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HIGH PERFORMANCE MAGNET POWER SUPPLY OPTIMIZATION*

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Introduction

The power supply system for the joint LBL-SLAC proposed accelerator PEP provides the opportunity to take a fresh look at the current techniques employed for controlling large amounts of dc power and the possibility of using a new one. A basic requirement of ± 100 ppm regulation is placed on the guide field of the bending magnets and quadrupoles placed around the 2200 meter circumference of the accelerator. The optimization questions to be answered by this paper are threefold:

(1) Can a firing circuit be designed to reduce the combined effects of the harmonics and line voltage unbalance to less than 100 ppm in the magnet field.

(2) Given the ambiguity of (1), is the addition of a transistor bank to a nominal SCR controlled system the way to go or should one opt for an SCR chopper system running at 1 kHz where multiple supplies are fed from one large dc bus.

(3) The cost-performance evaluation of the above three possible systems.

The rate of "filling" the machine from SLAC with electrons and positrons is in the 3-5 minute area, so the velocity constant requirements are satisfied with a closed loop bandwidth of approximately 15 hertz. Because of this minimal requirement on system bandwidth for control reference inputs the 6 pulse thyristor controlled supply could suffice. Also, because of the attenuation to ripple components at the 6 pulse frequency and higher provided by the magnet structure and beampipe to these frequency components in the magnet voltage, again the nominal 6 pulse SCR supply will suffice with possibly some nominal filtering. In the third critical area where judgement must be passed on whether a 6 pulse supply is adequate for the task, that of response to line voltage perturbations, a new look at some old theory with some surprising results will show that the 6 pulse supply is marginally adequate. Finally, and obviously, the low frequency drifts and variations due to temperature, supply voltage, etc., as they affect the current monitoring means and front-end drift of the error amplifier can be minimized to whatever extent necessary independent of the kind of high-powered controller chosen for the task.

So what, after all, is this paper to be about if the conclusion is so obvious as the foregoing would imply? In a word, it is the Firing Circuit that makes a more careful analysis necessary. In the High Voltage Direct Current (HVDC) transmission field where controlled rectifiers and inverters are used to transmit large amounts of power in association with ac systems, the source impedance of the system can be such that normal and abnormal harmonics can develop sufficient voltage to affect the operation of the firing circuit in such a way as to cause further buildup of the harmonics by means of the terms present in the current drawn by the supply. This positive-feed-forward effect has been well documented both in HVDC simulators and in actual operating conditions and has caused a great deal of development into types of firing circuits where the positive feed-forward does not exist. At the Bevatron the "talking" between supplies is readily observable by monitoring a transductor signal with an oscilliscope from one supply among many. With the trace line-signal and 6 to 12 pulses of ripple observable, the pulses can be seen to be jumping up and down, sometimes randomly, sometimes forming a harmonic which fades in and out as the supply output varies in following the pulsing Bevatron. The variations are generally at the 1000 ppm level.

Firing Circuit and Six-Pulse Controlled Rectifier

In 1968 J.D. Ainsworth of English Electric Ltd. attacked the instability problem of controlled rectifiers operating from ac systems with nominal source impedances,[1,2] and solved it by employing a new type of firing circuit. The instability problem arises from the fact that conventional firing circuits can both generate and amplify harmonics other than the normal order of Kp ± 1 (5, 7, 11, 13, etc.). These non-characteristic harmonics occur because the conventional circuit uses six timing voltages from the 3 phase system to provide the zero crossings which determine the $\alpha = 0$ points for the six time delays controlled by the error voltage (see Figure 1). The ability of one phase to alter a subsequent one by means of its line current being reflected through the source impedance provides the means for other-than-normal harmonic magnification. Figure 3 shows in closed loop form the effect of feeding a converter from an ac source with $R_1 + L_1S$ impedance.

There is some difference of opinion between the various authors in the HVDC field regarding abnormal harmonic generation. Whereas Ainsworth shows by symmetrical components how the abnormal harmonics can be magnified by the interaction of the converter and a simple reactive ac system impedance, other authors such as Lips and Stratford attribute the difficulty to parallel resonances between the source impedance and series filters put in for the various normal current harmonics. At the least it can be said that a parallel resonance at one of the harmonics of the ac system would exacerbate the harmonic generation of the converter at that frequency.

Ainsworth solved this interaction problem by postulating and creating a firing system with a voltage-controlled oscillator where there is no direct tie to the ac system at all (Figure 2). In steady-state the error signal determines the output frequency to be exactly six times the ac supply frequency, with the phasing of the ring counter locked in step to give the correct distribution of the firing pulses. Of course, other phase-end stops must be provided to prevent the circuit from losing synchronism at turn-on or during large transients.

Among the many types of equally-spaced-pulse firing circuits being conceived, a fundamental structural difference divides them into two categories -- those with proportional and those with integral response to changes in control voltage. In the integral type such as those of Ainsworth and Ekstron,[3] a change in control will cause the phase of the firing pulses to continually change as long as the voltage is applied because these are basically frequency control devices. Thus the overall analogue loop must be closed to maintain an operating point. Whereas circuits of the type like those of Rumpf[4] and Groenboom[5] will change phase in proportion to a change in control voltage and thus are readily controllable open loop. The latter type of operation has a decided advan-

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tage in terms of flexibility and maintenance. It also permits the shaping of the frequency response characteristics to be tailored at will with compensation around the control operational-amplifier, rather than having to live with a characteristic inherent in the firing circuit. An additional important advantage of using a single (voltage controlled oscillator) + (phase locked loop) scheme multiplexed for the number of thyristors used, is that the varying offsets and gains of the multiple-AC-input-comparator scheme with the subsequent sub-harmonics in the dc output are eliminated.

It should be mentioned at this point in discussing harmonics that one of the system design decisions regarding whether or not to increase the number of pulses from 6 to 12 involves not only ripple and speed of response considerations on the dc side, but also what is the tolerable level of 5th and 7th harmonics on the ac system. The paper by Stratford and Steeper[6] contains a wealth of information of reactive compensation and harmonic suppression, including the abnormal-harmonic-converter problem. A brief summary of this work as it relates to the optimizing problem faced here follows. Converters that control dc power by phase-control of their firing-angle directly affect the reactive power drawn from the ac system as shown in Figure 4. The situation is alleviated by sequential control of multiple converters (2 shown in Figure), and/or by adding capacitors to the ac system. Unfortunately the capacitors must be switched depending on the reactive requirements, but economic considerations may necessitate it. Reactive volt amperes (VARS) cost from $0.15 to $0.30 per KVAR-month from a utility. The utility usually furnishes reactive power without charge for power factors of 0.95 and above.

Power companies do not charge for absorbing harmonic currents generated by power converters, but often insist that the user reduce the harmonic to an accepted level. This level is not well defined but generally is around 2%. The maximum amplitudes of harmonics are given by $I_n = I_1/n$ where I_1 is the fundamental and n is the harmonic number. Just taking the lowest order harmonic current product with the system impedance will give considerably lower voltage than that arrived at by using the Distortion Factor which includes all the harmonics.

If power factor capacitors are used, harmonic traps can be constructed by dividing up the capacitors and combining with the appropriate L^S and R^S. The parallel resonances with the source impedance must be carefully calculated to avoid harmonics of 60 Hz.

Perturbation Reduction

Before making a decision on whether or not a transistor-bank must be employed in addition to the thyristor controls on the dc current, there must be a clear understanding of the effective band-width of the system to line voltage perturbations. For it is through this voltage channel that wideband noise is introduced into the system; the slow thermal time constants are sufficiently reduced by the low frequency gain of the system.

The perturbation signal U is shown on Figure 5 to be introduced at the output voltage of the supply. Treating a system for the moment without any voltage filtering gives a G = 1 in the feed-forward path. In feedback is the term H = K/s, which is the result of cascading the magnet transfer function (pole), the transductor, the error amplifier with pole-zero compensation, and the power supply. The transfer function:

$$\frac{V}{U} = \frac{1}{1 + \frac{K}{s}} = \frac{s}{s + K}$$

is shown in the Figure 4 Bode plot to reach unity gain where s = K. This closing frequency is typically 80-100 hertz at best in a 6 pulse system to avoid the p60/2 frequency and sub-harmonic oscillations. Beyond this frequency the loop cannot attenuate any noise introduced at U. But the transference of interest is actually from the white noise input U to the magnet current (or better yet the magnet field Φ), so an added cascade term must be added. (Of course, this could have been done in the original loop as the feed forward term G, but separation as done here gives a more graphic and completely equivalent result). The Bode Plot of Figure 6 shows the additional cascaded term and the resulting overall transfer function from perturbation to magnet current. The result shows that the minimum attenuation available at any frequency is equal to the ratio of the closed loop frequency to the magnet corner-frequency (or the product $\omega_{cl.\ loop}\ T_{mag}$). With a magnet time constant of 1 second and an 80 Hz. closing frequency, for example, the ratio and therefore the least attenuation is 500. Thus a ± 5% white noise spectrum coming into a power supply through the line voltage would be everywhere reduced to at least ± 0.01%, and beyond the $f_{mag} - f_o$ range have proportionally greater reduction.

The emphasis of the above analysis is that the minimum attenuation to white noise inputs (typically 1-5%) can be possibly enough at all frequencies (depending on the f_o/f_m ratio) to meet specs; but the major pulse frequency component in the output voltage (32% at p = 6) may have to be reduced further to reach say 100 ppm in the current. This further reduction in the current ripple component is normally done by LC filters but at a substantial price because the loop closing frequency must be lowered to keep the loop stable, with a corresponding reduction in the all-band attenuation. A far better approach is to measure the transfer function from magnet voltage to $\int H \cdot d\ell$, taking advantage of the substantial attenuation through the magnet structure and beam pipe, and then design the filter based on the data. This measurement will shortly be done on the prototype PEP bends and quadrupoles.

Transistor Systems

Given the kind of attenuation that exists between line voltage perturbations and the magnet current or field, and assuming the new constant-pulse-spacing firing circuits will solve the harmonic instability problems, it would seem that the thyristor bridge circuit was as far as one had to go for 100 ppm system. But unfortunately the controlled rectifiers are made of thyristors which really act like switches and their "time-quantized" nature means that if just after a thyristor in one leg of a bridge has turned-on there is a line voltage perturbation, there cannot be a correction for on-the-average 1/360 seconds. Assuming the one second time constant used before, and an idealized corrective response from the analogue part of the current regulating loop, the error in current for a 5% perturbation would be 5% x 1/360 = 0.014% or ≈ 1/7000, slightly worse than allowable for a 100 ppm system. The optimum voltage filter would have a 90-150 Hz (not 120 Hz) corner frequency, in order to slow down the leading edge of the step while minimumly affecting the loop closing frequency.

Normally transistor banks, either in shunt or series, are employed to bring performance in line with the specifications (and go beyond the 100 ppm required here if needed). Two recent papers from CERN,[7,8] the first describing the ISR Main Ring Magnet Power Supply and the second describing the supplies for the Transport to the ISR, give excellent accounts of two different kinds of solutions. The first system with a dc rating of 1850 V and 3750 A, utilizes a transformer in series with the filter capacitor to couple a low impedance, ripple-bucking voltage source into the system, and gets good loop characteristics with the transistor source as a parallel feed-forward element along with the power supply (including a stretch from 900 Hz to 3.6 kHz where the gain is dropping at 60 db/Decade before crossing unity with only one decrement!). This approach seems similar to the shunt transistor banks used for the Bevatron EPB system in the early 1960's, but that system didn't have the magnitude of voltage employed here nor were the transistors protected from surges in the nice fashion the ISR units are (which accounts for why we periodically had to replace 100^s of 2N174^s).

The series system for the various transport magnets involves a large transistor bank because of the necessity for carrying all the current. The authors show that in open-loop the voltage perturbations coming from the power supply (with its separately closed voltage loop) are attenuated an order-of-magnitude by the common-emitter characteristics of the 2N3771 transistors. The voltage loop around the transistors closes at 1K Hz. In order for the four cascaded loops to remain in control at all times the cascaded "course" (follower) loops are successively faster than the speed of the "fine" (master) loops. Thus the thyristor loop with a closed loop break point of 30 Hz is the fastest loop.

Recent work with the Pole-Face-Winding-System of the Bevatron has opened up new packaging possibilities for transistor banks. Using glass-epoxy boards purchased with regular 2 ounce copper on one side for the base and monitoring circuitry (etched out), and 7 ounce copper over the entire other side for the emitter bus, the board mounts on the opposite side of the heat sink from the transistor on small insulators. The connections to the transistor base and emitter pins are made by Burndy female connectors which are riveted and then soldered to the appropriate buses. The connectors are cool at 10A and the bus can handle approximately 300A. Each transistor's emitter-resistor voltage is monitored and brought to a common point where a multiplexer periodically can check on the number of failures.

Chopper System

One way to avoid the difficult and expensive task of deciding which type of transistor configuration to use, how to make its loop compatible with that of the thyristor supply, and how to fabricate and protect the bank for maximum reliability, is to avoid the task entirely and use a chopper system instead with a thyristor as the switch. Even though the chopper is a time-quantized controller, (but one that must be artificially rather than naturally commutated as in the AC-fed circuit), it can decrease both the average delay time and small-signal loop time-constant in direct proportion to its increased repetition rate over the 6 pulse system. If a system is close to meeting its performance requirements with a 6 pulse thyristor system, going over to a 4 or 5 times faster chopper system might be more desirable than adding the transistor bank. The desirability naturally is a mix of a cost and reliability comparison of the two choices.

On a single supply basis the cost comparison between the thyristor bridge, with and without transistors, and the chopper can be made. But on a large system such as that of PEP, it would seem that substantially greater savings could result from converting a far larger block of power from ac to dc in a single transformer-rectifier supply and then running a large number of choppers and inverters from this one dc bus. A comparison of this larger nature will be done shortly for bend magnet portion of the PEP system.

The basic chopper circuits most commonly used is the Jones circuit, or one of its many variations, where a commutating capacitor is placed across the main chopper thyristor (which is already conducting) by turning on a second thyristor when it is time to turn off the chopper. The capacitor voltage back-biases the chopper thyristor, and the capacitor must have sufficient capacity such that with the load current now flowing through it, the chopper is kept back-biased for more than its turn-off time (T_{off} = 20 to 100 μsec, depending on the thyristor chosen). During the turn-off time the capacitor voltage is adding to the source voltage appearing across the load, with a proportional increase in the magnitude of ripple voltage. Between turn-offs (during on time) the capacitor voltage must be reversed and brought up to sufficient voltage for the next turn-off by additional circuitry. This Jones circuit has proven to be a reliable one but suffers the disadvantage that the minimum output pulse must be 5 times or greater than T_{off}, because of the addition of the thyristor off time and ring up time of the capacitor during its recycling (both occurring during the ON time).

A circuit which has completely eliminated the minimum ON time and also doesn't raise the load voltage to twice the supply voltage during commutation is shown in Figure 7.[9] Here the capacitor voltage is developed across the series choke and thus turns off the thyristor by bucking the supply voltage, giving an immediate voltage turnoff and current commutation to the free-wheeling diode at the output. During the OFF period the current in the series choke is kept circulating by means of the diode around it and at a higher value than that of the load current. Thus at the turn-on pulse the load current can immediately flow through the choke and thus not experience any turn-on time constant.

The length of this paper prevents going further into a detailed description of the circuit operation. The same commutating arrangement is used with a bridge composed of thyristors and diodes and an output transformer to make a single phase inverter. A three phase inverter is formed in the same way by adding another pair of thyristor-diode combinations with the center point brought out as the third point of the size. These circuits are in operation in various welding, induction heating, and dc power applications up to 500 kW in size. Choppers have been used widely in rail transportation equipment, especially in Europe, and have proved their reliability of operation.

Costs

In attempting to give a technical basis for choosing between the three alternatives proposed, this paper has run low on space for that very important fourth dimension of costs. A recently completed PEP Power Supply System cost estimate based on permanently installed, rack mounted units, with major functional elements purchased separately, shows twenty-three 200 kW, 167 V @ 1200 A, thyristor-transistor supplies as the major item. These supplies are estimated at $20,347 or $102/kW, which includes all the installation costs with substantial ac and dc cabling (45 ft. and 25 ft. respectively). Nine of these supplies are intended for the main Bend and Quad series circuit of the ring, with groups of three distributed around the ring at three locations. This 200 kW size supply lends itself nicely to 480 V distribution from control centers, 167 V is a reasonable voltage for a shunt transistor bank, and power control with minimum reactive power is readily accomplished with sequential turn-on. But the low dc voltage puts the chopper system at a cost disadvantage, which would be more than offset in all the other 200 kW applications (to separate loads) by running them from one large rectifier supply. For the record: on a 200 kW single supply basis with its own transformer, diode bridge, and chopper, rather than the quoted system above, even with the voltage disadvantage, the price still drops by $445.

But on a 600 kW basis, with one supply replacing the three 200 kW units in series, a chopper system costs $23,635, or only $40/kW compared to a thyristor system (without transistors) of $21,912, or $37/kW. A transistor unit would have to incorporate a transformer coupled system similar to that employed on the ISR at CERN mentioned earlier, and I don't know the costs well enough to make an estimate, but suspect they could come out well above the chopper cost, but far cheaper than the total for three seried 200 kW supplies.

Conclusion

The technical considerations between the three types of systems are understood, although actual performance data on the chopper system must be obtained. The costs are not yet well enough defined because of the different "mix" when going from the transistor-thyristor combination to a chopper system.

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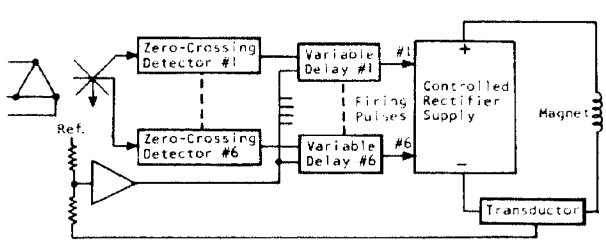

figure 1 Equal-Angle Firing System

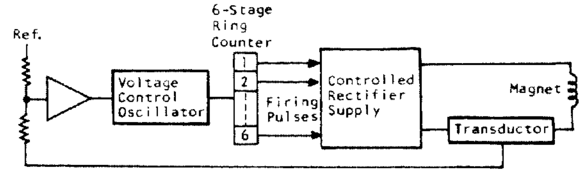

figure 2 Equal-Spaced-Pulses Firing System

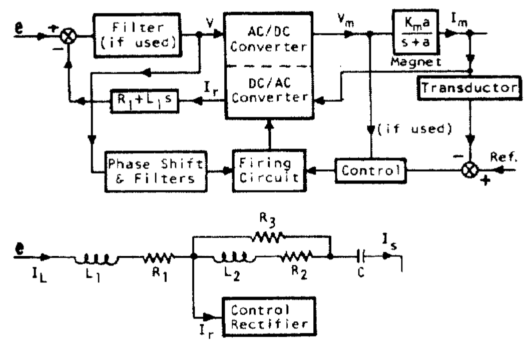

figure 3 Interaction of DC & AC Systems

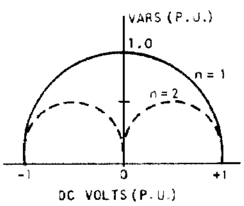

figure 4 Reactive Power vs Converter DC Volts (I_{DC}=100%, X_c = 0) n = Number of Converters

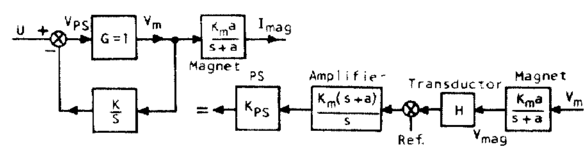

figure 5 Perturbation Attenuation Block Diagram

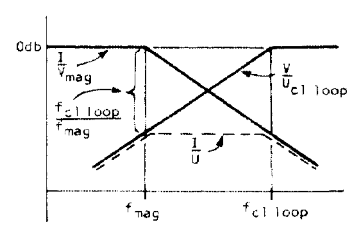

figure 6 Perturbation Attenuation Bode Plot

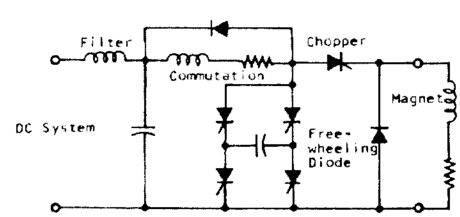

figure 7 Chopper Schematic