commutating reactor L_C and elements D_C, L_F, and the load. This charging of C_C stores energy in C_C to be used later for commutation. Starting the conversion circuit of Fig. 4, SCR_1 is turned on, rectifier D_c blocks current, and C_c is left charged to $e_c = E_s$. Voltage e_c remains $e_c = E_s$ until SCR_c is turned on. After SCR_c is turned on, C_c and L_c oscillate for 180°, as shown by the period of time *abc* of Fig. 4(b). The oscillation is a regular sine wave which operates for only 180°. At time *c*, rectifier D_c starts to conduct, and both SCR_1 and SCR_c are reversed. Inductance $L_c \ll L_F$, the load filter inductance. The cathode voltage e_K of SCR_1 is raised above supply voltage E_s at time *c* to $e_K = E_s + e_c \cong 2E_s$, as shown in Fig. 4(c). After $e_K > E_s$, current stops flowing through SCR_1, but load current I_L continues to flow through C_c, L_c, D_c, and L_F for the time interval *cde*. With I_L held constant by inductance L_F, capacitor C_c is recharged at a constant rate (dv/dt), as shown in Fig. 4(b). The time period *cd* is the commutating interval of t_{cd} for SCR_1 (time that $e_K > E_s$). Usually $t_{cd} = 20$ μs or longer, depending on the load and the type of SCR used for SCR_1. The interval of time t_{cd} is determined by $t_{cd} = 0.9\, E_s C_c / I_L$, where E_s is in volts, C_c in microfarads, I_L in amperes, and t_{cd} in microseconds. The constant 0.9 is used to allow for energy lost during the commutating operation.

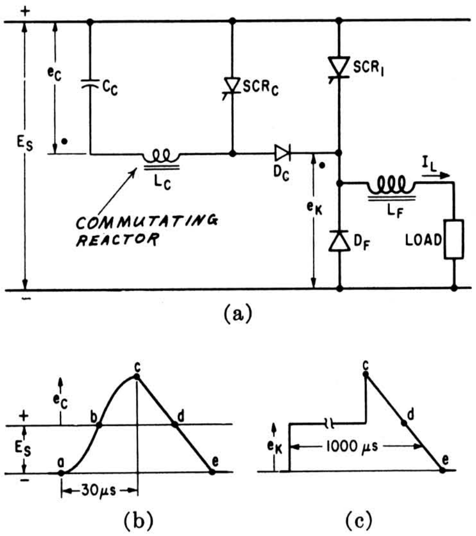

Fig. 4. TRC with linear commutating reactor.

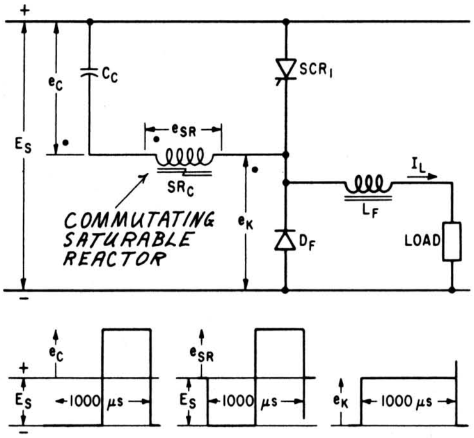

Fig. 5. TRC with saturable commutating reactor.

The functions of the commutating reactor L_c of Fig. 4 are: 1) inrush current to C_c through SCR$_c$ is limited to prevent destruction of SCR$_c$, 2) inductor L_c reverses the voltage e_c of capacitor C_c, and 3) inductor L_c delays the start of commutation of SCR$_1$ until capacitor voltage e_c is completely reversed.

In many solid-state conversion circuits, a feedback rectifier is required. This function is illustrated by connecting a diode type rectifier across SCR$_1$ to conduct in the opposite direction of SCR$_1$ [similar to Fig. 6(a)]. With this revision, commutating reactor L_c also serves the function of determining the length of time to commutate SCR$_1$. In this case, the commutating time is 120° of the resonating cycle of L_c and C_c at full load. At light or no load, the commutating time is 180° of the resonating cycle.

In some conversion circuits, the commutating inductor determines the length of time the main SCR conducts. At high frequency ($f > 10$ kc/s), Fig. 4 is used by omitting SCR$_c$ and shorting rectifier D_c. In this modification, SCR$_1$ conducts for 180° of the resonating cycle of L_c and C_c before SCR$_1$ is commutated. Including commutation time, SCR$_1$ is on for $180° + 120° = 300°$ of the resonating cycle (typically 50 μs).

By using a saturable reactor for the commutating reactor, the conducting time of SCR$_1$ can be extended to longer times, such as 1000 μs. This operation is illustrated in Fig. 5. In Fig. 5, the reversing of C_c is delayed after SCR$_1$ is turned on by the time for SR_c to saturate (500 μs). After SR_c saturates, C_c is reversed by the saturated inductance of SR_c in the same manner as L_c of Fig. 4. In Fig. 5, after e_c is reversed by SR_C, SR_C becomes unsaturated again and delays commutation another period of time (500 μs). The function of commutating saturable reactors is to set the time SCR$_1$ is on, over a range of 50 to 1000 μs.

In addition to the functions of reversing C_c, limiting C_c current, delaying commutation, and setting "on" time for SCR$_1$, the commutating reactors are used to suppress spikes of current and voltage on SCR$_1$. These suppressions extend the frequency capabilities of SCR$_1$, as shown in Fig. 3.

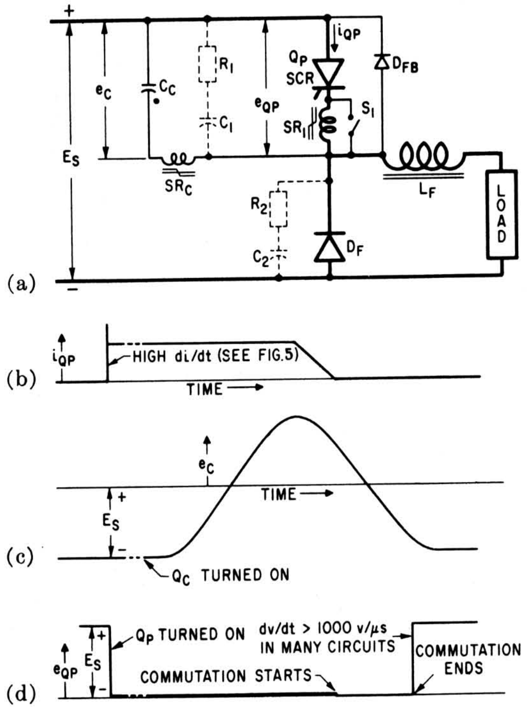

Fig. 6. TRC conventional circuit and waveforms.

Suppression Reactors

The functions of the suppression reactors are to limit the rate of rise of current (*di/dt*) in the SCR and extend its frequency capability. In Fig. 6(a), with S$_1$ open, suppression reactor SR$_1$ is a saturable reactor. After the SCR is turned on, SR$_1$ delays current flow until the SCR is fully switched on. The delay by SR$_1$ removes most of the switching losses from the SCR. With the switching losses reduced, the SCR is capable of operating at higher frequencies than could be permitted with S_1 closed.

SR_1 resets to the residual flux level in Fig. 6(a). In many conversion circuits, feedback rectifier D_{FB} is connected directly across the SCR, and SR_1 resets to negative saturation during the commutation operation.

Suppression reactors such as SR_1 are often required at low frequencies such as 100 c/s. The recovery current of filter rectifier D_F adds to the load current, as shown in Fig. 6(b). In addition to the high current which flows in the SCR while it is turning on, the SCR uses only a small part of its junction area during switching. With only a small part of the SCR junction conducting during the turn-on period of time, the SCR can be damaged by internal overheating, even though the stud may be cold.

The addition of SR_1 can raise the frequency capability of most SCR units to 2 or 3 kc/s before significant derating is required. The exact frequency capability depends upon the particular SCR unit.

SOFT COMMUTATION

A new technique of commutation for silicon controlled rectifiers (SCR) is presented. New commutating circuits relieve surges in the SCR, improving efficiency, economy, and reliability and reducing radio frequency interference. High-frequency power conversion (3 to 10 kc/s) can be achieved with very little derating, using the new soft commutation technique.

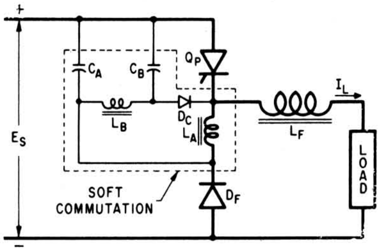

Fig. 7. TRC with soft commutation.

A time ratio control (TRC) circuit is used to present the soft commutation. The technique of soft commutation can be applied to inverters or converters. The TRC circuit is chosen for the presentation because of its relative simplicity. The principles of TRC, inverter and converter circuits, were previously described [1], [2], [9], [10] and will not be repeated in this paper.

BASIC NEED FOR SOFT COMMUTATION

The basic need for soft commutation is to reduce the switching losses of the SCR. The turn-on loss, as current rises (di/dt) in the SCR, is the main factor which limits SCR units at high frequency (2 to 10 kc/s). Inductor L_A, in the soft commutation circuit of Fig. 7, greatly reduces the turning on losses of Q_P. The turn-off losses are minimized in most systems by the commutation circuit. Capacitor C_B, in the soft commutation circuit, reduces the need for SCR units which are rated for high dv/dt (high rate of rise of forward voltage). With low requirements for di/dt and dv/dt, economical SCR units and slow-recovery rectifiers can be used for high-frequency TRC systems. Radio frequency interference (RFI) is also greatly reduced by soft commutation.

Most present TRC systems require high di/dt and high dv/dt capabilities of the SCR and are like the circuit illustrated in Fig. 6. These systems operate at low frequency, and surge suppression such as R_1, C_1, R_2 and C_2 can be tolerated. Serious reduction in the current capability of the SCR is required as frequency rises. This reduction in current is illustrated in Fig. 3. By contrast, very little reduction in current of the SCR is required (up to 10 kc/s) when soft commutation is used (Fig. 3).

Series SR Limited

A series saturable reactor such as SR_1 of Fig. 6 is commonly used to reduce the turning on losses of the SCR. The use of SR_1 reduced the turning on losses ($\int e_{QP} i_{QP} dt$). The reduction in SCR losses is illustrated by the waveforms of Figs. 8 and 9. Using SR_1, the SCR voltage e_{QP} drops to $E_{QP} \cong 0$ before SCR current i_{QP} rises. When i_{QP} rises, voltage e_{QP} also rises. Although the SCR losses are reduced when SR_1 is used, soft commutation is much more effective for reducing the turning on losses in the SCR than SR_1, as shown in Fig. 10.

Slow Recovery Rectifiers Can Be Used

Rectifier D_F of Fig. 7 can be an economical slow-recovery rectifier. By contrast, D_F of Fig. 6 provides a voltage spike, as shown by voltage e_{DF} in Figs. 8 and 9. As current i_{QP} rises, D_F conducts current backward until the junction in D_F recovers (one or more μs). As D_F stops the conduction of reverse current and blocks voltage, rectifier voltage e_{DF} rises to a voltage exceeding the source voltage.

While D_F conducts current backward, energy is stored in the leads and circuit of Q_P. This energy must be dissipated in the TRC circuit. In the soft commutating circuit of Fig. 7, this energy is transferred into the commutation circuit and used for commutation. After commutation, the energy is supplied to the load. The voltage spike of e_{DF} is avoided.

There are other solutions to the spike of e_{DF} (Fig. 6), but none are as satisfactory as soft commutation. Some of the other solutions are as follows:

1) Avalanche rectifier clips the spike of e_{DF} and dissipates the energy in D_F. At high frequency (2 to 10 kc/s), both the power lost and the heat of D_F are excessive.

2) Resistor capacitor clamp such as R_2 and C_2 (dotted in Fig. 6) can limit e_{DF}. The energy is dissipated in resistor R_2 and in resistor R_1. The power lost is excessive for high frequency (2 to 10 kc/s).

3) Fast recovery rectifier for D_F greatly reduces the energy in the spike of voltage e_{DF}, but the spike is not eliminated. By combining the fast recovery D_F with R_2 and C_2 of Fig. 6, e_{DF} is limited and the power lost in R_2 and R_1 can be tolerated in some TRC systems. The power lost in R_2 and R_1 is often 5 to 10 percent or more of the load power at high frequency (5 to 10 kc/s). By contrast, the energy is used for commutation and is not lost in soft commutation.

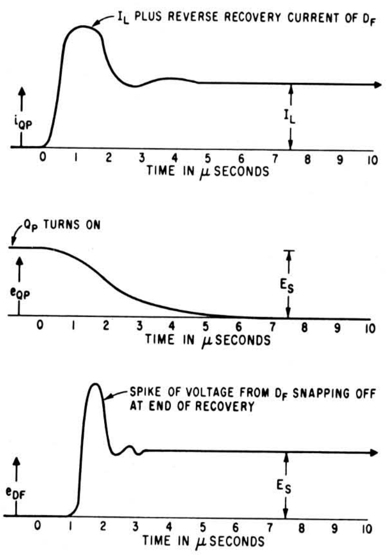

Fig. 8. Waveforms of Fig. 5 without SR_1 (S_1 closed).

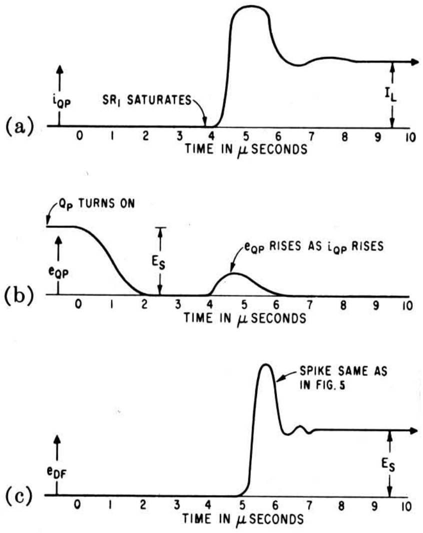

Fig. 9. Waveforms of Fig. 5 with SR_1.

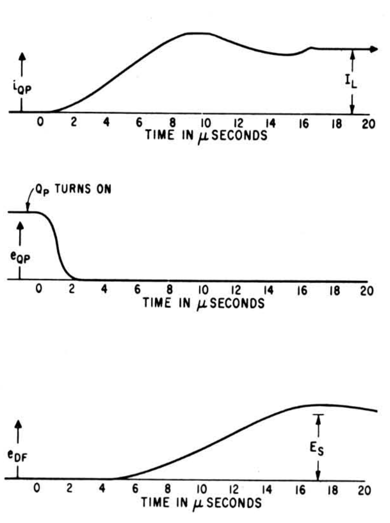

Fig. 10. Waveforms of Fig. 6 with soft commutation.

In some applications of soft commutation, fast recovery D_F may be desirable.

Radio Frequency Interference Reduction

Soft commutation reduces the radio frequency interference (RFI) generated in the TRC circuit. The soft commutation circuit provides a low rate of rise and fall of current (*di/dt*) and voltage (*dv/dt*) in the TRC circuit. Low *di/dt* in the power source is also provided. As a result, very little RFI is generated. The reduced burden of RFI saves cost, weight, and space by a much smaller RFI filter. In many systems, no RFI filter is needed.

SOFT COMMUTATION OPERATION

Soft commutation is a commutating circuit which provides relatively low *di/dt, dv/dt,* and RFI while providing commutation for the SCR. There is a variety of soft commutation circuits. This paper discusses a basic circuit for soft commutation. A variety of other commutation circuits can be used, but a discussion of other circuits is beyond the scope of this paper.

A basic soft commutation circuit is shown in Fig. 11. The two capacitors have approximately the same capacitance as the one capacitor of Fig. 6 when operating at the same load current I_L and supply voltage E_S. The two inductors L_A and L_B are approximately the same size as the saturable reactor SR_c of Fig. 6. The relative values of C_A, C_B, L_A, and L_B vary depending upon the desires of the circuit for relative *di/dt*, *dv/dt*, and the length of time Q_P is on. Typically, $C_A = C_B$ and $L_B = 2L_A$.

Commutation Operation

Inductor L_A limits *di/dt*, the rate of rise of current through Q_P and the amplitude of reverse current through rectifier D_F. After Q_P current reaches $i_{QP} > I_L$ load current, D_F stops conducting and blocks voltage. The energy stored in L_A is transferred to capacitor C_A and inductor L_B. Then all the energy of C_B is also transferred to L_B, and Q_P starts commutation. As e_{CB} reaches zero, all the energy of C_B is transferred to L_B. When e_{CB} = zero, D_C starts to conduct, and load current I_L is finally supplied through D_C. SCR current i_{QP} drops to zero, and the voltage across SCR unit Q_P reverses until commutation is complete (5 to 30 μs, depending on the SCR). After commutation, forward voltage rises across Q_P with a relatively low rate of rise of forward voltage (*dv/dt*). Capacitor C_B limits the *dv/dt* of Q_P.

More detail of the operation of soft commutation is illustrated in Figs. 12 through 14. The circuit of Fig. 12 is the same as the circuit of Fig. 11, except that the SCR unit Q_C and rectifier D_{C2} are added. The addition of Q_C and D_{C2} allows external control of the length of time that Q_P conducts current. The conducting time of Q_P is adjustable from the time provided in Fig. 11 up to Q_P conducting continuously.

The addition of Q_C and D_{C2} simplifies the explanation of soft commutation. The voltage and current waveforms of Fig. 12 are shown in Fig. 13, with time points indicated by

t_0, t_1, t_2, etc. For this explanation, Q_C is turned on at time t_4 after all energy of L_A is transferred to C_A with $i_C = 0$ and $i_{QP} = I_L$.

In Fig. 13, SCR unit Q_P is turned on at time t_0, and Q_P voltage e_{QP} drops to near zero very quickly (one μs). SCR current i_{QP} rises slowly (10 μs typical) to $i_{QP} = I_L$. Between t_0 and t_1, capacitor voltage e_{CA} and e_{CB} are constant and D_F is conducting. At time t_1, rectifier D_F stops conducting and starts blocking voltage, allowing commutating circuit current i_c to start to rise. Between t_1 and t_2, current i_c rises, and at time t_2, inductor L_A contains half the energy ($1/2L_Ai_c^2$) in the commutating circuit. Capacitor C_B contains the remaining half with $e_{CB} > E_S$ and C_B negative at the dot. Also at time t_2, voltage $e_{CA} = 0$. Between t_2 and t_3, current i_c drops to zero, and the energy of L_A is transferred to C_A with $e_{CA} \cong E_S$ and positive at the dot.

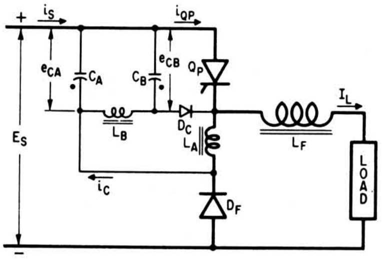

Fig. 11. TRC with soft commutation and conducting time for Q_p fixed

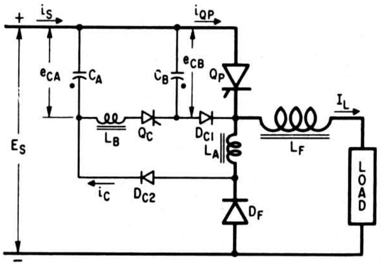

Fig. 12. TRC with soft commutation and conducting time for Q_p controllable.

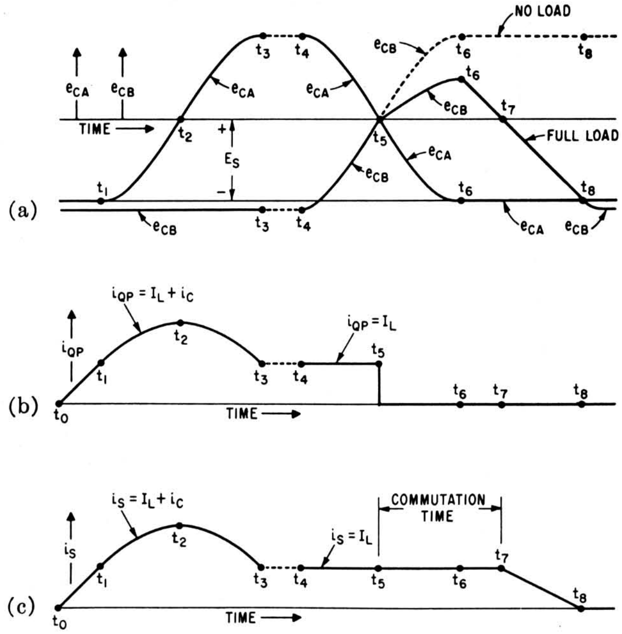

Fig. 13. Waveforms for Fig. 12.

The interval of time between t_3 and t_4 can be any length of time desired for the TRC system. At time t_4, SCR unit Q_C is turned on by an external signal. Between t_4 and t_5, all of the commutating circuit energy is transferred from capacitors C_A and C_B to inductor L_B, with Q_P continuing to conduct ($i_{QP} = I_L$). At time t_5, voltages $e_{CA} = e_{CB} = 0$, assuming C_A and C_B are equal. At time t_5, commutation of Q_P starts. As L_4 current exceeds I_L, voltage e_{CB} rises positive at the dot and reverses Q_P which ceases to conduct. At time t_6, inductor L_B current drops to the same value of current as I_L. Voltage e_{CB} begins to decrease at t_6, and e_{CA} is equal to the supply voltage E_S. At time t_7, commutation ends when $e_{CB} = 0$. Between t_7 and t_8, forward voltage rises (dv/dt) across Q_P, with the dv/dt limited by capacitor C_B. The load current recharges C_B to $e_{CB} = E_S$ at time t_8. After t_8, voltage e_{CB} becomes slightly greater than E_S, with $e_{CB} \cong E_S\ (L_A + L_F)/L_F$ where L_F is the inductance of the filter inductor L_F.

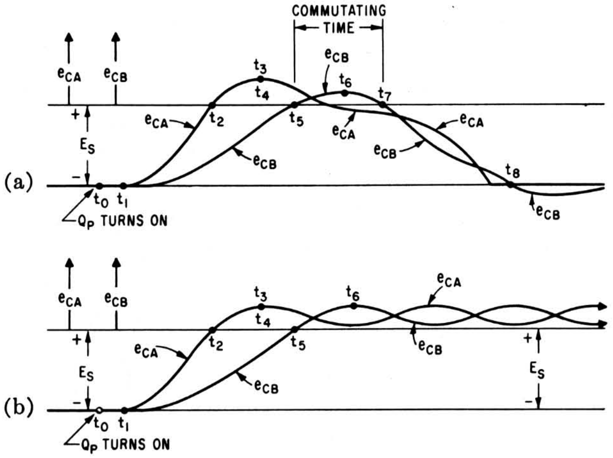

Fig. 14. Waveforms for Fig. 11.

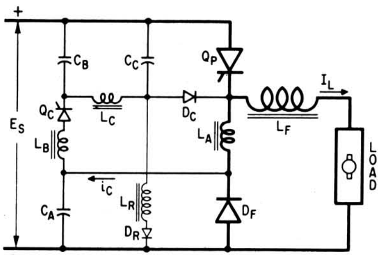

Fig. 15. TRC with soft commutation for back EMF loads such as motor.

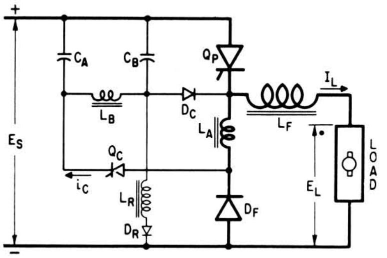

Fig. 16. TRC with soft commutation for back EMF loads with conducting time of Q_p controllable.

At no load ($I_L = 0$), capacitor C_B voltage rises at time t_6 to $E_{CB} \cong E_S$, and after t_6, voltage e_{CB} holds Q_P reversed [dotted curve of Fig. 13(a)]. In case of no load, C_B is reset by inductor L_R, as shown in Fig. 15.

The detail operation of the circuit of Fig. 11, with Q_C and D_{C2} omitted, is the same as described previously for Fig. 12, except that the voltage waveforms of C_A and C_B are intermingled. If Q_C and Q_P of Fig. 12 are turned on at time t_0, the operation of Figs. 11 and 12 is the same. The waveforms of capacitor C_A and C_B voltages are shown in Fig. 14(a) for full load (I_L = max). The corresponding waveforms for no load ($I_L = 0$) are shown in Fig. 14(b).

Operation at No Load

At no load (load open circuit), capacitors C_A and/or C_B cannot get recharged, as shown in Figs. 13(a) and 14(b). Both C_A and C_B must be recharged, as shown at time t_0 of Fig. 13, before Q_P is turned on to provide another cycle. If C_A and C_B are not recharged at time t_0, the commutating circuit does not contain enough energy and the circuit will fail to commutate when load is applied.

When a load on the TRC cannot draw current, an added circuit element must be added to recharge C_A and C_B. Inductor L_R of Fig. 15 recharges capacitors C_A and C_B after commutation. While capacitor voltage e_{CB} is cycling, as shown in Fig. 14(a), energy is stored in L_R. After commutation, the energy of L_R is then transferred to C_A and C_B, recharging C_A and C_B to the voltage shown at time t_1 of Fig. 13(a). The operation of L_R was described in greater detail and will not be repeated here [10]. Inductor L_R can also be used in Fig. 11. The circuits of Figs. 11 and 12 can be operated at no load without L_R when "lock-out" techniques are used to prevent Q_P from turning on until C_A and C_B are charged. Lock-out techniques were described and will not be repeated here [10].

Motor Load or Filter Capacitor

When the load is a dc motor armature, back voltage can occur with E_L positive at the dot (Fig. 16). If the motor is coasting, the load current I_L drops to zero. In this mode of operation of the TRC system, the inductor L_R is needed to recharge C_A and C_B. The addition of L_R to Fig. 11 is insufficient, and the addition of Q_C in the circuit of Fig. 15 is needed. In Fig. 11, excessive current could flow from the load through L_A, L_B, and L_R. In Fig. 15, SCR unit Q_C blocks this current path. Otherwise, the circuits of Figs. 11 and 15 operate the same. A capacitor filter in the load, as used in regulated power supplies; can also disturb the operation in Fig. 11 but not in Fig. 15. In Fig. 15, the SCR units Q_P and Q_C are turned on at the same time. If Q_C is off when D_F starts to block voltage, the energy of L_A is consumed by D_F, and D_F would be damaged. The modification of Fig. 15 shown in Fig. 16 allows Q_C to be turned on at any time after Q_P is on. Figure 16 operates similarly to Fig. 12.

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