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"Secure Bus"
Disturbance-Free Power at the Utility Substation Level

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I. INTRODUCTION

High-tech manufacturing facilities, in particular semiconductor manufacturing plants, require quality power for the operation of voltage sensitive equipment. The type of machine tools operated in these facilities is very sensitive to short term voltage sags, exceeding 10 to 15% of nominal voltage and lasting for only a few cycles, or to total power outages of more than half a cycle. In the event of even a short power outage or voltage sag some of the equipment might turn off and a whole sequence of manufacturing processes could be interrupted. Reported loss of production in a high-tech manufacturing plant can reach values of hundreds of thousands of dollars for a power disturbance incident[1]. At the present time, the desired quality power to such customers is achieved with the concept of the utilities providing the best available power supply systems using conventional designs with dual feeds and/or a ring bus and the customer installing uninterruptible power supplies(UPS). This design places a heavy burden on the customer with valuable floor space in the manufacturing facilities occupied by battery banks and power conditioning equipment. Maintenance expenditures in the form of personnel and material for UPS systems are high, and the availability of UPS systems is often not as high as desired.

Some electric utilities are striving to provide those customers in need of premium power with disturbance-free power. The goal is to make premium power available to the customer at the medium voltage level of the substation. In this approach the burden of power quality is placed back on the utilities, away from the customer. This is a real advantage to the customer, considering that in modern manufacturing plants the average lifetime of a machine or a process is sometimes less than 3 to 5 years. By providing quality power at the substation level the facility engineer has considerably more freedom in retooling a new manufacturing facility without revamping the power improvement equipment.

Over the last 18 months Public Service Company of New Mexico (PNM), El Camino Real Engineering, Inc. (CRE), Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL) have worked on the development of disturbance-free power at the medium voltage substation level. The work resulted in the Secure Bus concept, a system in which a medium voltage bus in a substation is immune to power outages and voltage sags on the utility source. The Secure Bus voltage is also immune to voltage sags resulting from faults on any distribution feeder connected to the bus.

The Secure Bus concept originated from work conducted to improve power quality for large high-tech manufacturing facilities, in particular for large semiconductor manufacturing plants. For the demands on quality power of a modern facility conventional equipment is not adequate for protecting the end user. For example, the operation of conventional vacuum breakers during short circuit conditions on a feeder circuit, requiring 3 to 5 cycles for breaker opening, does not allow for fast enough current interruption to avoid a voltage dip on the main bus. A severe voltage sag could result in a shut down of sensitive equipment being supplied by the other feeder circuits, which are connected to the main bus. To circumvent the problem, a fast breaker was introduced which interrupts the short circuit before the current causes a significant voltage disturbance. To make the bus immune also to power disturbances caused by power outages, energy storage is introduced to provide the necessary energy back-up in case the primary source is not available.

II. SECURE BUS DESCRIPTION

A. Design Philosophy

The Secure Bus is designed to provide a disturbance immune voltage bus by taking corrective action for all types of abnormal bus conditions. Bus voltage disturbances from both source-side and load-side feeder disturbances are corrected. This prominent feature enables the bus to remain disturbance-free, thus secure, while a fault, source interruption, or voltage sags are present on the power system. The two most likely disturbances are loss of generation and short circuits on a feeder circuit.

Should a fault occur on one of the substation distribution feeders, a primary design criterion is that the remaining feeders must not experience even a sub-cycle, significant voltage sag as a result of the faulted feeder. A second and equally important design criterion for the Secure Bus is the ability to maintain a disturbance-free voltage during the loss of the primary utility power source. In the case of utility power loss, the load can either be switched to a completely independent second power source, or to an on-site stored energy system. Because many utility systems are tightly interconnected, a second independent voltage source is often not available. To support the Secure Bus during a power outage on the primary source, an on-site energy storage system with a power conversion system is necessary.

A simplified one-line diagram for a Secure Bus is depicted in Fig. 1. In the diagram the medium voltage bus is normally supplied by the utility transmission source through a transformer. Four distribution feeders are shown, connecting the load to the bus. In each feeder, near the bus, a fast acting circuit breaker, called a fault current interrupter (FCI), is installed. The FCI replaces a conventional circuit breaker. A similar FCI with a higher current rating is also installed between the bus and the transformer. In the case of a feeder short circuit, the appropriate FCI interrupts the short circuit current in a short enough time before the maximum fault current develops, thus limiting the voltage drop on the Secure Bus to an acceptable value. For a power outage of even half a cycle the energy storage system and the power conversion system will provide the bus with enough energy and reactive power to avoid a voltage dip. In the case of a short circuit in the transformer, or on the feeding utility transmission line, the FCI in the transformer branch

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will prevent the energy storage system from feeding the supply side fault. This FCI operation prevents a voltage sag from occurring on the Secure Bus.

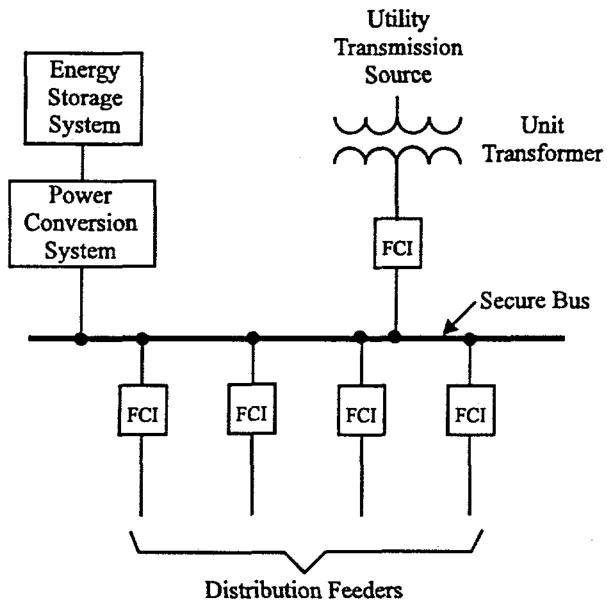

Figure 1. Circuit diagram of the Secure Bus.

Not all loads in a manufacturing plant require quality power. Therefore, it is anticipated that many plants will choose to split the substation bus into critical and non-critical sections. A simplified one-line diagram for a split bus configuration for a high-tech manufacturing facility is shown in Fig. 2. Secure bus ratings and configurations can be customized to meet the requirements of each facility.

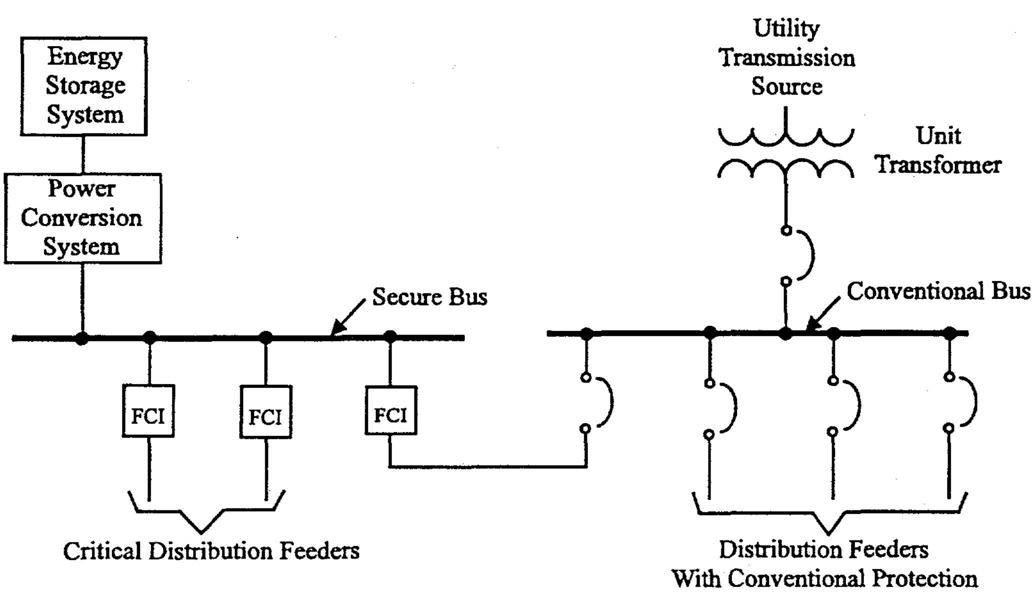

Fig. 2. Circuit diagram of a split bus.

The Secure Bus is designed for medium voltage utility substation applications. For discussion purposes it is assumed that most applications will be in a range between 10 MW and 30 MW at the 15 kV voltage class. Assuming that power outages of 1 second to 10 minutes are to be bridged by the energy storage device, energy storage ratings of 10 MJ to 18 GJ must be available for extraction from the storage device. For reasons of power conversion economics and discharge characteristics of the energy storage scheme not all the energy would be extracted from the device during a discharge. Only about one half of the stored energy is extracted, which results in the actual peak installed energy varying between 20 MJ to 36 GJ(10 MWh).

B. Fault Current Interrupter

A key component for the Secure Bus to function properly is the fault current interrupter. Fast current interruption in subcycle times can not be achieved currently by mechanical circuit breakers. However, at least three types of solid-state circuit breakers are available and capable of interrupting, in subcycle times, short circuit currents of power systems in the megawatt power and in the medium voltage range. These breakers use solid-state switches of the thyristor and the gate turn-off thyristor (GTO) type. Thyristor switches have been used in the electrical power industry for over 20 years in high voltage dc transmission systems, static var systems, and thyristor controlled series compensation systems. GTO switches are just recently finding applications in advanced static var systems and flexible ac transmission (FACT) systems being developed by the Electric Power Research Institute. While the thyristor is technically a more mature device, the current and voltage rating of the GTO has increased considerably in the last few years. It must be pointed out that the solid-state switch must be designed for the full voltage in a Secure Bus installation.

Figure 3 shows the circuit diagram of three solid-state switches. The ac current controller in the form of an antiparallel set of thyristors, as shown in Fig. 3a, is the least complicated device. Current interruption occurs at the moment of the current zero crossing. In the worst case the short circuit current is interrupted in a voltage cycle. The peak short circuit current can not be influenced by the switch. Limiting the peak short circuit current is important because the voltage sag on the bus is directly proportional to the short circuit current. The current interrupting action of the ac current controller is shown in Fig. 4, assuming the fault occurs in the worst case at the moment of the zero crossing of the voltage.

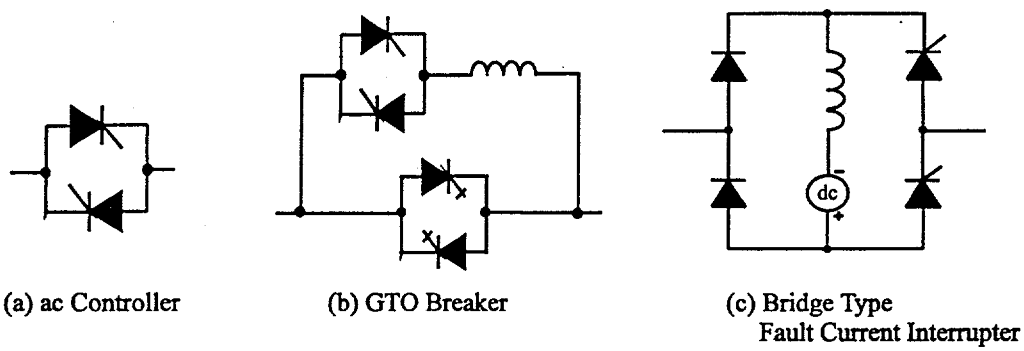

Fig. 3. Solid-state breaker variations.

A GTO based switch is shown in Fig. 3b. The GTOs are not rated to carry the fault current. During normal operation each GTO conducts one half cycle of the load current. In the case of a fault, the GTO interrupts the fault current when it is still rising to its peak current. In the case of an inductive load, the GTO transfers the current to a thyristor switch with a current limiting inductor. The inductor prevents the short circuit current from reaching its maximum value. Westinghouse Electric Corporation has built and has in service a 13.8 kV, 670 A GTO based breaker, which interrupts before the fault current reaches 2500 A. Current interruption time can be as fast as a quarter of a cycle[2].

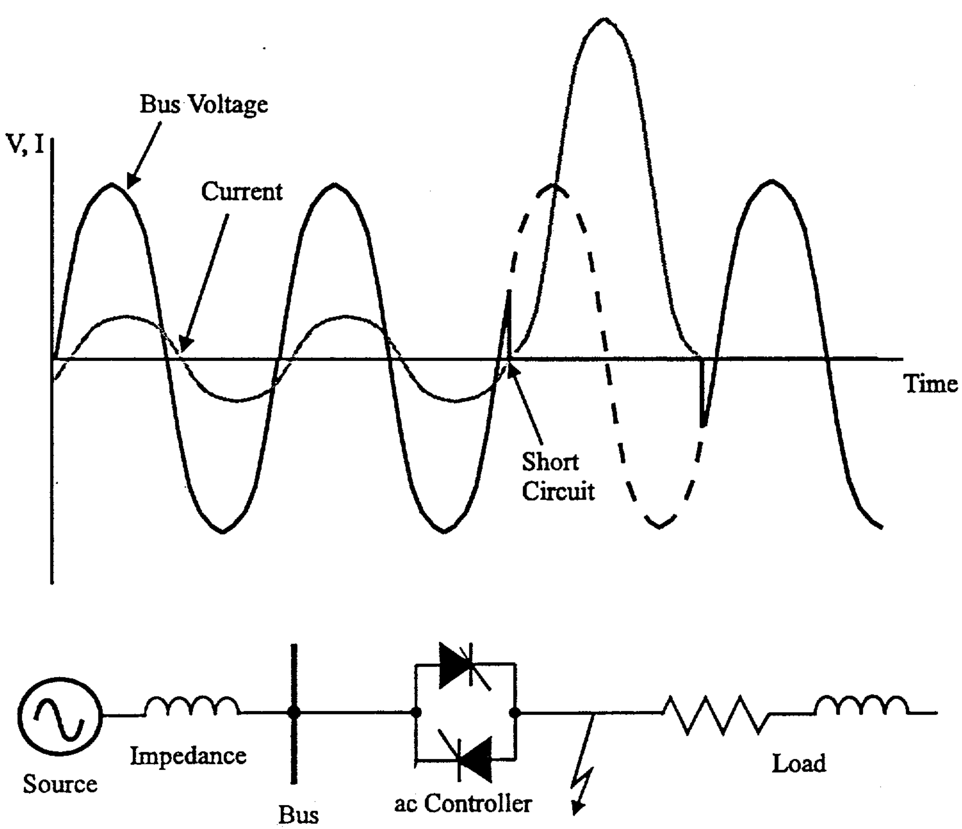

Fig. 4. Voltage and current during current interruption by an ac controller.

A hybrid type of fault current interrupter, using thyristors and diodes, is shown in Fig. 3c. A variation of the hybrid circuit using four thyristors is also a viable alternative. The shown dc source biases the four semiconductor devices to a value higher than the peak amplitude of the load current. In the case of a short circuit the short circuit current will exceed the bias current, which results in at least two semiconductors ceasing the current conduction. The current in the other semiconductors is forced to flow through the bridge inductor. In the worst case the short circuit current is completely interrupted in about three fourths of a cycle. The automatic insertion of the bridge inductor, when the load current exceeds the bias current, already limits the short circuit current in the first half cycle. The amount of current limitation is determined by the value of the inductor and of the source impedance. In a simulation, using the Electromagnetic Transients Program (EMTP), current interruption of a single-phase bridge type FCI using four thyristors is shown in Fig. 5. Initially, a very small current flows in the load. After the short circuit the line current is interrupted in about three fourth of a cycle. In 1995 a single phase, 2.4 kV FCI of the total thyristor type was successfully tested as a fault current limiter. A special feature of the test unit was the construction of the bridge inductor as a high temperature superconducting coil[3].

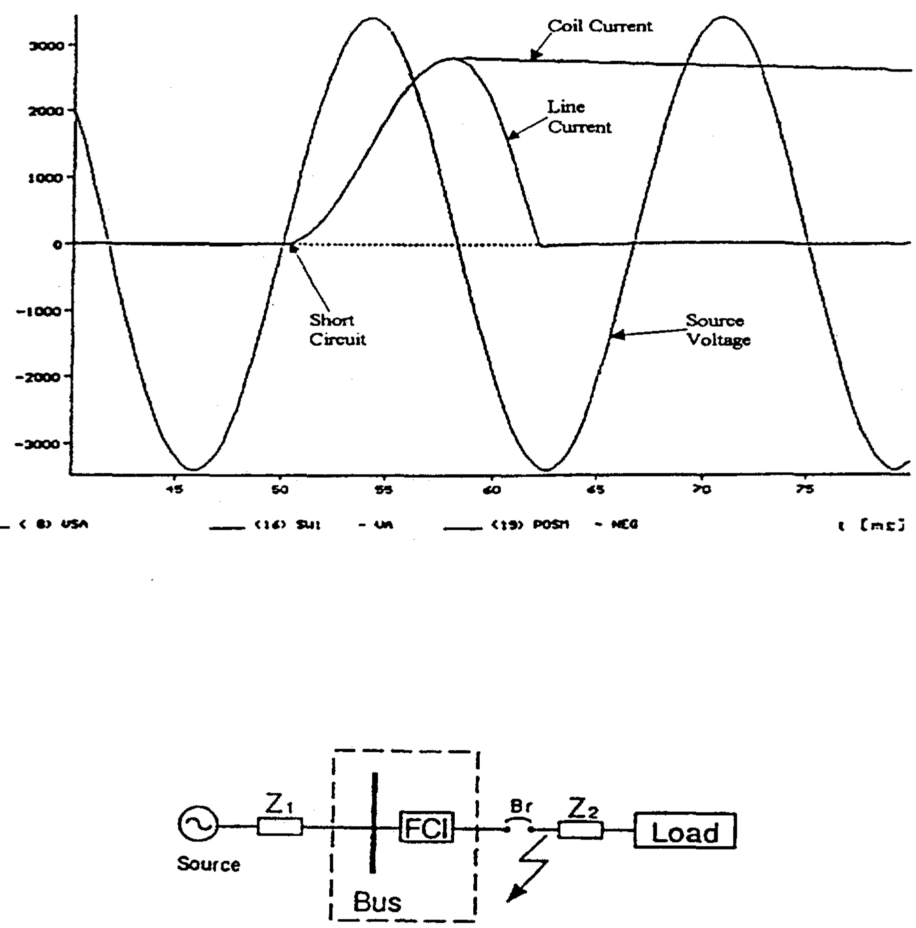

Fig. 5. Fault current simulation for a fault current interrupter (FCI)

The effect of a fast short circuit current interrupter has been investigated for a single phase circuit using the EMTP. Figure 6 shows the result of such a simulation. Two sources feed the Secure Bus, the second source being a representation of the energy storage unit. A short circuit on load 1 is interrupted in about one half cycle by the fault current interrupter in the load 1 branch. The secure bus shows a very slight disturbance while the fault is present, not enough for disturbing the second load. In the simulation a fast circuit breaker according to Fig. 3c was used, however, a breaker with GTO devices would show similar results.

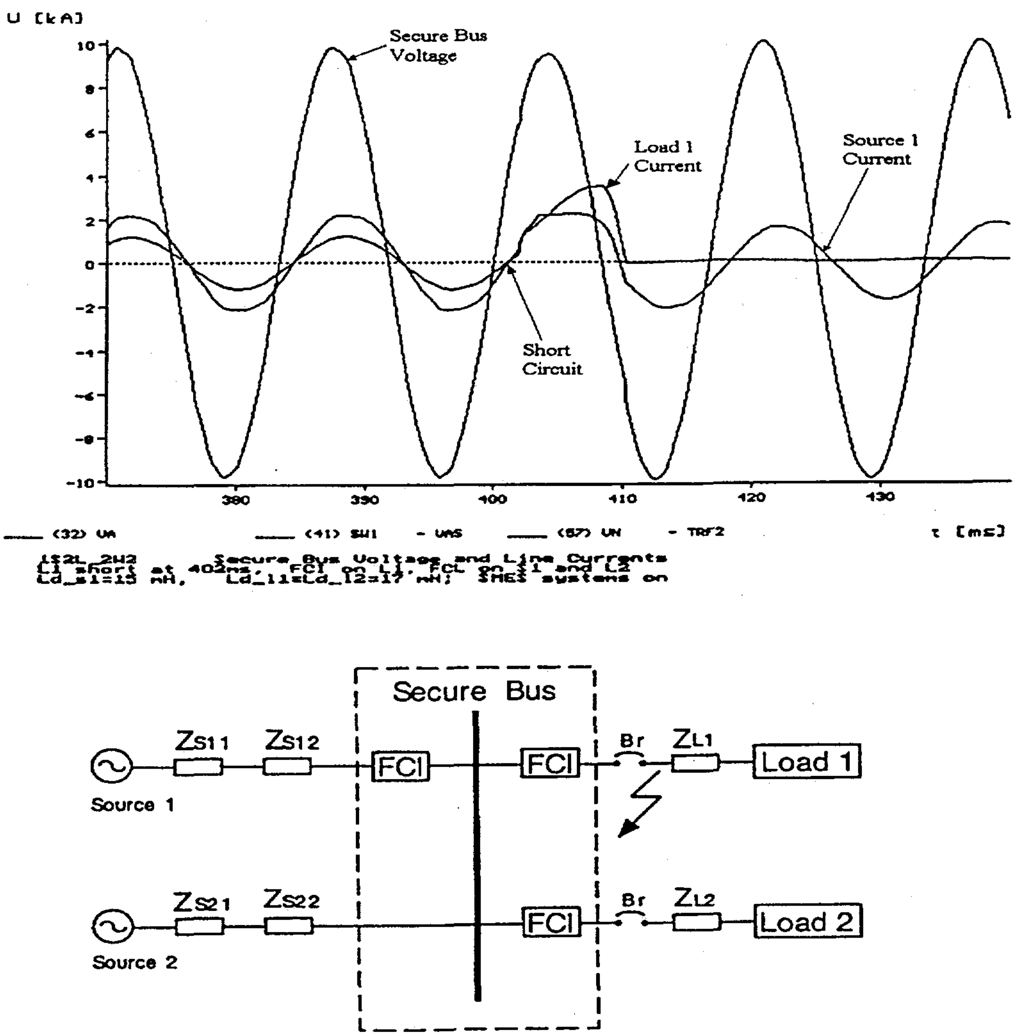

Fig. 6. Secure Bus simulation during a fault on a load feeder.

C. Energy Storage Alternatives

To keep the bus immune from power outages or disturbances on the incoming transmission line, some type of alternate power source is required. In tightly interconnected systems an independent generation source is not always available. In that case back-up power can be provided by an independent energy storage system. Four alternative technologies for energy storage are considered for the Secure Bus. The four types are capacitors, batteries, flywheels and superconducting magnetic energy storage.

Each of the above technologies has advantages and disadvantages that must be considered for site specific installations. The listed storage options are being considered because they are available to the bus in less than 1 ms. Slower responding options such as diesel generators or gas turbines are not being investigated at the moment. However, combinations of a fast acting storage device and a slowly acting standby generation device should not be overlooked.

Capacitors store energy in an electrical field. The advantage of capacitive energy storage is that it is completely passive, that it has low storage losses and that the capacitor voltage can be easily chosen for optimum matching with the medium voltage power conversion system. A disadvantage of capacitive energy storage is the low energy density. High energy density capacitors can be used for this application, because voltage reversal is not a requirement in contrast to ac capacitor applications. Capacitive energy storage systems have been built in the tens of Megajoules, usually in pulse power application, such as laser fusion experiments. An installation for 250 MJ for the National Ignition Facility is being planned to be completed in 2002. Because in energy storage applications the capacitor is energized continuously to the rated voltage, pulsed capacitors must be derated to about half the rated voltage to achieve a 15 to 20 year life time. In a volume of 1 cubic meter about 1 MJ can be stored in a capacitor can. The packing factor of a capacitor bank is about 50%. Capacitive energy storage is attractive up to the lower tens of MJs. This energy rating covers only short power outages. The development of new capacitors (supercapacitors) will expand the application range of capacitive energy storage.

Batteries are still the workhorse for energy storage systems. The energy density is very high and the cost is low. Disadvantages are the environmental concern, precise temperature control to achieve longer battery life, safety concerns and the requirement of connecting many cells in series for a higher voltage conversion rating. Batteries are suitable for energy storage requirements of several minutes to hours at a power rating in the MW range.

Flywheels have been used for inertial energy storage experiments up to energies of 4 GJ for fusion experiments. More closely related to the electric utility industry, inertial energy storage in flywheels is being used in short circuit test laboratories. Research in flywheel technology is being done in all industrialized nations. Using superconducting bearing technology and high strength materials will extend the range of extractable energy. Flywheels are currently being developed for energy storage applications exceeding 5 GJ. Flywheels have a tremendous potential for longer term energy storage in power ratings where units could be paralleled for substation applications. However, modern high speed flywheels are still in the developmental phase for industrial and utility applications.

Superconducting magnetic energy storage(SMES) is still a new technology. Systems in the lower Megajoule range have been built[4], and detailed designs have been made for a 20 MWh system. Conceptual designs of units with energy storage capability up to 5000 MWh for diurnal load leveling have also been completed. Commercial units with very limited energy storage ratings of 3 to 5 MJ are currently being offered in the United States by two companies. The discovery of high temperature superconductors, working at liquid nitrogen instead of liquid helium temperature, is a very promising development for SMES. Unfortunately, as of today, the cost for high current, high magnetic field, high temperature superconductors is still excessive and the industry has difficulties manufacturing cable of sufficient length with persistent performances to satisfy the market.

In spite of all the environmental and safety concerns with batteries, this technology still provides, at the present time, the lowest cost per Joule or kWh of storage. This technology is also still the most adaptable to varying storage duration requirements ranging from several seconds to several hours. It should not be overlooked that according to an EPRI study over 90% of all outages are of a duration of 2 seconds or less[5]. Short term capacitive energy storage could be an attractive alternative for these short term applications.

C. Power Conversion System

The power conversion system is the interface between the energy storage unit and the medium voltage Secure Bus. As its function it converts the power made available from the storage device into 60 Hz, medium voltage, three phase power. All power conversion systems use as the final stage of the conversion process an inverter, transforming dc power into 60 Hz ac power. In the literature many conversion systems for energy storage units have been described, with a 1975 EPRI study done by Westinghouse probably being the first comprehensive study[6].

For inertial energy storage the power conversion system consists of a variable speed three-phase generator, mechanically connected to the flywheel, a rectifier and an inverter. In the rectifier the variable frequency ac power is rectified and the inverter changes the dc power of the rectifier into 60 Hz ac power. To achieve a high energy efficiency of the overall conversion by means of the rectifier and the inverter with the least complexity of the solid-state switching systems, it is suggested to use the largest power thyristors available for the rectifier and the largest GTO devices available for the inverter. High voltage GTOs are available from industry to allow for inverter input voltages of over 3 kV. The step-up voltage transformation from the inverter output voltage to the medium voltage of the substation is accomplished with a transformer. A circuit diagram for power conversion system for an inertial energy storage system is shown in Fig.7.

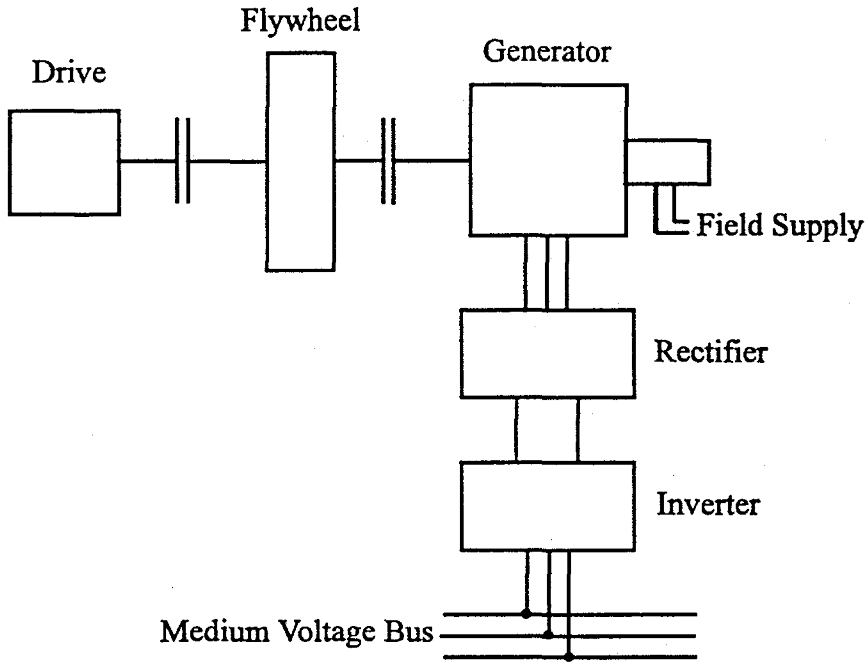

Fig. 7. Diagram of a flywheel energy storage power conversion system.

The power conversion system for a battery energy storage unit is available commercially from several companies, in particular manufacturers of UPS systems. Almost without exception, these systems, using voltage source inverter technology, operate at voltage levels of 480 V or below. For a Secure Bus installation, with the higher power throughput, for better efficiency and a reduced component count, the voltage should be increased to levels of 2 to 3 kV. The inverter should use the soft switching technology. Inverters with a power rating of 3 to 5 MW can be built using available high power GTO devices, without connecting individual devices in parallel or in series.

For a capacitive energy storage system the power conversion hardware is similar to the one used for the battery storage unit. Again a voltage source inverter can be used. For superconducting magnetic energy storage a current source inverter or a high power chopper with intermediate capacitive energy storage and a series connected voltage source inverter have been suggested as two variants by two different design teams for the 20 MWh unit. Omitting the chopper the circuit can be adapted as the power conversion system for capacitive energy storage. These approaches, one of them is shown in Fig. 8, can also be implemented for the Secure Bus.

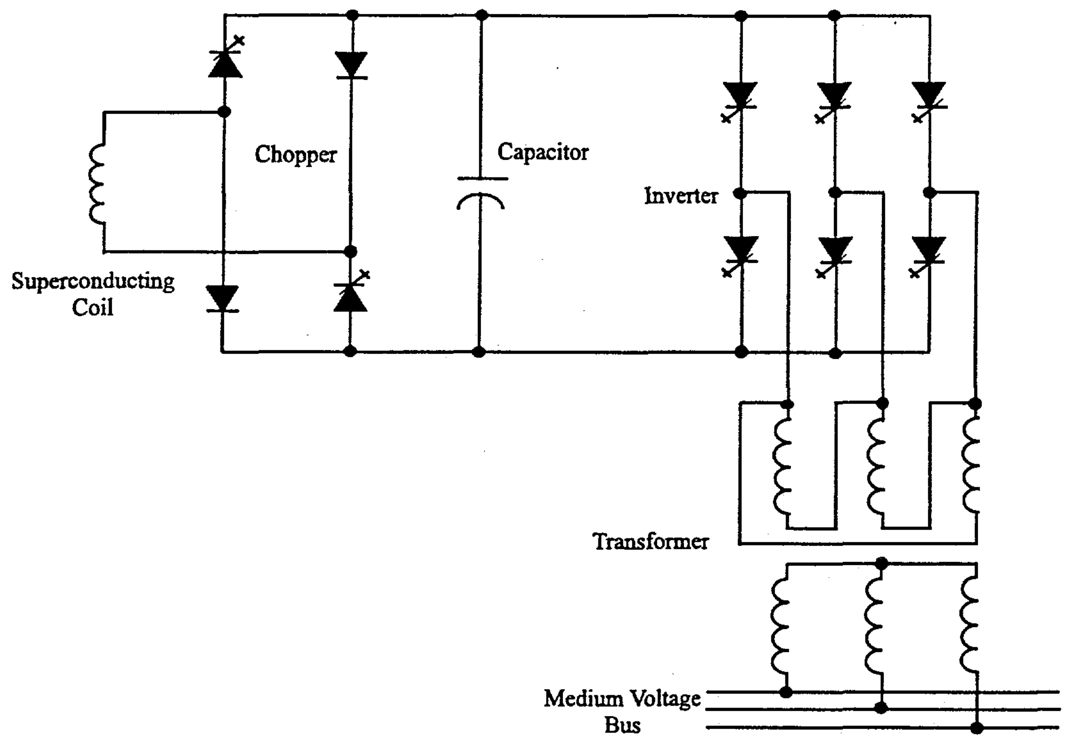

Fig. 8. Power conversion system for a superconducting magnetic energy storage unit.

For whatever storage media chosen, the power conversion system should be designed at a voltage level of 2 to 3 kV, taking full advantage of the ratings of available high power GTO devices.

III. STATUS OF THE SECURE BUS PROJECT AND OUTLOOK

Work has been underway for approximately eighteen months on developing the conceptual Secure Bus. The project to date has been a collaborative effort that includes CRE, LANL, PNM, and SNL. The project has a goal of building a medium voltage Secure Bus demonstration unit in a 12 kV substation at SNL in 1998.

It is anticipated that the Secure Bus demonstration unit will be rated at 10 MVA, and installed to serve two critical distribution feeder loads from a new unit substation. One of the feeder loads is a microelectronics development laboratory, the other one is a robotics laboratory. The substation will be rated 20 MVA, and also serve other loads with conventional switchgear in the configuration shown in Fig. 9. Both a source interruption breaker and a feeder short circuit interrupter are included in the demonstration Secure Bus for testing purposes. The demonstration unit will be designed to allow for staged short circuits both on the load side and the source side and for loss of generation simulations.

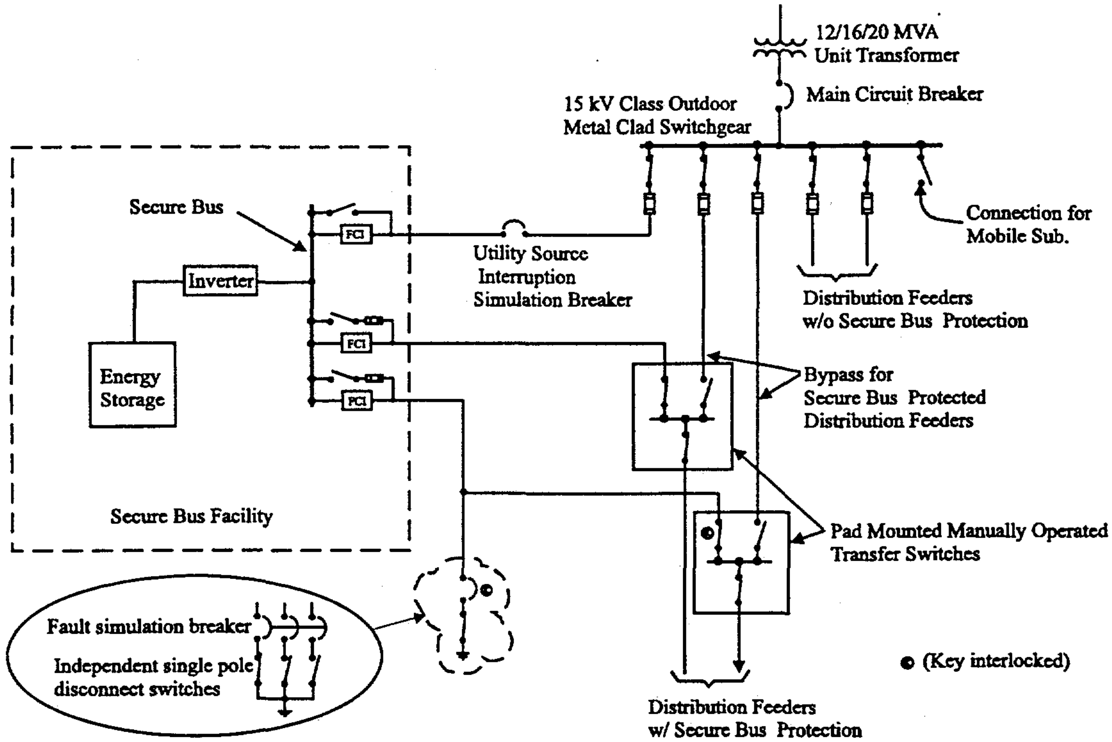

Figure 9. Circuit diagram for Secure Bus demonstration unit with staged fault devices.

Previous work has focused on the performance of the secure voltage bus, which has been modeled using the EMTP. Currently, work is focusing on protection issues surrounding a Secure Bus. Since the fault current is limited by the FCI device, and a faulted element quickly interrupted, downstream coordination can not depend on available fault current to isolate a faulted branch feeder. A solution to this issue is being incorporated into the SNL demonstration unit. Other design issues being addressed are the effects of harmonics and of switching surges and overvoltages on the bus.

A patent application has been filed for the Secure Bus through LANL. In addition, the name Secure Bus has been trademarked for future commercial use. Both PNM and CRE have been participating in this project with the intent of commercializing the Secure Bus.

Efforts are continuing with several high-tech manufacturers, including several semiconductor manufacturers, to assure the SNL demonstration project meets the performance needs for their facilities. Teaming arrangements are being developed with component manufacturers to assure that cost and performance specifications meet the criteria established by the potential high-tech user industries. Market research indicates a robust market is available, if the unit price can be kept below $500/kVA. It is expected that medium voltage units will be commercially assembled in 10 MVA, 20 MVA, and 30 MVA ratings.

Although the Secure Bus project has maintained considerable momentum by the participants, work is still underway in locating financial investors for the Secure Bus demonstration unit. It now appears that this hurdle will be overcome by the end of 1996. In parallel with the efforts for the 10 MVA demonstration unit, the team is investigating the design of a smaller prototype unit (25 to 50 kVA) with battery energy storage, to be built at considerably lower cost. The same component and system controls would be developed for the small prototype as for the high power unit. It is anticipated that the control hardware would be transferred to the larger demonstration unit. The next eighteen months will be critical in building a demonstration device as a commercially attractive and cost effective product.

IV. CONCLUSIONS

Electric utilities are attempting to provide quality power to customers having sensitive loads in their manufacturing processes. The installation of a Secure Bus system at the medium voltage utility substation level provides the customer with disturbance-free power, thus eliminating or at least minimizing the need for UPS systems. In a Secure Bus arrangement the load is immune to power disturbances and protected against power outages, power sags, and short circuits on parallel feeders. The Secure Bus consists of fast acting circuit breakers and an independent second feed in the form of an energy storage system with power conversion equipment, capable of making the second source available to the bus in less than a ms. The fast acting solid-state circuit breakers isolate part of a system before the voltage sag caused by a short circuit can have an adverse effect on the remaining loads. Power outages or sags from the feeding utility system are not noticeable on the bus because in the case of such a disturbance the second, independent power source will take over and provide uninterruptible power. Different energy storage technologies are available, with batteries currently the most preferred.

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Heinrich J. Boenig received a Diplom Degree from the Technical University of Karlsruhe, Germany, and a Ph.D. degree from the University of Wisconsin, Madison. Both degrees are in electrical engineering.

From 1971 to 1974 he worked as a development engineer at the Siemens R&D Center in Erlangen, Germany, in the areas of static var systems, uninterruptible power supplies, and electrical machine control. During the academic year 1974—1975 he was a visiting associate professor in the Department of Electrical Engineering at the University of Wisconsin, Madison, teaching courses in electrical machines and doing research in electrical drives. Since 1975 he has worked at the Los Alamos National Laboratory, Los Alamos, New Mexico, in the areas of power electronics, pulsed power, application of both low- and high-temperature superconductors to electrical power system components and in inertial, capacitive, and superconducting magnetic energy storage.

Dr. Boenig has several patents and has been a consultant to private industry, government institutions, and universities. He is a member of the IEEE Power Engineering Society, Industry Applications Society, and Power Electronics Society.

William H. Jones received a B.S. degree in electrical engineering from the University of Illinois and an M.B.A degree from the University of Colorado.

Since 1993 he has been a vice president of El Camino Real Engineering, Inc. (CRE) in Corrales, New Mexico, with most of his consulting work focusing on large scale power quality solutions. He worked for Public Service Company of New Mexico (PNM) from 1980 to 1993, and was its Director of Large/Industrial Market Services from 1991 to 1993. He previously held PNM positions as Plant Engineering Supervisor at the San Juan Generating Station and Bernalillo Operations Division Manager. While at PNM he spent 1992 onsite at Intel's Rio Rancho chip manufacturing facility managing an Electric Power Research Institute power quality case study. Prior to working for PNM he worked as an electrical engineer for Coors Porcelain Company and Stearns-Roger Corporation in Denver, Colorado.

Mr. Jones is a member of the IEEE Power Engineering Society and Industry Applications Society, and is a licensed professional engineer in Colorado and New Mexico.