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Summary

In mid-December 1966, severe fracturing of the Bevatron generator pole dovetails was discovered before the failure became catastrophic. New poles had to be procured and installed on both generators. This refurbishing consumed six months during which the Bevatron was inoperable--raising doubts in the scientists minds whether the failure could indeed be termed noncatastrophic.

The failure was eventually attributed to a fatigue condition arising from increased alternating stress loads associated with generator speed changes during flattop. When the generators were returned to service a restriction was placed on the length of flattop. Cracks again began to be seen on the outermost laminations after several months. Many means were investigated to make corrections by mechanical changes, but all such schemes were repugnant because of large costs and extended shutdown for installation.

In parallel with the mechanical studies, electrical engineers were investigating different electrical approaches - schemes that would achieve flattopping but minimize generator speed change. In June 1968 a test installation was made of the most promising method. The restricted flattop then being allowed was achieved with less generator speed change than occurs during normal full-energy pulsing. Flattop times have gradually increased from 0.6 to 2 s, while generator speed change has still been held to no more than normal pulsing. No propagation of existing cracks or initiation of new cracks has been observed, but careful surveillance continues.

Dovetail Neck Cracks and Fractures

The initial dovetail neck fractures were discovered at a regular weekly maintenance inspection. The air gap over a particular pole was much reduced. Closer inspection disclosed the parted dovetails. However, the extent of the fracture was not fully appreciated until the pole was removed (see Figs. 1 and 2). A second pole had approximately 1/3 this degree of fracturing, and the outer faces of two other dovetails were cracked entirely across.

Fractures had started at the top of the pole-retaining key, which was also the tangent point (stress concentration point) of a dovetail radius. The top of the key was sharp and appeared to have generated a detectable notch in the dovetail laminations. This would appear to be sufficient cause for the observed damage. However, as more poles were removed and examination became more comprehensive, this theory had to be relegated to that of a contributing factor, not the fundamental cause, because many dovetails had cracks on the face opposite the key and no crack on the key side. Of 64 possible locations for fracture initiation, 40 had cracks. Five end laminations were fractured entirely across, 16 cracks had started on the key side, and 14 had started on the face opposite the key.

Operations History

The generators had delivered 37.4 million pulses to the Bevatron when the dovetails fractured; 22.6 million of these pulses occurred while normal full-energy pulsing was the mode of operation, before the Improvement Program of 1962-63. However, this early period also contained the higher rate of electrical faults--a trouble which was gradually reduced over the years. It is estimated that approximately 10^4 faults at half energy or above had occurred prior to the dovetail failure.

After the Improvement Program, flattopping became the dominant type of operation. Initially, flattops were only 300-ms long. This mode became very popular; more and longer flattops were supplied. It is estimated that the latter part of the 14.7 million cycles between 1963 and the failure contained 4 million cycles of 1-s flattop operation.

During normal pulsing, both 48-kVA generators deliver current to the Bevatron magnet. At peak current the electrical equipment is inverted, the generators become motors, and the stored energy in the magnetic field is returned (except for system losses) to 70-ton flywheels. During the period from 1963 to June 1968, flattopping was accomplished by inverting only one generator when a peak current was reached. One generator thus maintains a constant current through the magnet while driving the other generator as a motor. For long flattops the speed of the driving generator is much reduced (since energy is drawn from stored energy of rotation) and speed of the driven generator is much increased. To maintain average speed the driving-driven relationship is alternated every other pulse. This scheme is relatively prodigal of power, since 50 MW is used to make up the 13 MW of copper and fixed losses required for maintaining constant magnet current. Nevertheless, operation was very reliable and controllable, and much new physics was accomplished during the years of its use.

TABLE I. HISTORY OF LOAD CYCLES AND CALCULATED STRESS LEVELS ON THE BEVATRON GENERATOR POLE DOVETAIL END LAMINATIONS*

Period of operation, number of pulses and mode of operation	Usual generator speeds (rpm)		Dovetail combined stress Steady stress ± cyclic stress	Remarks
1) 1958 to June 1962 (pulses 0 to 22.6 million) Normal full-energy pulsing - no flattop	870 maximum 816 minimum	54 range	41,400 ± 6,000 psi	No dovetail troubles
2) March 1963 to December 1966 (pulses 22.6 to 37.4 million) Start of flattopping operation 4 million of 14.8 million cycles at 1 sec flattop	887 maximum 775 minimum	112 range	43,000 ± 11,900 psi	Massive dovetail fracturing - 2 poles 28 of 64 possible regions have cracks Install new poles
3) June 1967 to May 1968 (pulses 37.4 to 41.3 million) Flattop restricted to 0.8 secs 3.9 million net pulses	885 maximum 791 minimum	94 range	43,600 ± 9,900 psi	6 cracks initiated and grow slowly 1 crack grows rapidly into 9th lamination
4) May 1968 to February 1969 (pulses 41.3 to 44.4 million) Flattop restricted to .52 secs (.5 million pulses) New flattop mode to 2 secs (3.4 million pulses)	880 maximum 807 minimum	73 range	44,300 ± 8,200 psi	No new cracks No further growth of existing cracks

*Note: In all cases end lamination stress = 2.33 mid-rotor lamination stress.

Cause of the Fracturing

Many factors were examined in attempting to identify the source of the trouble; space restrictions prevent their discussion here. D. C. Philbrick of the generator manufacturer's engineering staff finally proposed the mechanism of failure now believed to be the source of the trouble. As shown in Table I, full-energy pulsing causes a generator speed change of 54 rpm per pulse. Changing centrifugal forces produce alternating stresses estimated by the author at ±6000 psi in the pole dovetails. The larger speed range of 112 rpm due to 1-s flattopping essentially doubles this cyclic stress. The dovetails had seen approximately 2 million cycles of this extra load before failing. This extra cyclic load is believed to be the culprit.

An uncertainty exists as to the actual magnitude of these numbers. The loads and stresses on laminations near the middle of the generator rotor can be estimated with a high level of confidence. However, the end laminations carry the extra load of the coil crossing over the ends of the pole. Attempts to estimate the distribution of this additional load suffer from the number of assumptions required. That failure is known to have occurred allows use of another route. Calculate various degrees of loading and plot them on a Goodman diagram. This line intersects the failure line on the diagram, thus defining the probable load factor. Such an estimate is shown in Fig. 3, yielding a probable end-lamination load factor of 2-1/3, i.e., the end lamination carries 2-1/3 more load than mid-rotor laminations. The stresses shown in Table I were calculated by using this factor.

Other unknowns may operate to affect the actual magnitude of the numbers shown. For example, the laminations have an "as sheared" edge in which tiny cracks (0.001 to 0.003 in.) are observed. These cracks have the effect of an additional stress-concentration factor, which would raise the apparent cyclic stress. The end-factor load line would move up, and failures would occur at reduced load factor. Nevertheless, the relative proportions of cyclic load between the four cases shown in Table I would change little, and the fundamental argument remains valid.

Full-scale dovetail fatigue tests were undertaken to evaluate the surface-condition effect and to prove other aspects of the failure. Trouble has been encountered in making the sample grip reproduce the very stiff restraint of the generator rotor slots. This program is continuing as nonpriority time becomes available on a large testing machine.

Granting this hypothesis as the source of trouble and knowing that millions of cycles had occurred before failure, one recognizes that a small reduction in alternating stress would give a very large increase in dovetail life. Accordingly, when the new poles were installed and the generators returned to service, the flattop operation was restricted as shown in Table I. An extensive program of surveillance was also instituted. All accessible dovetail faces were visually inspected each week. In addition, a new type of strain gage was utilized. This gage changes resistance a few percent before a crack can be visually observed. In service the gages gave about two weeks' warning before a crack was visually confirmed.

During the first 10 months of operation with the new poles, five new cracks were observed on end laminations. Their growth was carefully watched, and eventually small holes were drilled at the ends to stop further propagation. As long as the cracks were confined to the first one or two laminations it was presumed that their initiation could be attributed to load-relieving mechanisms peculiar to the poorly restrained end faces. However, after 10 months and 1.9 million pulses, another crack generated and progressed rapidly (1 week) into the 3rd and 4th laminations. Drilling holes to stop propagation had little effect. The cracking finally reached the 9th lamination. At this juncture the speed range due to flattopping was again restricted, as shown in Table I. No further propagation of existing cracks was observed and no new cracks were initiated in the next two months. At this time the new mode of flattopping described in the following sections was introduced. Flattop of 0.6-s showed generator speed change of 40 rpm--less than that for full-energy pulsing. Speed change for 2-s flattops is comparable to that for full-energy pulsing. No further crack initiation or propagation has been observed. At some future scheduled shutdown the pole with defects through the 9th lamination should be exchanged for an existing spare. Thereafter, with care, further increases in flattop time or energy should be permissible, provided generator speed change is limited to something less than 70 rpm.

Electrical Reconnection of the Power Supply

The electronics department considered the electrical reconnection of the converters of the power supply to obtain continuous power balance between the two motor-generator sets. With power balance, the speed range of the M.G. sets would be reduced to a minimum, and the mechanical problems would be alleviated. If a compatible reconnection were possible the cost would be small compared with any mechanical redesign, and the outage time of the Bevatron would be minimal.

Method and Apparatus

The Bevatron magnet power supply consists of two motor-generator sets and eight converter units. Each of the 12 phase generators consists of four three-phase electrical systems connected to four three-phase half-wave converter units. To provide voltage and current capabilities, two converter units are connected in series and two series groups are paralleled across an interphase transformer. The range of control of each converter unit provides for rectification (positive output voltage) and inversion (negative output voltage).

Original Flattop Connection

The original connection for providing the flattop mode is illustrated in Fig. 4. One generator with its associated converters is designated by "A," the second system by "B." The number associated with a letter--i.e., 1A--is the converter unit number. The numbers joined by hyphens--i.e., 1-5-9--represent generator phase numbers. Positive and negative signs at the converter terminals represent the dc output polarities during the flattop periods only. The direction of flow of the magnet current is represented by the arrow and the capital I. The interphase transformer is designated by IPT.

This connection permitted the net voltage of each generator and converter system to be independent of the other, and thus the speed range of the two M.G. sets could be as great as 120 rpm; this large speed excursion occurred with the introduction of flattop operation. Flattop operation required reducing the net magnet voltage to only the resistive drop of the magnet; this was accomplished by inverting all the converter units of one generator and rectifying the others. The rectification and inversion sequence was alternated between two generators on each consecutive magnet pulse: therefore, a large amount of energy was exchanged between the generators, and the speed varied accordingly.

Within certain limits the converter units are electrically independent and can be controlled separately. Thus the eight converter units allow electrical reconnection in certain orientations to provide power balance. In addition, a number of other requirements must be fulfilled: (a) A torsional oscillation of the motor-generator shaft is produced by step power changes during a magnet pulse.. By posicast control of the converter units it is possible to suppress the shaft oscillation. Posicasting requires a compatible phase-sequence order of the converter units.
(b) The interphase transformer can support only 15 V-s before the core magnetically saturates. Therefore, a correct phase sequence of the converter units across the transformer is required so that the ripple voltage does not saturate the core. Saturation, during switching periods of the converters, unbalances the currents in the parallel branches, thereby relaying off the power supply.
(c) A means of synchronizing the two generators is required if the converter units of the two generators interface each other within an interphase transformer connection. This is necessary to accommodate the limitations of the interphase transformer and to provide for precision control of the power supply.

Experimental Results

An evaluation of four reconnections was made and a preferred one selected.

Connection No. 1

The first test circuit required only changing the controls to the converter units so that the flattop electrical excitation to each generator was identical--each containing two rectifying units and two inverting units. For a 6500-A, 1-s flattop, the speed excursion of each M. G. set was only 46 rpm, compared with 120 rpm for the origianl connection. This programming did not provide the necessary posicasting of the torsional oscillations of the M.G. shaft. The most serious difficulty encountered was related to an extremely loud 180-Hz noise emitted from the generator during the flattop period. This noise was due to the mechanical vibrations of the amortisseur bar assemblies located on the generator rotor. These circuits were excited from an unbalanced air-gap flux resulting from the incongruous current excitation of the armature. Vibration tests were performed on the pole assembly, and resonances of 170 Hz were noted. During the operational tests of this connection, amounting to less than 50-h, three amortisseur bars on the rotor of one generator were damaged; this connection was considered unacceptable.

Connection No. 2

The second reconnection required rearranging the converter units within the existing interphase connection to provide the necessary symmetry of generator excitation. The power balance was good and the speed range, for a 6500-A, 1-s flattop, was 46 rpm. No posicasting of the torsional vibration of the shaft of the M.G. set was available. In addition, the interphase transformer was subjected to an exceedingly high voltage of 170 Hz; this also created an extremely loud noise within the core. To accept this connection would require redesign of two transformers and necessitate a prolonged operation with the original connection, therefore, this connection was not acceptable.

Connection No. 3

The third reconnection required interconnecting the converter units of the two generators; one parallel branch of each interphase transformer was associated with one generator. This connection required that the two generators be synchronized to maintain a correct phase relationship between the converter units. The voltages of the converter units could not be sufficiently regulated to force paralleling of the current through the parallel branches; as a result synchronization was very difficult and erratic. At times the branch currents would totally shift into one branch and relay off the power supply. This connection was rejected.

Connection No. 4

The fourth reconnection was a reorganization of the converter units with each parallel branch containing one unit of each generator (see Fig. 5). This again required synchronizing the generators, but now each branch was sequentially symmetrical. This sequential phase order of the converter units permitted the posicasting of the torsional oscillations. The converters were controlled to force the net voltage and current excitation to the stator of each generator to be identical at all times. To maintain continuous speed regulation, the power was balanced by controlling the current through the parallel branches. A current error was obtained from transductors and was used to differentially control the firing angles of the inverting converter units only during the flattop period of the pulse; the currents were sufficiently balanced during the rise and fall time of the magnet current. With the power balanced, synchronization was accomplished by sensing the difference in electrical phase of the generators and differentially adjusting the power flow of the drive motors of each M.G. set. Power balance must be better than 0.5% to stay within the control range of the motor. A 6° phase error in synchronization produced high voltage across the interphase transformer abnormally stressing the winding insulation. Larger phase errors produced severe unbalancing of the currents in the parallel branches during the converter switching periods, thereby forcing the generators out of synchronism or "relaying" the generators. The optimum phase displacement is 0° between corresponding phases of two generators. For a given pulse loading on the M.G. set the average speed can be adjusted, thereby changing the speed profile. If the speed reference is set too low a noticeable 300-Hz noise is emitted from the generator. Previous vibration analysis of the rotor confirms resonances at this frequency, therefore operation is maintained above this speed.

This reconnection was acceptable, and was selected for extended operational evaluation.

Conclusion

The preferred reconnection of the power supply was installed on a temporary basis for testing and evaluation on June 24, 1968. The 6000-A flattop period has been extended from the original limit of 800-ms to 2.25-s with a maximum speed range of only 70 rpm; an even longer flattop period is permissible. There has been no detectable growth in the dovetail fractures, no new damage to amortisseur bars, and the cracking of field pole connections has been arrested. Magnet control signals derived from the synchronized generators have provided more reliable operation; pulse-to-pulse repeatability of the magnet current is better. Synchronizing the generators requires approximately 2-min after they are excited and loaded. Preparations are being made to finalize the designs and to install the connection permanently.

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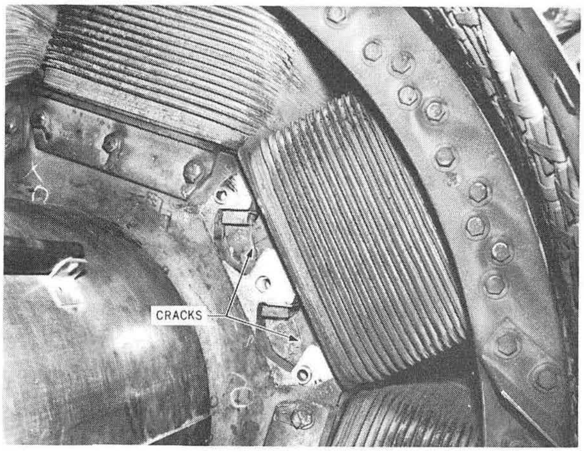

Fig. 1 Cracks on Dovetails

Fig. 2 Extent of Dovetail Cracks

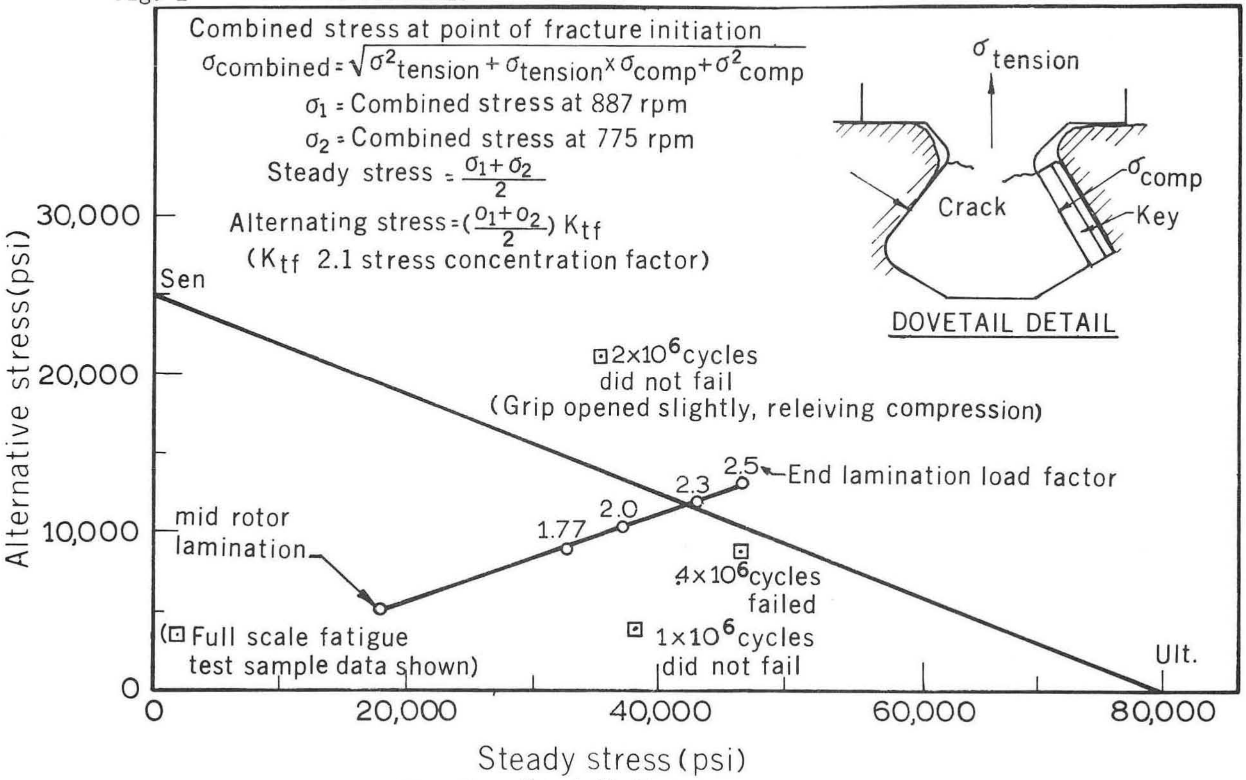

Fig. 3 Dovetail Stresses

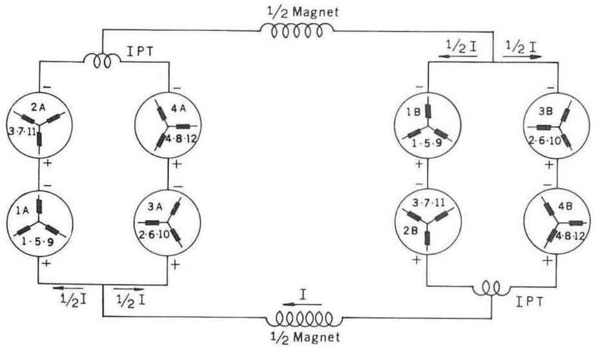

Fig. 4 Original Flattop Connection

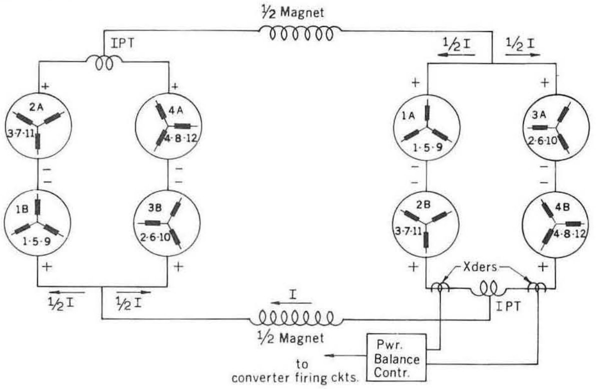

Fig. 5 Preferred Flattop Reconnection

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