RF ENERGY COMPRESSOR*

Z. D. Farkas
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Abstract

The RF Energy Compressor, REC described here, transforms cw rf into periodic pulses using an energy storage cavity, ESC, whose charging and discharging is controlled by 180^o bi-phase modulation, PSK, and external Q switching, βs. Compression efficiency, C_e, of 100% can be approached at any compression factor C_f.

Introduction

There are many applications where we need a train of rf pulses, each pulse containing a given energy over a given time such as for charged particle accelerators, for radar and for communication. Usually the energy is built up during the time between pulses in a capacitor which discharges into an rf tube that converts the dc energy into rf. The REC performs a similar task, but it stores rf instead of dc energy. Just like a capacitor in a hard tube modulator, the ESC acts as a flywheel. It takes energy in between pulses and delivers it during the pulse. The control that tells the ESC when to accept and when to deliver energy is a low power 180^o bi-phase modulator. The energy is delivered at a rate determined by a switch that controls the effective size of the cavity opening, i.e., its external Q. We arrange the duration and rate of ESC charging and discharging such that average energy level in the cavity is such that during charging it accepts all the generator energy available and during discharging, delivers it, together with the generator energy available during discharge, into a load.

Theory

The differential equation that governs the emitted field amplitude of a tuned cavity with an incident field E_i is[1]

$$T_c(dE_e/dt) + E_e = \alpha E_i \tag{1}$$

$\beta = Q_o/Q_e$, $\alpha = 2\beta/(1+\beta)$, $T_{co} = Q_o/\pi f$, $T_c = T_{co}/(1+\beta)$ where β is the coupling factor, the ratio of emitted to dissipated power, α is the steady state emitted field, T_c is the cavity time constant, Q_o is the unloaded Q factor, T_{co} is the unloaded cavity time constant. Its solution during a time interval t_n, during which T_c and E_i are constant is

$$E_{en\ell} = E_{enf} + \left[E_{eni} - E_{enf}\right]\ell^{-\tau_n} \tag{2}$$

where

- E_{en} = the emitted field at the end of time interval t_n,
- E_{enf} = the steady state emitted field, the emitted field that would have been reached if t_n were infinite = $\alpha_n E_i$.
- E_{eni} = the emitted field at the beginning of interval t_n.
- τ_n = the normalized duration of the nth interval = t_n/T_{cn}.

If we have a given E_{ia} and Q_{ea} during interval 'a' and E_{ib} and Q_{eb} during the next interval 'b' and this interval pair repeats indefinitely, then the initial and final emitted fields during the two intervals are:

$$E_{ea\ell} = E_{eaf} + \left[E_{eai} - E_{eaf}\right]\ell^{-\tau_a} \tag{3}$$

$$E_{eb\ell} = E_{ebf} + \left[E_{ebi} - E_{ebf}\right]\ell^{-\tau_b} \tag{4}$$

* Work supported by the Department of Energy under contract DE-AC03-76SF00515.

Using $E_{eai} = \beta_a^{\frac{1}{2}} E_{cai}$ and $E_{cbi} = \beta_b^{\frac{1}{2}} E_{cbi}$ in Eqs. (3) and (4) and noting that E_c does not change during transition and hence $E_{cai} = E_{cb\ell}/\beta_b^{\frac{1}{2}}$ and $E_{cbi} = E_{ca\ell} = E_{ea\ell}/\beta_a^{\frac{1}{2}}$, we obtain

$$E_{ea\ell} = E_{eaf} + \left[(1/k)E_{eb\ell} - E_{eaf}\right]\ell^{-\tau_a} \tag{5}$$

$$E_{eb\ell} = E_{ebf} + \left[kE_{ea\ell} - E_{ebf}\right]\ell^{-\tau_b} \tag{6}$$

where $k = (\beta_b/\beta_a)^{\frac{1}{2}} = (Q_{ea}/Q_{eb})^{\frac{1}{2}}$. Solving Eqs. (5) and (6) simultaneously and using $\tau_2 = \tau_a + \tau_b$ we obtain

$$E_{ea\ell} = \frac{E_{eaf}\left(1 - \ell^{-\tau_a}\right) + (1/k)E_{ebf}\ell^{-\tau_a}\left(1 - \ell^{-\tau_b}\right)}{1 - \ell^{-\tau_2}} \tag{7}$$

$$E_{eb\ell} = \frac{E_{ebf}\left(1 - \ell^{-\tau_b}\right) + kE_{eaf}\ell^{-\tau_b}\left(1 - \ell^{-\tau_a}\right)}{1 - \ell^{-\tau_2}} \tag{8}$$

Using $E_{cai} = E_{eai}/\beta_a^{\frac{1}{2}}$ and $E_{cbi} = E_{ebi}/\beta_b^{\frac{1}{2}}$, we obtain $E_{eai} = (1/k)E_{eb\ell}$; $E_{ebi} = kE_{ea\ell}$; $E_i = 1$ during 'a' and -1 during b; hence, $E_{eaf} = \alpha_a$, $E_{ebf} = -\alpha_b$. The field traveling away from the cavity E_r, is the superposition of the field reflected from the cavity wave guide interface, $-E_i$ and E_e. Hence, $E_r = E_e - E_i$ and $E_{ra} = E_{ea} - 1$, and $E_{rb} = E_{eb} + 1$. Thus, by imposing the periodicity condition, we have solved for all fields. Two periods of E_c, E_e, and E_r are shown in Figs. 1a, 1b, and 1c respectively. An oscillogram of $|E_r|$ vs. time is shown in Fig. 2.

Conversion Efficiency

Define the modulation period, $t_2 = t_a + t_b$, the compression factor, $C_f = t_2/t_b$, and the conversion efficiency, which is the normalized pulse power, P_p, divided by the period, $C_e = 1/t_2 \int_0^{t_b} E_{rb}^2 dt$. Since $E_{rb} = E_{ebf} + \left(E_{ebi} - E_{ebf}\right)\ell^{-t/T_{cb}}$ we can obtain C_e as a function of β_a, t_2, C_f, k.

To gain insight and obtain an approximate solution for C_f as a function of k at maximum efficiency, we will consider the limiting case of τ_a, $\tau_b << 1$, β_a, $\beta_b >> 1$. Then, $E_{eaf} = \alpha_a = 2$, $E_{ebf} = -\alpha_b = -2$, $1 - \ell^{-\tau} = \tau$, $\ell^{-\tau} = 1$, $E_{ea\ell} = 2(\tau_a - (1/k)\tau_b)/(\tau_a + \tau_b)$. Imposing the zero reflection condition we set $E_{ea\ell} = 1$ and using $T_{ca}/T_{cb} = Q_{ea}/Q_{eb} = k^2$, and $C_f = (t_a + t_b)/t_b$, we obtain $C_f + (1+k)^2$ or $k = \sqrt{C_f} - 1$. In the limit $E_{ea} = 1$, $E_{eb} = k$, $E_{rb}^2 = (1+k)^2$. Thus $E_{rb}^2 = C_f$. Hence, in the limit of $\beta_a, \beta_b >> 1$ and $t_2/T_{co} << 1$, for any C_f from 1 to ∞ we can choose the proper k and obtain 100% conversion efficiency. It turns out that not only does the above relationship between C_f and k yield $C_f = 100\%$ at ideal conditions but also yields maximum efficiency when C_f is considerably less than 100%.

The maximum efficiency for the nonideal case is obtained as follows. For a given t_2, C_f, T_{co} there is a unique value of β_a that maximizes C_e. If β_a is too large, then T_{ca} is too small and a large fraction of the charging energy is reflected; if it is too small then a large fraction of the charging energy is dissipated in the cavity and α_a is too small. Plots of C_e vs. β_a for several values of τ_{2o} and for $C_f = 10$ are shown in Fig. 3. The curves are nearly independent of C_f. Figure 4 is a plot of C_e vs. τ_{2o} with β_a optimized for maximum conversion efficiency. As C_f increases above its optimum value, P_p increases but at a slower rate than C_f to a limiting value of $k\alpha_a + 1$. Thus, C_e decreases first slowly and in the limit of large C_f, inversely as C_f. The curves of Fig. 5 are plots C_e and P_p vs. C_f normalized to $C_f = (1+k)^2 = C_{fo}$, for which $C_e = 1$ under ideal conditions. The points shown were experimentally obtained.

If, during t_b, the incident field is turned off instead of shifted 180° we have βs only and $E_{ebf} = 0$ instead of $-\alpha_b$. Then, the ideal gain is $C_f - 1$ which can be approached if $C_f = 1 + k^2$. The bottom two curves of Fig. 5 are plots of C_e and P_p for βs only. The points shown were experimentally obtained.

Practical Considerations

The period is given by:

$$t_2 = \tau_{2o}T_{co} = \tau_{2o}Q_o/\pi f = \tau_{2o}\Gamma/R_s\pi f$$

Γ is the cavity geometric factor which depends only on cavity geometry and mode. $R_s = 2.61 \times 10^{-4} f^{1/2}$, f is the operating frequency in MHz. The surface resistance of a niobium cavity operating at liquid helium temperature, 4.2°K, $R_{ssc} = R_s 10^{-9} f^{3/2}$.[2] If we use a TE_{011} cavity for the ESC and we accept an efficiency of 86%, then $\Gamma = 780$ and from Fig. 4, $\tau_{2o} = 90 \times 10^{-3}$. Thus, with a copper ESC the maximum t_2 is 0.56 μs and with a superconducting ESC it is 3.7 ms. Using TE_{023} spherical cavities, such as used by Ray Alvarez at Lawrence Livermore Laboratories, Γ, and hence t_2 is increased by a factor of five.

The minimum pulse width, t_b, which determines the maximum C_f for a given period, is determined by the speed of PSK and βs switches. The maximum power output depends on the power handling ability and the maximum period on the minimum dissipation of the βs. Birx and Scallopino have reported a high intensity electron beam switch which can function in an evacuated x-band superconducting waveguide.[3] They obtained Q_e ratios of 4×10^3 and T_{ca} of 500 μs. Using an electron beam is analogous to a hard tube modulator. However, it can be much simpler because it does not require to hold off the high power amplifier voltage, and to carry the amplifier current.

The PSK switch does not limit output power because the power amplifier is interposed between the PSK switch and the ESC as shown in Fig. 6, so that the PSK switch operates at low power. Thus, for C_f approximately four, only low power switches are required. If $C_f = 4$ then $k = 1$ and, therefore, for this special case we approach 100% compression efficiency without β-switching, using PSK only. At the Stanford Linear Accelerator Center (SLAC) using single pulse PSK, and TE_{015} ESC we have obtained output powers in excess of 125 MW. To illustrate the versatility of the REC I'll list in the table below the parameters of the present and several REC modes of SLAC operation, if we keep the 114 kw AC power input but replace the 50% efficient 38.5 MW, pulsed klystrons with 65% efficient 60 kW cw klystrons (assume 80% AC to DC efficiency), and install REC with niobium ESC at 4.2 K. The values are calculated as follows. $T_{co} = 75$ ms, $\tau_{2o} = t_2/T_{co} = 13.3/\text{PRF}$. Obtain C_e from plot of C_e vs. τ_{2o}, Fig. 4. $P_p = 10^3 P_{cw}C_e/(\text{PRF})(\text{PW})$, $V = 30(P_p/38.5)^2$. P_{cw} is the cw klystron power in kW, PRF is the pulse repetition frequency in s^{-1}, PW (or t_b) is the pulse width in us, and V is the SLAC beam voltage. The peak current I_p, and average current I_a are limited either by 10% loading, I = 2.86V, or by cw beam breakup, I = .4V, or by 1.5 us pulse beam breakup, I = 70V/24. dc is the duty cycle.

PRF 1/s	PW us	P_p MW	V GeV	I_p ma	I_a ua	dc %
360	2.5	38.5	30	87	50	.06
360	2.5	61	38	87	50	.06
180	1	287	82	200	11	.005
133	.9	427	100	200	8	.004
cw	cw	.06	1.2	.400	400	100
10^5	2.5	.24	2.4	7.0	1120	16
10^4	2.5	2.35	7.4	21.6	345	1.6
10^3	2.5	23	23	67	107	.16

With REC we can attain higher peak power, duty cycle, and average current than without REC. REC can be installed were cw klystrons already exist, as in electron-positron storage rings, and increase the beam energy as the number of bunches in the ring decrease. It is possible to have relatively closely spaced 2 or more pulses, and consider t_b as the sum of their widths, as long as in a super period the energy into the cavity is equal to the energy lost by it. It is also possible to have different length consecutive periods as long as for each period $C_f = (1+k)^2$.

A means has to be provided to separate the reverse and forward powers. The simplest way is to connect the generator, cavity, and load, each to one of the arms of a three-port circulator. A second method, which does not have the power limitations of the circulator is to connect the generator, two identical cavities and the load to consecutive ports of a 3-dB hybrid as shown in Fig. 6. A third method is to use a resonant ring.

Conclusion

It was shown that rf energy compression with a gain of four at compression efficiencies nearly 100% and up to a gain of eight with compression efficiencies above 60%, at power outputs in excess of 100 MW are possible, using a low power microwave switch whose insertion loss is of no consequence. At low power, high efficiencies and high compression ratios can be attained if we limit the period. To attain high compression factor at high power levels depends on further development of a low loss, fast turn-on turn-off high power microwave switch.

Acknowledgement

Thanks to D. L. Birx of Lawrence Livermore Laboratories for enlightening discussions.

References

1. Z. D. Farkas et al., "SLED: A Method of Doubling SLAC's Energy," Proc. of 9th International Conf. on High Energy Accel., p. 576, May 1976.

2. P. B. Wilson, "The Theoretical Surface Resistance for Superconducting Lead and Niobium at High Frequencies," SLAC-TN-70-35, December 1970.

3. D. L. Birx and D. J. Scallapino, "Microwave Energy Compression Using a High Intensity Electron Beam Switch," to be published in Applied Physics Letters, 1980.

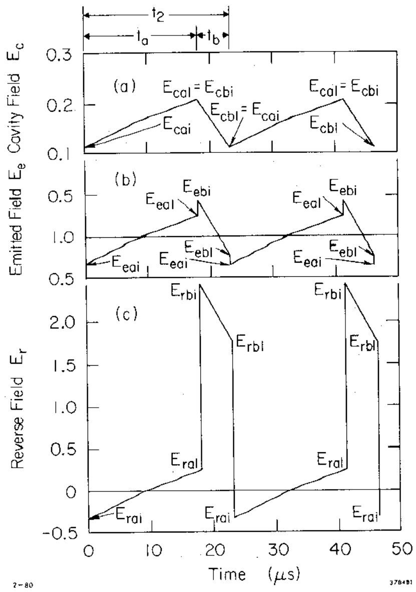

Fig. 1. REC fields vs. time.
(a) Cavity field, E_c.
(b) Emitted field, E_e.
(c) Reverse field, E_r.

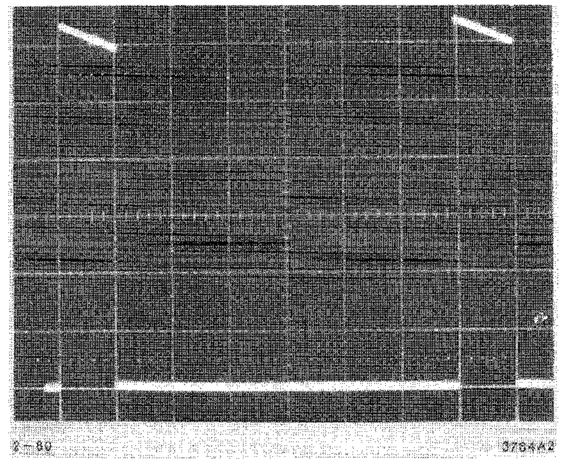

Fig. 2. Oscillogram of $|E_r|$ vs. time (10 μs/cm).

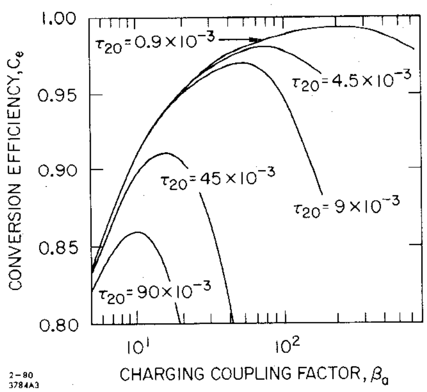

Fig. 3. Conversion efficiency C_e vs. charging coupling factor β_a, for several normalized periods, τ_{2o}.

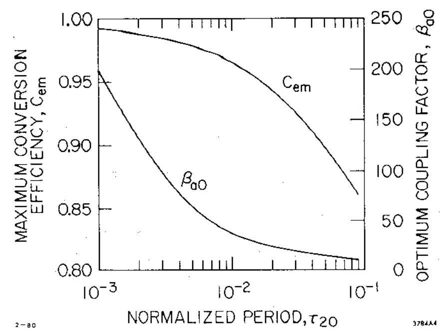

Fig. 4. Maximum C_e, C_{em} and optimum β_a, β_{ao}, vs. normalized period τ_{2o}.

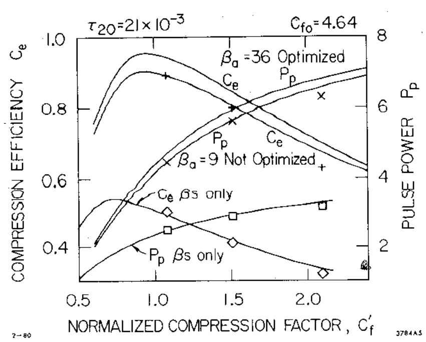

Fig. 5. Conversion efficiency, C_e, and normalized pulse power, P_p, vs. normalized compression factor $C_f' = C_f/C_{fo}$.

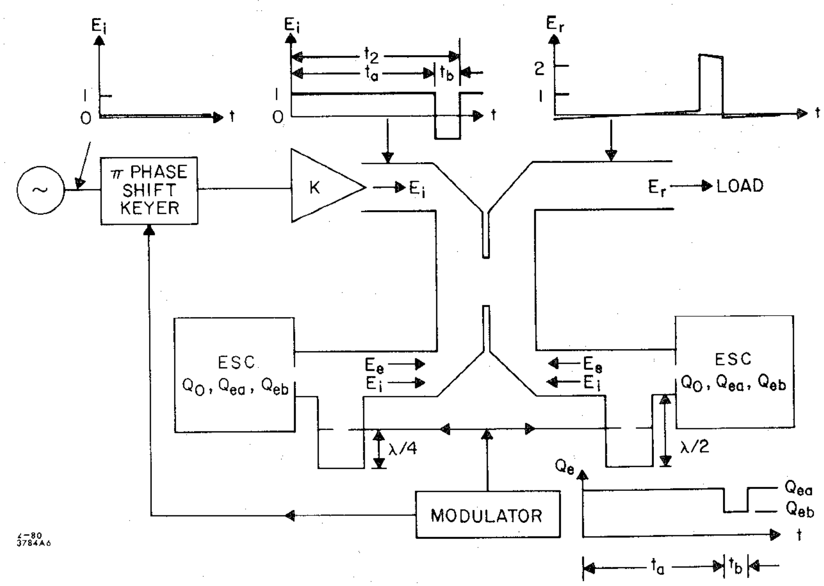

Fig. 6. RF energy compressor system.