Designing large multisource power systems within available short-circuit ratings of medium-voltage equipment

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The synchronizing-bus approach has a high first cost, but it provides the greatest flexibility for future growth.

In-plant generation of electric power is an integral part of the pulp and paper industry. Its vast consumption of steam and electrical energy provides ideal conditions for the use of steam turbines (extraction or condensing) and gas turbines with heat-recovery boilers as prime sources of power. Changes in cogeneration laws in 1978 provided mills with additional incentives to generate electric power by allowing the sale of excess power to the utility company over the utility tie line. The utility tie is generally regarded as a necessary source of backup power. Mills typically export excess power created by changes in operating conditions rather than design for a steady sale of electric power to the utility.

Modern grassroot mills are being designed to accommodate ever-increasing levels of production. Those who design the electrical systems for these large plants must work around the limitations imposed by the available switchgear. In 1986, our company was commissioned to design an electrical system for the Fort Howard paper mill in Savannah, Ga. This report discusses the problems encountered during this process and the solutions that were implemented with the help of extensive computer studies.

I. Ratings for metal-enclosed load-break-type 15-kV air switches[a]

Voltage rating, kV	Continuous current rating, A	Fault close rating, kA	Momentary rating,[b] kA	Load break rating, A
15	600	None	40	600
15	1200	None	61	1200
15	2000	None	80	1200

[a]Source: Ref. (1)

[b]RMS (root mean square) total current that the switch must carry for at least one cycle.

II. Types of metal-enclosed load-break-type 15-kV switches that are generally available

Voltage rating, kV	Continuous current rating, A	Fault close rating, kA	Momentary rating, kA	Load break rating, A
15	600	40	40	600
15	1200	61	61	1200

Design considerations

Steam and electric power requirements through the final phase of expansion were studied to determine the optimum combination of the following sources of power:

- Two 25-MW gas turbines, each with a separate heat-recovery boiler
- Two extraction-type steam turbines, one 45 MW and one 34 MW
- Utility tie with a 30-MVA transformer.

Our task was to design a safe, reliable, and cost-effective electrical system capable of handling 129 MW of electrical power generation and a 30-MVA utility tie. The key design considerations included:

- Short-circuit current
- Voltage regulation
- System stability.

Short-circuit current

An early problem encountered in designing this system related to the handling of excessive short-circuit current available from the large sources of electric power. Standard subtransient reactance for the four generators was estimated at 12%. Reactance for the utility-tie

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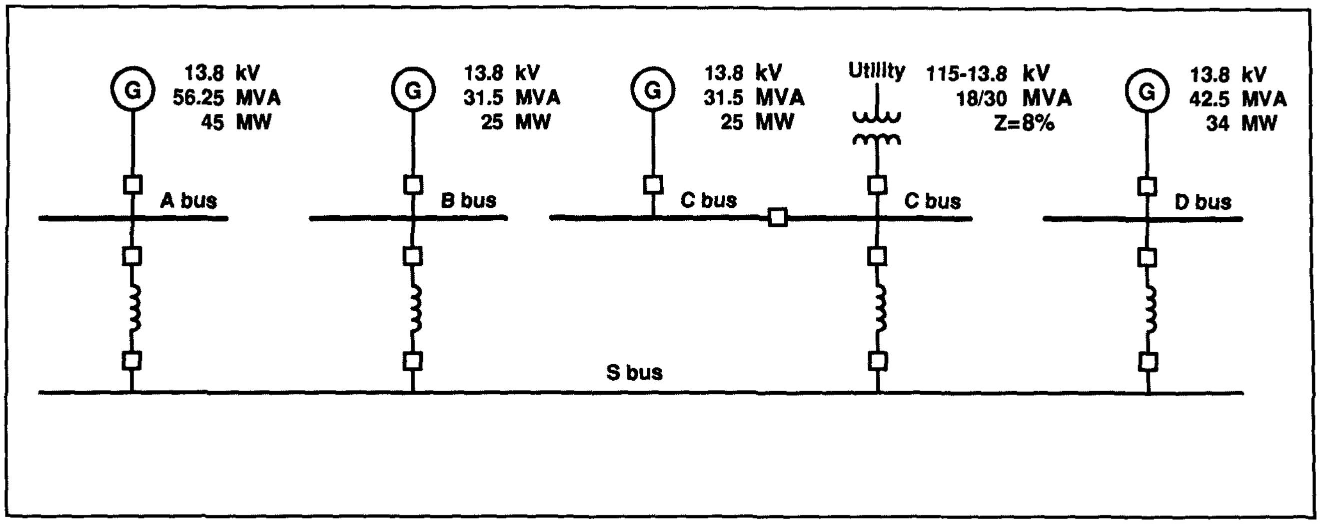
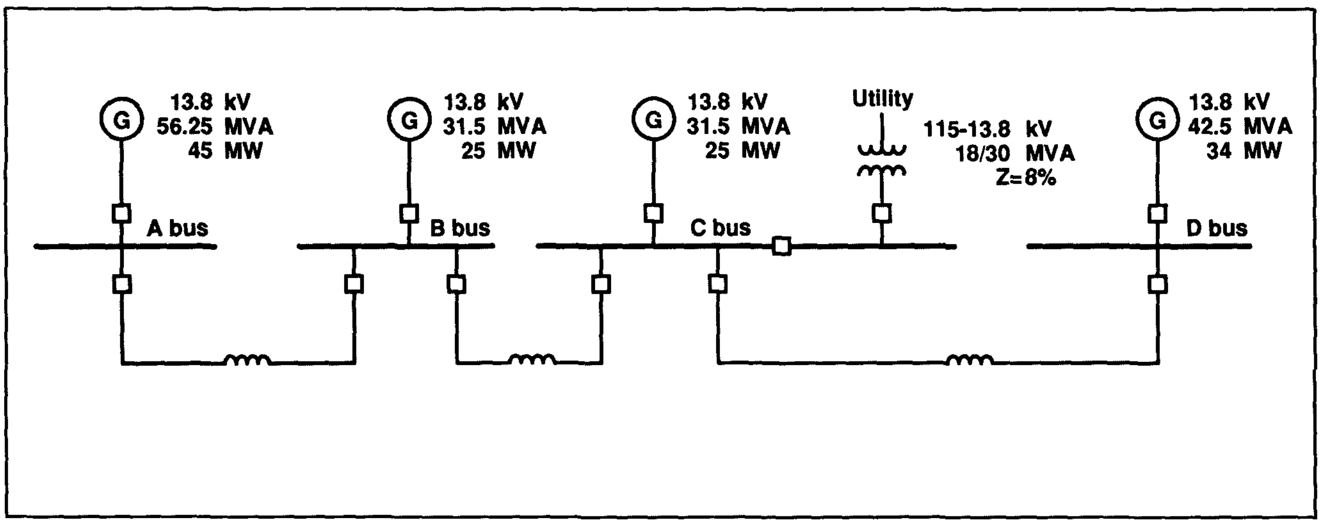
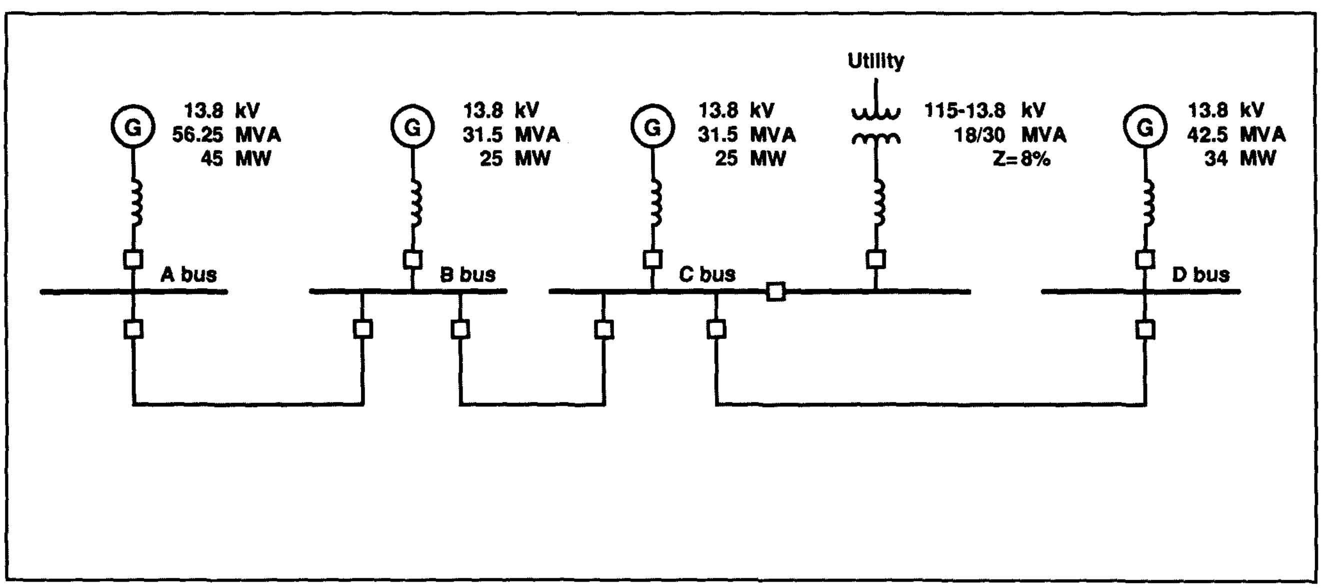
1. Synchronizing bus



2. Bus tie reactor



3. Generator reactor



transformer was estimated at 8%. The available short circuit can be quickly estimated as:

Generators = 129 MW/0.8 power factor = 161.25 MVA

Utility tie transformer = 30 MVA

Available short circuit = (161.25/0.12) + (30/0.08) ≅ 1719 MVA

Motor contribution to short-circuit current was estimated to be approximately 25%. Therefore,

Net available short circuit = 1719 × 1.25 ≅ 2150 MVA.

Options for handling short circuit

Once it was determined that the system had to be capable of handling a potential available short circuit of 2150 MVA, the following options were identified:

- Design a system using 13.8-kV switchgear to handle 2150 MVA of short-circuit duty.
- Reduce the short-circuit duty for the switchgear to a practical level by using current-limiting reactors.
- Split the power system so that each island system would have a duty not exceeding practical limits.

What is available?

The following switchgear ratings were available for 13.8-kV circuit breakers:

1. Metal-clad switchgear—air, vacuum, or sf6 type—up to a nominal short-circuit rating of 1000 MVA.
2. Outdoor substation-type switchgear—oil or sf6—up to a nominal short-circuit rating of 2500 MVA.

Comparison of hardware and installation costs for 1200-A and 3000-A circuit breakers from these two categories quickly showed that the cost-effective approach was to use lineups of metal-clad switchgear in combination with current-limiting reactors. A split-power system was considered as a last alternative because of its operational problems and lower reliability.

The switch dilemma

After deciding to use 1000-MVA metal-clad vacuum switchgear, we realized that there was an availability problem for load-break switches with the required rating. Typically, paper mills use a system where multiple transformers are fed from each circuit breaker. Incoming line switches are therefore used to obtain isolation for repair and maintenance. In most cases, phase relays associated with the circuit breaker are set high enough to override the inrush that occurs upon simultaneous energization of multiple transformers. However, this approach means that the phase relays cannot protect the transformers. Fuses are installed on the incoming line switches to compensate for the lack of protection.

Table I shows the preferred ratings for the metal-enclosed load-break-type 15-kV switches. These ratings are taken from ANSI standards (*1*). **Table II**, compiled from a review of vendor catalogs, lists the switch ratings that are generally available.

At first it appeared that there were no switches available to meet the rating of the circuit breaker feeding them (fault-close and momentary-duty ratings of 77 kA). Further investigation revealed that some manufacturers listed the same switches for higher fault-close and momentary rating when used with current-limiting fuses. One manufacturer listed its 1200-A switches for 80-kA fault-close and momentary-duty ratings. However,

- There were no industry standards that addressed the ratings of the switch and current-limiting fuse combinations.
- There were no standard testing procedures available.

ANSI/NEMA are currently working on a standard (*2*) that provides guidelines for switch/fuse combined rating and clarifies fault-close ratings.

Voltage regulation

One of the critical considerations in designing a power system with current-limiting reactors is its ability to maintain the voltage regulation of all buses within tolerable limits. This pertains to all feasible operating conditions and emergency conditions imposed by sudden equipment failure. ANSI provides fluctuation limits for service voltages above 600 V (*3*):

- Range A (>600 V)—Voltage can fluctuate from -2.5% to +5%. Occurrence of service voltages outside these limits should be infrequent.
- Range B (>600 V)—Voltage can fluctuate from -5% to +5.83%. These limits, although part of practical operation, should be limited in extent, frequency, and duration. When they occur, corrective measures should be taken within a reasonable time to improve voltages to meet the stricter requirements of Range A.

Our design limited the voltage regulation from -5% to +5% on all buses under all operating conditions.

System configuration

At this point in the study, the following design criteria had been established:

- Design a system using current-limiting reactors and 13.8-kV metal-clad switchgear. The available switchgear had a maximum short-circuit rating of 1000 MVA.
- Regulate voltage at all 13.8-kV buses within ±5%.

We evaluated three system configurations that could satisfy our design criteria:

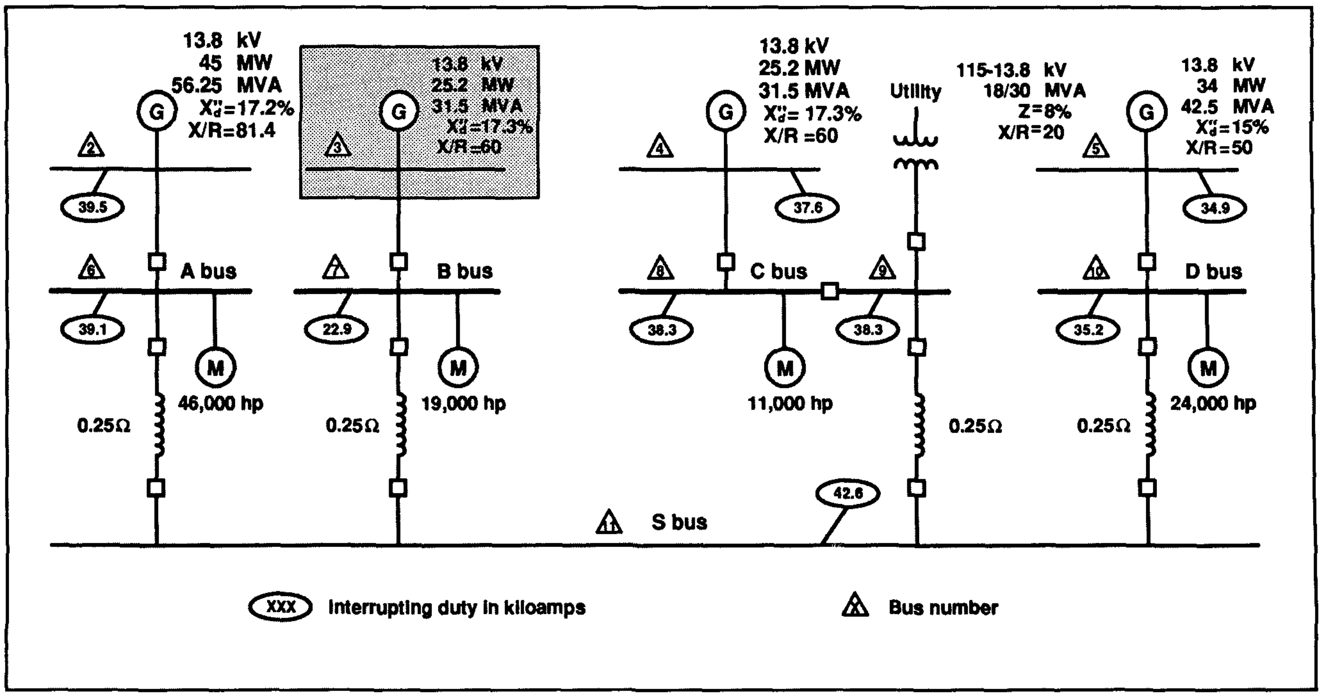
1. Synchronizing bus
2. Bus tie reactors
3. Generator reactors.

These systems are illustrated in **Figs. 1-3**, respectively.

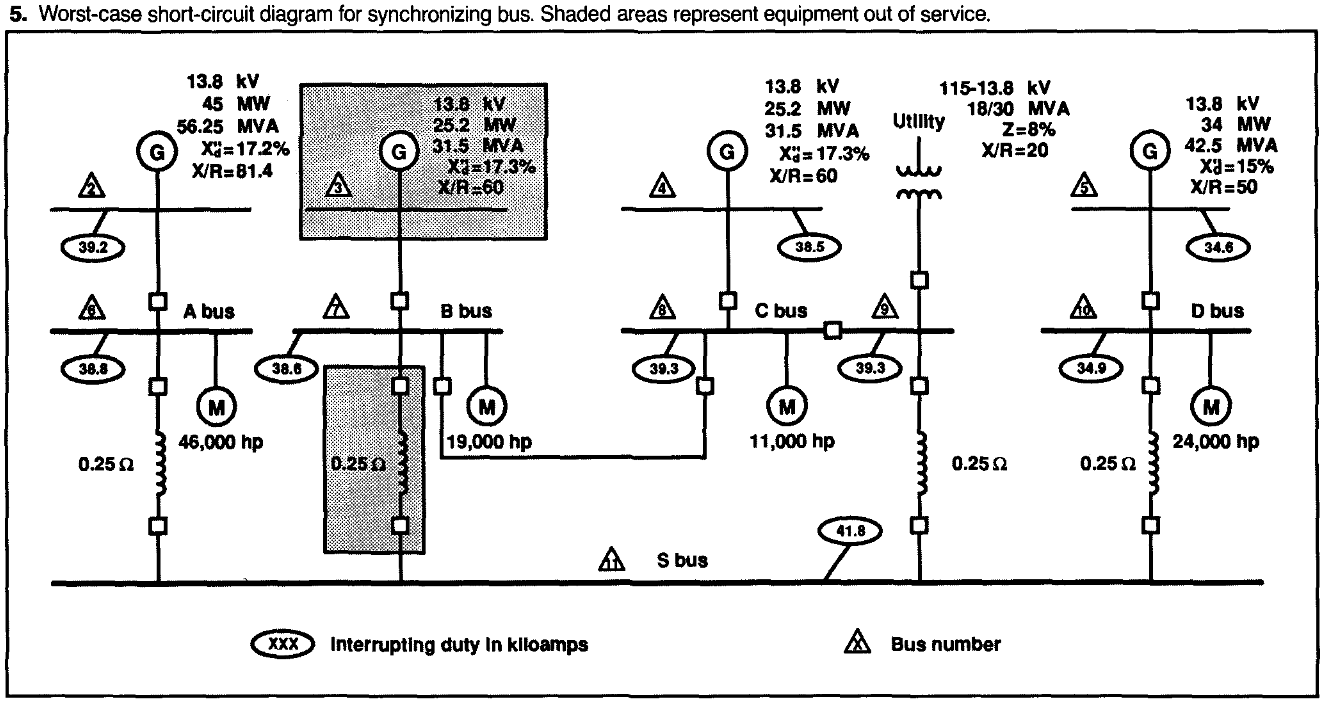
A system with multiple generators lends itself well to a configuration with a single bus for each large generator (or two smaller generators). This allows balancing of loads and generation on each bus, thus maintaining a minimum power flow through bus ties under normal conditions. While such a system provides uniform voltage at all buses, it also is the most economical, since power loss during normal operation is negligible.

The system configurations depicted in Figs. 1-3 were compared by simulating a variety of short-circuit and load-

4. Short-circuit diagram for synchronizing bus. Shaded area represents equipment out of service. X''_d = direct-axis subtransient reactance.



5. Worst-case short-circuit diagram for synchronizing bus. Shaded areas represent equipment out of service.



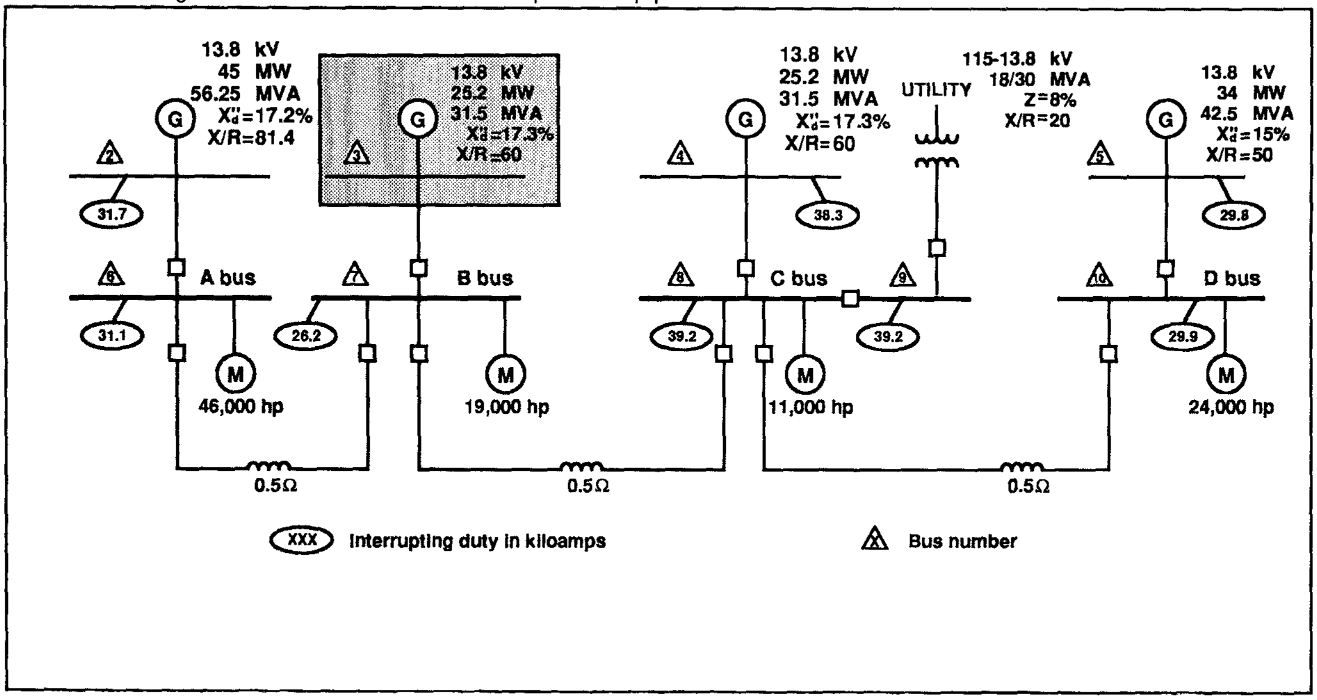
flow conditions. The computer-generated short-circuit runs are presented in **Figs. 4-7**. The worst-case scenario for short-circuit duty was defined as four out of five sources on line. These short-circuit runs indicate the sizes of reactors required to limit the short-circuit duty within the interrupting rating (41 kA) of the 13.8-kV, 1000-MVA switchgear for each system. The corresponding load-flow runs are presented in **Figs. 8-10**. The load-flow runs indicate the bus-voltage conditions following loss of a generator. For example, Fig. 6 shows that 0.5-Ω bus-tie reactors are required to stay within the short-circuit rating of the switchgear. Figure 9 shows that voltage regulation, in this case at Bus D, will be approximately 9%.

Table III compares the relative merits of the three alternative system configurations. The synchronizing-bus arrangement was chosen as the best design for the mill.

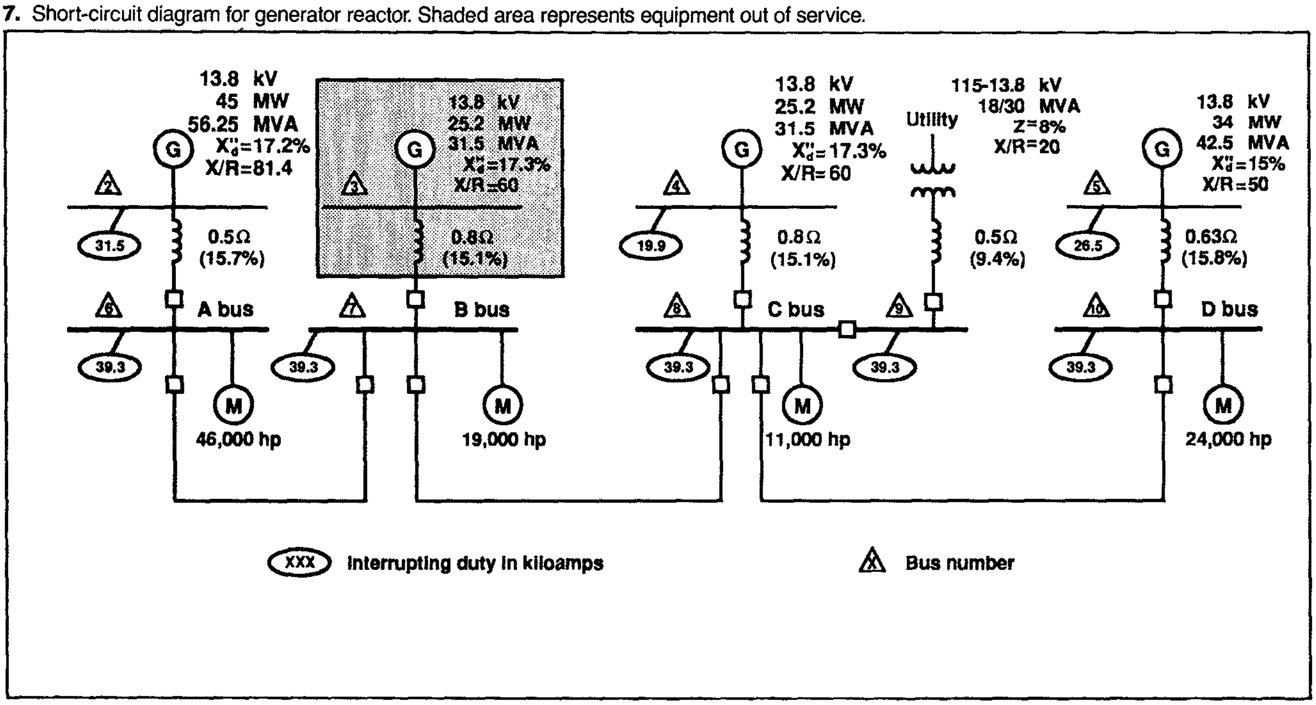
Selecting reactor sizes

Determining the ohmic value of the current-limiting

6. Short-circuit diagram for bus tie reactor. Shaded area represents equipment out of service.



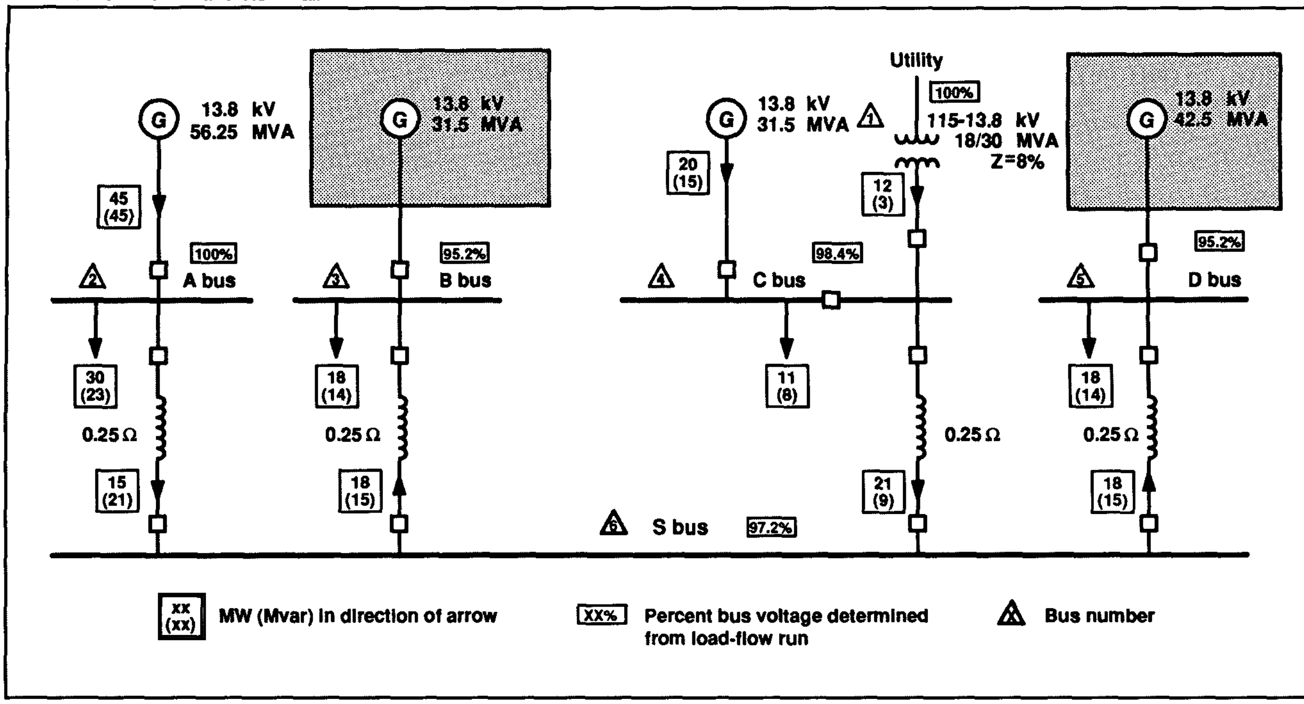
7. Short-circuit diagram for generator reactor. Shaded area represents equipment out of service.



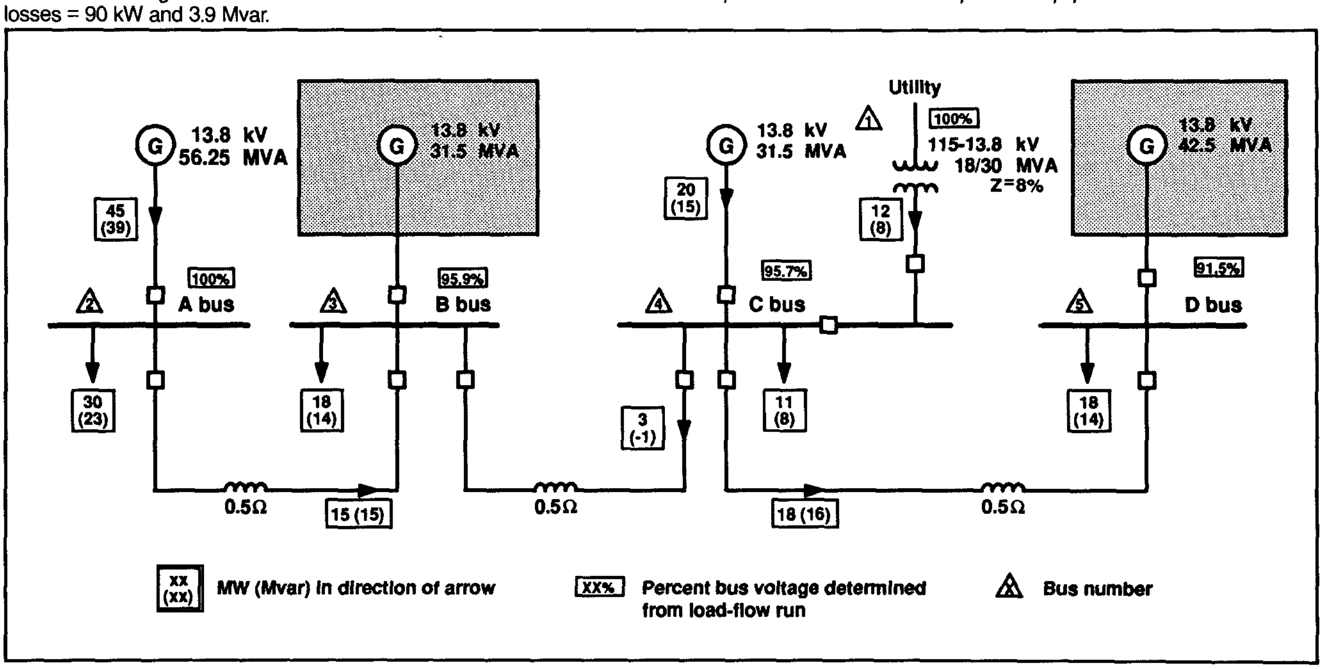
reactors is not simply a case of calculating the reactance required to reduce the short-circuit current to an acceptable level. Various combinations of reactor sizes are studied to determine the one that provides acceptable short-circuit levels for the maximum number of operating conditions, while maintaining voltage regulation and power losses within acceptable limits.

For a given circuit, reduction of short-circuit current through addition of current-limiting reactors is nonlinear with respect to the reactor's ohmic value. **Figure 11** shows that as the reactor ohmic value is increased, the incremental percent reduction in short-circuit current decreases. For example, doubling the reactor size from 20% to 40% of the system reactance provides only a 73% increase in the percent reduction in short-circuit current. The voltage regulation, however, increases almost linearly with the increase in reactor size. **Figure 12** shows that doubling the reactor size (e.g., from 4% to 8%) for a 0.8 power factor (pf) load also doubles the voltage drop (e.g., from 2.5% to 5%). Therefore, system designers should try to minimize

8. Load-flow diagram for synchronizing bus. All circuit breakers are in the closed position. Shaded areas represent equipment out of service. Total losses = 80 kW and 3.8 Mvar.



9. Load-flow diagram for bus tie reactor. All circuit breakers are in the closed position. Shaded areas represent equipment out of service. Total losses = 90 kW and 3.9 Mvar.



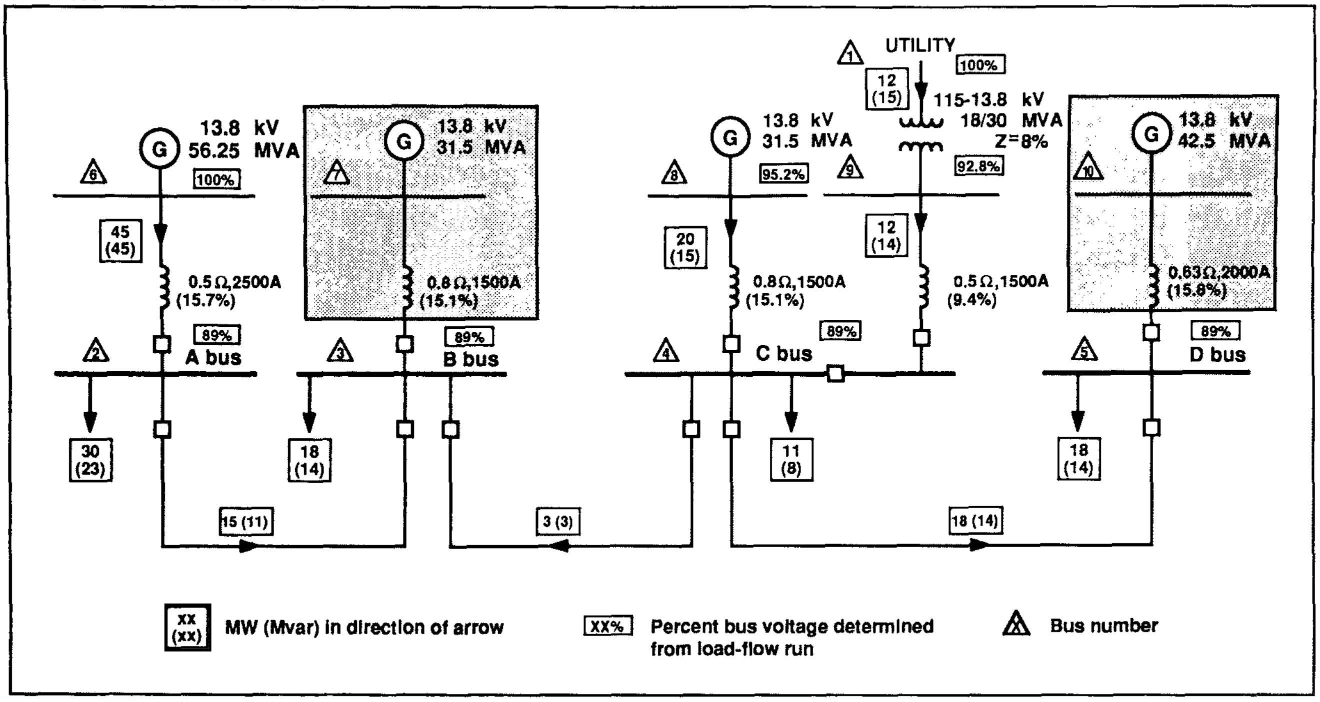
reactor sizes to prevent excessive voltage regulation from offsetting the benefits of reduced short-circuit current.

Load-flow calculations

Load flows were simulated to determine (a) power losses through the reactors and (b) bus voltages under various operating conditions. Several runs were made for normal operating conditions. Additional runs were made simulating the loss of one or two sources, which would cause abnormal power flow through the synchronizing bus. We found it preferable to use the same size reactors (ohms) to connect comparably sized generators to the synchronizing bus. This makes it easier for operators to predict system conditions following the loss of a generator.

Figure 8 shows the result of a load-flow run with Bus B and Bus D generators out of service for the synchronizing-bus system. As indicated on the diagram, Buses B and D can be served from the generators on other buses without exceeding the 5% maximum voltage regulation. In the

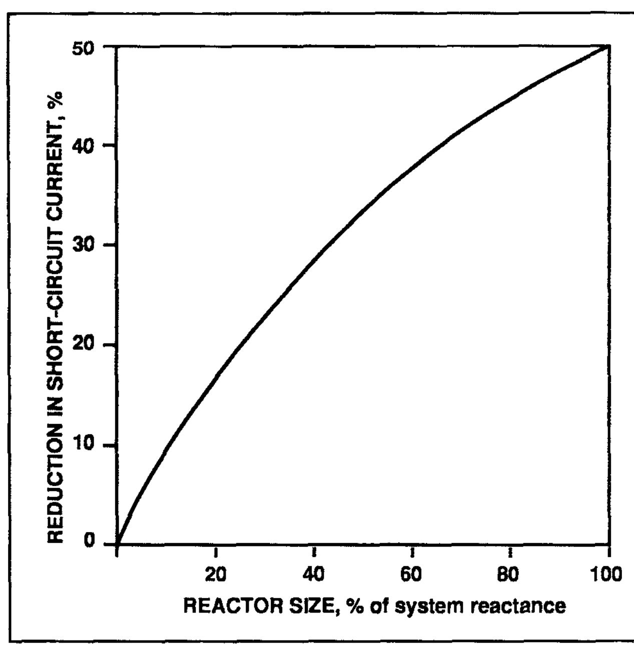
10. Load-flow diagram for generator reactor. All circuit breakers are in the closed position. Shaded areas represent equipment out of service. Total losses = 140 kW and 16.1 Mvar.



III. Relative comparison of alternative system configurations

	Synchronizing bus arrangement	Generator reactors	Bus tie reactors
Voltage regulation			
Normal	Low	Medium	Low
Emergency	Medium	Very high	High
Operation complexity	Medium	Low	Medium
First cost	High	Medium	Low
Operating losses	Low	High	Low
Adaptability to future growth	Excellent	Good	Fair

11. Reduction in short-circuit current as a function of reactor size.



worst case—loss of the generator on Bus A—the voltage regulation will be slightly higher than 5%. Some amount of load shedding on Bus A would then be necessary.

System stability

The addition of current-limiting reactors to reduce the short-circuit current has an adverse effect on system stability. Reactors can be imagined as miles of transmission lines separating the generators from each other. This results in lower stability limits for both steady-state and transient conditions (*4*). Neglecting the resistance and shunt capacitance of the circuit, the maximum power that can be transmitted over a circuit before the steady-state stability limit is reached can be calculated as shown in Eq. 1.

$$P_{max} = (E_s E_r)/X \quad (1)$$

where

E_s = magnitude of voltage at sending end (generator in per unit)

E_r = magnitude of voltage at receiving end (motor in per unit)

X = magnitude of line reactance in per unit

Systems without large reactor sizes (ohms) do not generally require a study of transient stability because, in this case, generators swing together. As a rule of thumb, a synchronizing-bus system exceeding the following reactance limits can be expected to experience transient-stability problems (*5*):

> Synchronizing bus reactance which limits the short circuit current contribution to a given bus to be less than 75% of the short circuit current contribution of the largest generator on a given bus.

In the selected system with 0.25-Ω reactors (Figs. 4 and 5), this criterion for a stable system has been met in each case. For example, contribution from the synchronizing bus for a fault on Bus A will be 121% of the contribution from the only generator on the bus. (The contribution from the synchronizing bus is 16.5 kA, and the contribution from the generator is 13.6 kA.)

Medium-voltage feeder and transformer primary-ground faults in paper mills are generally removed by instantaneous relays using zero-sequence current transformers. Differential relays that operate instantaneously are provided around such major equipment as medium-voltage switchgear, generators, and large transformers. Considering that almost 95% of all faults occurring in an industrial installation are ground faults, stability of the system is considerably enhanced with such high-speed isolation of faults.

Generator reactance

Generator subtransient reactance has a direct bearing on the selection of reactor sizes. Subtransient reactances for industrial-type generators generally vary between 10% and 17%. Generators with higher subtransient reactances tend to have lower short-circuit ratios. Holding the regulator and other parameters of the generator constant, varying the generator short-circuit ratio (1.0/direct-axis synchronous reactance) affects its stability when operating in parallel with other synchronous machines. Generators with higher short-circuit ratios are relatively more stable (*6, 7*). Therefore, an economic analysis is required to select generators with the most desirable impedances, short-circuit ratios, and voltage-regulator response.

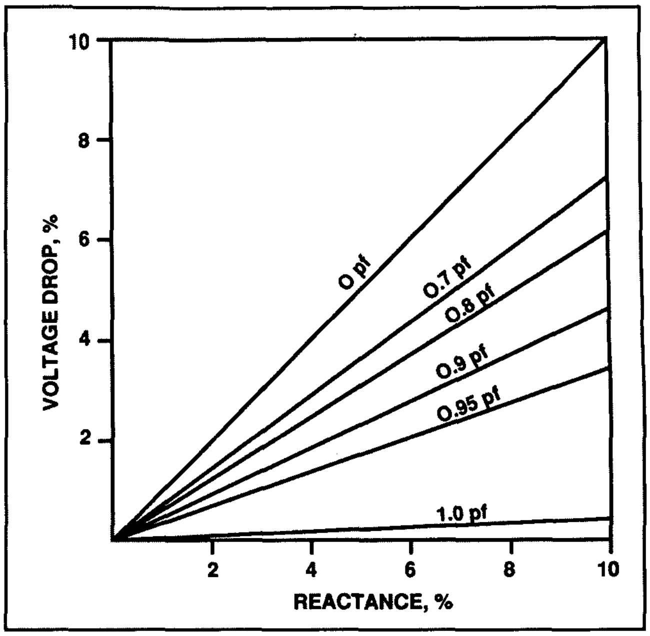
Conclusion

Designers of large modern paper mills must consider the scope of the facility when configuring the power system. Designing for immediate needs without considering future growth will render the system incompatible to expansion. The cost of future corrections will be prohibitively high.

The synchronizing-bus arrangement is still the most suitable design for large, multiple, in-plant power sources in parallel. However, short-circuit and load-flow studies should be conducted to establish the minimum reactor sizes that can reduce the short-circuit current to practical limits. Other system configurations also should be evaluated for cost effectiveness and for compatibility with special situations.

For systems using large reactor sizes, or where frequent disturbances to the power system are expected, transient-stability studies also should be conducted to anticipate the result of such disturbances. Criteria for high-speed relaying and load-shedding schemes can then be established to counter the effects of the disturbances.□

12. Voltage drop as a function of reactor size for six power factors.



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