OPERATION OF ACCELERATORS DIRECTLY OFF THE UTILITY SYSTEM*

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Summary

The operation of accelerators directly off the utility line is primarily restricted by the voltage fluctuation it causes on the utility system. To limit the voltage fluctuation, it will be necessary to design equipment and circuitry to reduce the MVARs during flat-topping and at the beginning of inversion.

The advantages gained with the elimination of motor generator (M-G) sets will outweigh any disadvantages of more complicated equipment and possible operating restrictions. Based on a one second acceleration time, restricted MVAR during flat-topping and a range of 0.5%-1% voltage fluctuation, the stored energy in the ring magnet in MJ may be between 0.25% and 0.5% of the short circuit capacity (SCC) of the system at the point the accelerator is interconnected.

Action of the generator voltage regulators will reduce the calculated voltage flicker or the required SCC.

There are many systems that are large enough to permit direct operation of medium sized accelerators or standby operation of large accelerators at reduced capacity. Large accelerators will require large utility systems.

Introduction

With power systems growing larger and interconnections becoming stiffer, it is of interest to investigate the possibility and feasibility of operating accelerators without the use of M-G sets. This is the purpose of this study. It shall also establish the requirements and restrictions imposed by and upon the utility, the accelerator user, and designer.

The utility requires that the system remains stable under the pulsating load. The cyclic frequency swing shall be held with acceptable limits and the voltage flicker shall not disturb other users. The harmonic voltages and currents created by the commutation of rectifiers shall not produce intolerable noise in communication circuits.

The requirements of the accelerator user are that any restrictions imposed by this scheme will not influence the beam performance, decrease the repetition rate or flat-top length, limit flexibility, or cause increased down time. It must also be reliable.

Requirements of the Utility

The following analysis is based on the assumption that the beam is accelerated in one second, which is fairly representative for large accelerators. The influence different acceleration times have on the performance shall be discussed.

Stability

A stability study on a fictitious system has been made. The system consisted of five generating stations, each of 400 MW. An accelerator with a stored energy of 50 MJ was connected to the 230 kV bus of one of the stations. The remaining four stations were each tied to the 230 kV bus of the first station by a 30-mile long 230 kV line. A 50 MW synchronous motor was tied by a 30-mile line to the first station. In a second study, the system was interconnected with a second equally large system with a 200-mile long 230 kV line.

The studies showed that the differences in phase angles of all synchronous machines during the pulse were too small to cause any units to fall out of step with each other. The difference between the synchronous and the actual phase angle was quite large, but since all the machines were moving together and contributed to the load, this was of no importance.

Based on these studies, a system would, for stability reasons, permit a stored magnet energy in MJs of 2.5% or more of the system capacity in MW.

This result is not surprising. Each system is designed to retain stability with the loss of its largest unit. This is a more serious disturbance than a cyclic load of the same average rating. Generally, 200 MW systems have units considerably in excess of 50 MW.

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A different acceleration time has little or no influence on the stability.

If direct operation is intended, the design approach must be to make a computer study of the system and load involved to verify that unacceptable power swings in tie lines and stability problems do not exist.

Frequency Swing

The frequency swing, $\Delta\omega$, is independent of the acceleration time as long as governor action is not taken into consideration. It is directly proportional to the energy stored in the ring magnet:

$$\frac{\Delta\omega}{\omega} = \frac{1}{2}\,\frac{\Delta E}{E} \tag{1}$$

ΔE is the magnetic energy stored in the ring magnet in MJ. E is the mechanical energy in the system in MJ. The stored mechanical energy of turbogenerators in MJ is assumed to be about three times their rating in MW. If a frequency swing of $\pm 0.1\%$ would be permitted, which is about the maximum range expected during most severe system disturbances, the permissible stored energy in MJ in the ring magnet would be limited to 1.2% of the system capacity in MW. This estimate does not take into consideration the inertia of the connected load which would increase the permissible stored magnet energy.

A much larger system is therefore required to limit the frequency swing than to maintain stability. All systems on the American continent are closely interconnected and represent a combined capacity of about 245,000 MW. As soon as the frequency of one system is slightly changed, the other systems will start to contribute to the load, thereby reducing any further frequency deviation. The actual frequency swing will, therefore, be much less than calculated for a single system.

Voltage Fluctuation

For this estimate, the saturation of the ring magnet is neglected and it is assumed that the current increases linearly during the acceleration period. A ring magnet with a stored energy of 50 MJ would require 100 MW at the end of the rectification period. To this, about 20% has to be added for I^2R losses in the ring magnet. If the efficiency of the rectifier units is estimated to be 95%, the required peak power at the ac side of the rectifiers would be 120/0.05 MW = 127 MW. The power factor at this point is assumed to be 90%. This gives 127/0.90 = 141 MVA and 141 x 0.436 = 61.5 MVAR.

To the reactive losses of 61.5 MVAR, the reactive losses in the high voltage line and the step down transformer must be added. If their combined reactive requirements are assumed to be about 25% of the total load of 163 MVA, reactive losses of 40.8 MVAR must be added, which gives a total of 102.3 MVAR and 163 MVA at the end of rectification.

The accelerator can be operated by changing the firing angles of all rectifiers and, in this case, the reactive losses during flat-topping and at the beginning of inversion will almost equal the total MVA. If means are provided to restrict the reactive losses during these periods, the peak reactive loss occurs at the end of rectification.

The reactive MVARs cause a balanced three phase voltage fluctuation. For the frequency of pulsing, a 1% fluctuation is considered the threshold of irritation and 0.5% the threshold of perception. The acceptable limitation with this type of disturbance should, however, be established by tests on the actual system. In particular, the action of generator voltage regulators will reduce voltage fluctuation and the required SCC. It might even make it unnecessary to restrict the MVARs during flat-topping. For the above case, a SCC in the range of 10,200 - 20,400 MVA is required at the point of interconnection. A magnet stored energy in MJ between 0.25% and 0.5% of the SCC in MVA is permitted if the MVARs are restricted during flat-topping.

It is interesting to speculate on the kind of system which could provide the desired SCC. It is assumed that all generating stations are tied to the point of interconnection by lines not longer than 30 miles. The duration of the disturbance is short enough so that a generator reactance between transient and subtransient can be assumed. It is furthermore assumed that all generators are 80% power factor, two- or four-pole turbogenerators.

Using these assumptions, the reactance at the point of interconnection is less than 65% based on the total system capacity and the SCC would be about twice the system capacity in MW. Under these assumptions, the voltage fluctuation limits the stored energy in MJ on the ring magnet to about 0.5% - 1% of the system capacity in MW. This shows that a larger installed capacity is required to solve voltage fluctuation problems than the problems of system stability and frequency swing.

Generally systems are designed to obtain a high SCC. However, limiting means may have to be provided to keep the SCC within the capability of the available equipment. The available

SCC at the point of interconnection may therefore be less than calculated above.

A system can be modified or designed to provide higher SCC at the point of interconnection, but the expenses incurred might offset the economic advantages otherwise gained with the operation off the utility lines.

If the accelerator is supplied by two or more independent supply lines, a higher MVAR swing than corresponding to the SCC at each interconnection point will be permissible and the voltage fluctuation at the point of supply to the nearest customer can be still less than the permissible limit. In this case, the Laboratory high tension (HT) bus will have a higher voltage fluctuation and it will be necessary to check whether this is acceptable to voltage-sensitive equipment. A tripping signal would also have to be provided to stop accelerator operation in case one of the supply lines had been lost to avoid higher flicker voltage.

The voltage fluctuation is inversely proportional to the acceleration or deceleration time. A longer pulse would decrease the MVAR swing; on the other hand, fast pulsing accelerators would be less suitable for operation directly off the line.

Interconnected systems will contribute very little to reduce the voltage flicker.

Telephone Interference

During commutation two phases are short-circuited through their rectifier tubes and the common cathode voltage is the average of the two phase voltages. This creates a notch in each phase, the magnitude of which might be up to 86% of the peak voltage during inversion. In a 12-phase rectifier system, there are 12 notches per cycle, all 30° apart. These notches are also imprinted on the HT system voltage in the ratio of the reactance behind the step down transformer to the total reactance. The peak-to-peak value of these notches has been estimated to be about 2% of the peak value of the voltage based on a system where the peak MVARs occur at the end of rectification and where the voltage fluctuation is limited to 1%. For a simplified analysis of a 12-phase system, these notches can be assumed to be a 12th harmonic with an rms of less than 1% of the fundamental. (A Fourier analysis actually shows these to be 11th and 13th harmonics.)

The harmonic current produced will then be about 1/12th of 1% of the short circuit current. If, again as an example, the system with 50 MJ stored energy and a SCC of 10,000 MVA is considered, the harmonic currents would be 35 A on a 138 kV line, but only 21 A on a 230 kV line.

Both voltage and current harmonics are balanced and can produce objectionable noise in parallel telephone lines.

The harmonic currents flow only in the HT lines. The noise induced in a communication circuit is given by:

$$NM_I = K_I \left(IT_I \right) \quad . \qquad (2)$$

NM_I = noise in noise units/1000 feet of exposure induced by currents, K_I = current coupling factor for balanced currents and (IT_I) = product of line current and current telephone interference factor. The communication line is at least 100 feet away from the power line and the factor K_I is 3.10^{-3} or less. The noise induced for the worst case would be:

$$NM_I = 3 \times 10^{-3} \left(35 \times 3 \times 10^3 \right) = 315 \quad . \qquad (3)$$

Eight hundred noise units and more are permissible on a communication line. This would permit up to 3000 feet of parallel communication circuits.

The harmonic voltages can induce noise from the HT lines and the 12 kV or 4 kV distribution circuits.

The induced noise is given by:

$$NM_E = K_E \left(KV \times T_E \right) \quad . \qquad (4)$$

NM_E = noise in noise units/1000 feet of exposure induced by voltages, K_E = voltage coupling factor for balanced voltages, and $(KV \times T_E)$ = product of line-to-line voltage in KV and voltage telephone interference factor.

On a 230 kV line, the coupling factor K_E is again about 3×10^{-3} and the induced noise would be:

$$NM_E = 3 \times 10^{-3} \left(2.3 \times 3.10^3 \right) = 21 \quad . \qquad (5)$$

On a 12 kV line, joint use of poles is possible and a coupling factor can be as high as 0.83.

The induced noise would be:

$$NM_E = 0.83 \left(12 \times 10^{-2} \times 3.10^3 \right) = 300 \quad . \qquad (6)$$

This permits about the same length of exposed communication line as the current induced noise from a 138 kV line. Summing up, there is the possibility of telephone interference and a coordination study will be required in the early planning stages if direct operation is contemplated.

Influence on Accelerator Operation and Design

Reduction of MVAR Swing

If an accelerator is operated by controlling the firing angles of all the rectifiers in the same way, the MVAR during flat-topping and the early part of inversion may be increased up to 200% of the MVAR at the end of rectification. This would require a very high SCC and it is essential that the MVARs are restricted during these periods.

There are fundamentally three ways to accomplish this.

1. Operation of one-half of the series connected rectifier groups in rectify and the other half in invert. Higher currents do permit less phasing back of the firing angle during invert and the scheme is more efficient at reduced currents. Even then the MVARs at the beginning of the invert can not be reduced below 140% of the MVAR at the end of rectification. This type of operation would also increase the ripple in the dc voltage. Tests on existing accelerators are suggested to establish the amount of possible reduction with this mode of operation under various operating conditions.

2. Bypassing part of the rectifier groups.

3. Change of voltage on the step down transformers with an SCR under-load-tap-changer.

The latter schemes are both very efficient, but these circuits are only in the development stage. They still have to be designed and no operating experience is available. The last scheme would even permit reduction of the MVARs at the end of rectification by switching somewhat earlier to lower voltage steps.

These three schemes would have to be investigated to determine whether they influence the beam adversely.

An alternative would be the installation of series capacitors in the line. This scheme is simple, readily available, and requires no development or operation of sophisticated equipment. The relatively high cost of capacitors may be offset by development costs for the other solutions.

However, series capacitors will increase the telephone interference and decrease the commutation reactance of the rectifiers and this might limit their application.

Line Design and Step Down Transformer

The size of the step down transformer will be three to five times larger than the one required to supply the driving motor of an M-G set. Also, a special low leakage reactance would be desirable. The HT supply lines have to be correspondingly reinforced. A separate line for the accelerator might be required if the voltage fluctuation on this line is not acceptable to other equipment at the Laboratory.

Increase of Pulse Length

To reduce the MVARs at the beginning of inversion, a lower voltage has to be applied and this might increase the pulse length by 200 to 300 ms. Since there is no need of reaccelerating an M-G set, theoretically some of this time loss could be regained by eliminating the rest period. However, a minimum rest period may be necessary for the magnet field to stabilize prior to the start of the next pulse.

Control of Supply Voltage

The excitation system of the generators of the M-G set permits the programming of the supply voltage during the whole pulse. Thus a program most suitable for beam acceleration can be selected during rectification and a suppressed voltage during flat-topping will reduce the ripple. Operation off the utility does not permit this flexibility. The voltage will drop with the increased current and experience a further sharp drop at flat-topping, if flat-topping is accomplished by phasing back of the rectifier firing angles.

The flexibility obtained by the voltage regulator of the M-G set is, however, very limited by the long time constant of the generators. If an SCR under-load-tap-changer with sufficient number of taps and as described before would be provided, the flexibility would be much superior to that possible with the M-G set.

Loss of System Voltage

Under unusual conditions, the system might become suddenly deenergized. The conducting phases of the rectifiers will continue to conduct and the magnet coils will discharge in the form of an oscillatory current into the natural capacities of the high voltage system until protective relaying has closed the magnet shorting switches or the spark gaps of the magnet coils have operated. Such a discharge will cause voltage transients. The lightning arresters on the step down transformers will keep these transients below the level dangerous to equipment.

Advantages of Off the Utility Operation

The narrow frequency swing will permit starting each pulse at the same phase angle, frequency and voltage. This will make the pulses much more repetitive, which could result in improved beam capture and acceleration efficiency. Since no M-G sets have to be accelerated or decelerated, the flat-topping period can be extended under any pulsing condition to the thermal limit of the equipment.

The auxiliary voltage for the firing control, which has to be in synchronism with the supply voltage, can be taken from the normal Laboratory supply. Contrary to the auxiliary voltage derived from the M-G set, this voltage will be constant and also does not require any filtering.

If the diameter of the ring magnet system is large, as it is in the proposed 200 GeV accelerator, there is some difficulty to transmit the power from the generators to the ring magnet. With operation off the utility line, this problem can be considerably simplified by selecting a higher primary voltage of the rectifier transformers.

With no M-G set maintenance required, preventive maintenance periods can be shorter and the accelerator can be operated at higher efficiency.

Economic Comparison

It can be shown that there is a considerable savings in initial cost, power cost, and operating expenses. A very preliminary cost estimate made on the proposed 200 GeV accelerator,[1] showed a saving of over $3,000,000 in initial cost, of $16,000/month in power cost, and $100,000/year in operating expenses.

Conclusion

The economic advantages and the history of major failures of M-G set components, which have already occurred at most of the present operating accelerators, makes an operation off the utility lines very desirable.

Such an operation is possible if the short circuit capacity of the system at the point of interconnection is large enough and if the schemes to reduce MVARs during flat-topping and inversion have been developed and provide satisfactory operation. There is no question that a voltage fluctuation of 0.5% can be imposed on a system, but it is believed that the fluctuation on the HT part of a system should be well below 1%. If this can be obtained, particularly if this requires only conventional flat-topping and inversion, operation off the utility line is the obvious choice. There are many large systems that would permit direct operation of medium-sized accelerators under such conditions.

Based on the design study, the planned 200 GeV accelerator would require a minimum SCC in the range of 10,200 to 20,400 MVA. If the acceleration time is extended to one second,[1] the required SCC will be between 8,600 and 17,200 MVA. Generator voltage regulators will reduce this requirement. Large, closely integrated systems can provide an SCC of 5,000 to 10,000 MVA at 138 kV with a 15,000 MVA equipment limitation of 15,000 to 20,000 MVA at 345 kV with a 25,000 MVA equipment limitation.

Provisions to operate off the line at reduced capacity would give an inexpensive standby in case of M-G set failure. This applies particularly if the M-G set has only one driving motor. On a readily interruptable standby basis, a 1% voltage fluctuation is very likely permissible. If this should, on occasion, prove to be too high, it is easy to decrease the MVAR swing on request by reducing the energy or by increasing the accelerating time.

The Zero Gradient Synchrotron (ZGS) could, in this way, operate up to 16 kG or 9 GeV.

References

(1) A. Rohrmayer, J. F. Sellers
"Operation of the Planned 200 GeV Accelerator Directly Off the Utility System"
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