ELECTRIC POWER RESEARCH INSTITUTE

EPRI Family of Low-Cost Multifunction Switchgear Systems

Design Workshop and Future Work Plan

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Technical Update, December 2006

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REPORT SUMMARY

Background

This project is to develop a family of low-cost solid-state switchgear systems for a range of distribution applications. These devices will be designed for use in switchgear replacements and for new installations. Additional benefits will come from other functionality (besides interrupting current) to be built into the switchgear systems. The switchgear systems will be useful in current distribution system infrastructure and, as a part of ADA, in migration to the distribution system of the future. The requirements definition work for this switchgear system was performed in 2005. The 2006 work was focused on development of an initial design specification and a more detailed multi-year plan for use in procuring a development contractor.

The solid-state switchgear system will provide added functionality beyond mere current interrupting and will be an important component of the distribution system of the future. Candidate functions include current limiting capability, waveform analysis for fault anticipation, and the ability to monitor distribution system electrical and environmental parameters at the switchgear location. The new switchgear system will contribute to outage prevention and recovery, optimal system performance under changing conditions, and reduced operating costs. It will be applicable to multiple distribution system applications, leading to lower cost and higher reliability through use of a single product family.

Objective

The overall objective of this multi-year project is to develop and commercialize a family of low-cost, multifunctional, solid-state switchgear systems for distribution applications.

Approach

The following is a list of tasks that were performed as part of the 2006 effort:

- Conduct a design workshop to obtain inputs for the design and project plan from utilities
- Prepare an initial design specification for the switchgear system
- Prepare a project plan for development and testing of the multi-function switchgear system
- Develop an initial applications research plan
- Draft a procurement specification for selecting a contractor for subsequent phases

Results

The report presents the results of the design work and an updated project plan for development and testing of the solid-state switchgear technology and identifies the key functionalities and criteria that need to be met in order for this technology to gain market acceptance. It also provides an initial applications research plan for applications research, which will be the final phase of the project. Finally, it outlines a procurement specification to select a developer for future work.

EPRI Perspective

EPRI Project 124.002 is part of EPRI Program 124 on Advanced Distribution Automation (ADA), which has the objective of creating the technology basis for the distribution system of the future. The scope of project 124.002 is to develop and test a multi-function system to replace distribution-class switchgear. This is referred to as a "switchgear system". It is to be a device that can interrupt current and perform other functions. The added functionality is to include, as a minimum, remote communication and control, which will allow the switchgear system to be used as a monitoring node for the distribution system electrical parameters, in conjunction with a larger monitoring system concept under development in Project 124.005. Use as a monitoring node is a desired function in all equipment developed in the EPRI ADA program. To have maximum compatibility with utility communications systems, the communication interface's information model (object model) for each such new type of ADA equipment developed in Program 124 will be made available to an IEC standards working group for evolving into an international standard, as part of the 61850 series of standards. Hence, the equipment will be useable in 61850-conforming systems (the most robust case) and will be backwards compatible with less robust legacy systems now in use. Other functions have been identified for inclusion in the switchgear system and have been prioritized with sponsors for inclusion in the development work for the first-generation product according to funding availability.

Keywords
Solid-State Switchgear System
Advanced Distribution Automation
Distribution System of the Future
Distributions System Monitoring and Communications

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1
INTRODUCTION

The overall objective of the EPRI Advanced Distribution Automation (ADA) Program is to create the enabling technology for the Distribution System of the Future. The Distribution System of the Future will have the following features:

- New system configurations, such as looped feeder circuits, islandable circuits (sometimes called "micro-grids") and bidirectional power flows
- New operating capabilities, such as smart sectionalizing and reconfiguring, emergency response, and integrated volt/VAR management.
- Strategic use of intelligent electronic devices (IEDs), information technology, and other new distribution technologies.

Such capabilities will make the system more flexible, able to operate more reliably, and better at preventing (or recovering from) outages. ADA will facilitate the integration and strategic use of new intelligent electric devices or IEDs (such as power electronic components, intelligent universal transformers, advanced VAR management systems, power quality enhancement equipment, distributed generation, fault anticipator/locator technologies, and demand management information systems). These IEDs not only enable the more flexible electrical architecture mentioned above, but also provide the means for expanded customer service options. One such IED is the ***family of low-cost multifunction solid-state switchgear systems***.

The next generation multifunction solid-state switchgear technology will provide added functionality beyond mere current interrupting and be an important component of the Distribution System of the Future. Candidate functions include current limiting capability, waveform analysis for fault anticipation, and the ability to monitor electrical and environment parameters at the switch location as a component of a larger ADA monitoring system. The new switchgear will contribute to outage prevention and recovery, optimal system performance under changing conditions, and reduced operating costs. Collectively, these benefits will lead to higher customer and regulator satisfaction. The new solid-state switchgear will be designed for significant improvement of reliability in the current interruption function, which will add to overall system reliability. The new solid-state switchgear will be designed for low cost relative to conventional switchgear, and will have added functions (like system monitoring) relative to conventional switchgear. This will result in significant capital expense savings for the overall distribution system. The new switchgear will be applicable to multiple distribution system applications, leading to lower cost and higher reliability through use of a single product family.

Starting from 2005, EPRI has undertaken the development of a family of power electronics based switchgear applications at ***distribution*** class voltages. EPRI, as the leading research institute in the power industry, is ideally suited to take the first step to initiate the research in this direction based on a long-term research plan targeting the development of medium and high voltage, high-power semiconductor switches and parallel development of circuit topology, controller, and prototype of solid-state distribution switchgear.

EPRI's multifunction solid-state switchgear program is planned to broadly encompass the following phases:

- Requirements definition, assess key application areas for this product and identify development options[1] that can give us the flexibility to align with funding received (completed in 2005)
- Conduct design workshop to obtain valuable inputs about the design and applications from program sponsors and other utilities (2006)
- Initiate competitive procurement process to select vendors who are best suited to implement the solid-state switch technology
- Multi-function switchgear design analysis
- Laboratory development
- Field prototype development
- Select test hosts for demonstrating the product and its applications
- Interface closely with program sponsors over the program life cycle
- Work and interact with other utilities over the program life cycle
- Work and interface closely with multiple vendors on implementation of solid-state switch technology throughout the development cycle, laboratory testing, field demonstration and after development during early commercialization
- Addresses customer engagement in applications research during the latter stages of development and after development during early commercialization
- Address key integration issues and additional refinements to take advantage of the new technology

In particular, the project's broad tasks from the multi-year plan (see Figure 1-1) for Program 124 include:

- **Requirements Definition** (completed in 2005).
  - Assess the needed characteristics for switchgear in current and future distribution system applications (from prior EPRI work and current literature).
  - Study the current state-of-the-art in conventional and solid-state switchgear and identify the technology gaps that must be filled to meet the needs.
  - Conduct a conceptual design and cost/benefit analysis of a few candidate solid-state switch concepts for the prospective family.
  - Identify candidate functions to be included in the switchgear products.

[1] For example, the minimum system developed could be a current interruption device with a communication interface that enables it to be used as a monitoring node in ADA and that allows remote control of the switch. Other functions, like fault current limiting or use in fault anticipation/location schemes, can be options added to the minimum system, if funding allows.

  - Conduct a feasibility assessment for developing the chosen concept.

- **Development of Initial Design and Plans for Testing and Evaluation, Commercialization, and Applications Research**
  - Proceed in 2006 with detailed design for a specific low-cost multi-function switchgear concept
  - Proceed in 2006 and develop a plan for development, test and evaluation, and applications research phases of the project.
  - Proceed in 2006 and assess key application areas for this product
  - Proceed in 2006 and identify development options[2] that can give us the flexibility to align with funding received
  - Proceed in 2007 and initiate competitive procurement process to select vendors who are best suited to implement the solid-state switch technology
  - Proceed in 2007 and develop design drawings.
  - Proceed in 2007 and develop technical specifications for the component technologies (electronic and communications)
  - Proceed in 2007 and update the cost/benefit analysis for the switchgear family
  - Proceed in 2007 and determine the communication architecture needs for the switchgear, building on existing standards and legacy systems.

- **Development of Multi-Function Switchgear Family**
  - Conduct laboratory bench model development and then field prototyping of the chosen concept. The product would be designed for easy mapping to open architecture communication standards for distribution switchgear, when they become available in the IEC 61850 series. It is not known at this time when those IEC (International Electrotechnical Commission) standards will be written. However, the product development will include a communication interface with a nonproprietary object model for the device, which can be provided to IEC to aid in development of a standard.
  - Update cost/benefit analysis and plans for future phases based on the results of development work in this task.
  - Develop specifications for the commercial products.
  - Conform the switchgear family to open-systems-based communication architecture standards, with backwards compatibility with major legacy communication systems. In particular, EPRI will seek to harmonize this product with IEC 61850 standards and part of the project resources will therefore be used for active participation in the IEC standards development.

[2] For example, the minimum system developed could be a current interruption device with a communication interface that enables it to be used as a monitoring node in ADA and that allows remote control of the switch. Other functions, like fault current limiting or use in fault anticipation/location schemes, can be options added to the minimum system, if funding allows.

  - Develop specifications for the commercial switchgear family. Identify shortcomings and technology gaps that may be addressed in other project work and/or a second-generation family.
- Test and Evaluation
  - Select test hosts for demonstrating the product and its applications
  - Field test switchgear in one or more actual utility systems, depending on availability of willing utility partners who are able to provide funding for purchase and installation of the equipment.
  - Document test results to aid in final product specification.
  - Update cost/benefit analysis and plans for future phases based on the results of system testing and evaluation.
- **Finalization of Design and Packaging for Commercial Release**
  - Correct problems identified in field testing.
  - Design packaging.
  - Transition results to vendor(s) for commercialization.

- **Applications Research**
- Addresses customer engagement in applications research during the latter stages of development and after development during early commercialization
- Interface closely with program sponsors over the program life cycle
- Work and interact with other utilities over the program life cycle
- Work and interface closely with multiple vendors on implementation of solid-state switch technology throughout the development cycle, laboratory testing, field demonstration and after development during early commercialization
- Perform technical application studies/guides on opportunities to use the multifunction switchgear technology
- Work with potential vendors, program sponsors, and other utilities to select a host site to test and demonstrate the product and its key applications
- Perform trial applications of the multi-function switchgear in major types of distribution system environment
- Conduct experience evaluation and documentation for major application types to aid prospective users in adoption.
- User group, workshops, subscription support services, as may be specified in the applications research plan.
  - Address key integration issues and additional refinements to take advantage of the new technology

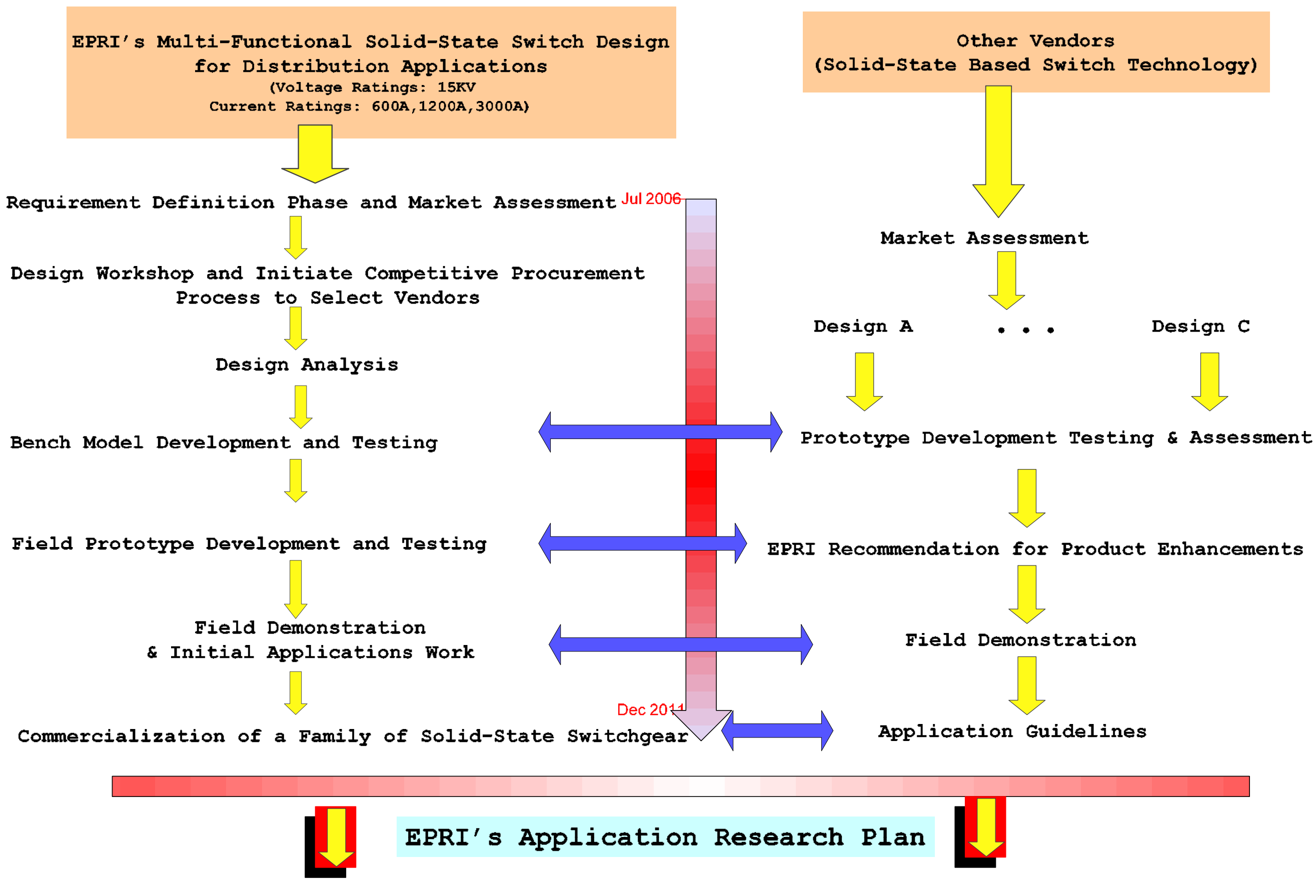

Figure 1-1
EPRI's MultiFunction Solid-State Switchgear Program

This program will provide participants with a family of low-cost solid-state switchgear for a range of distribution applications that will lower capital costs for switchgear and improve system reliability. These devices will be designed for use in retrofits and for new installations. Additional benefits may come from other functionality (besides interrupting current) that may be built into the switches, such as current limiting capability, waveform analysis for fault sensing, and the ability to monitor electrical and environment parameters at the switch location. Thus, the feasibility of using the switch for real-time distribution system monitoring and other functions will be examined. The switchgear will be useful in current distribution system infrastructure and, as a part of ADA, in migration to the Distribution System of the Future.

The intent here is not to make recommendations for a specific design or a specific semiconductor device. The question is, "Is there a possibility that other designs may evolve that might meet the need"? This decision will have to be made by the manufactures to come up with other innovative designs that will meet the specification or through a competitive procurement process to select a vendor/developer/partner.

Based on the preliminary results and on-going research in these areas, "***all solid-state***" based switchgear designs as well as "***hybrid***" designs have the potential to offer a myriad of advantages that prospective purchasers may find attractive and may make them successful in the marketplace. It was emphasized that EPRI should consider both “all solid state” as well as “hybrid” bids and that if a hybrid bid is made, the path to all solid state in the long run must be shown by the bidder. These designs will guide the development of the smart solid-state switchgear.

Report Intent

The overall objective of this multi-year project is to develop a family of low-cost multi-function switchgear for ADA. The 2006 design phase will focus on a design workshop with project sponsors and preparation of an initial project plan to be used in competitive procurement for a developer/manufacturer contract. The following is a list of tasks that were performed as part of the 2006 effort:

- Conduct a design workshop to obtain valuable inputs about the design and applications from project sponsors and other utilities
- Initial design specification for the switchgear system
- Evaluate a conceptual design candidate of solid-state switch concepts and conduct a feasibility analysis (economic as well as technical)
- Project plan for development and testing of multi-function switchgear system
- Develop an initial applications research plan
- Procurement specification for selecting a contractor for subsequent phases

The research conducted as part of the 2006 work is the next step before embarking on development of the hardware and associated controls for development of a family of low-cost solid-state switchgear for a range of distribution applications a prototype version of solid-state switchgear.

Report Organization

Chapter 2 incorporates specific input from the workshop and describes important elements of the design and application that should be considered, especially as they are different from the original design concept developed last

Chapter 3 defines the functionality requirement and an initial design specification for this multi-function solid-state switchgear for use in the competitive procurement for the next phase of the project

Chapter 4 provides a project plan for development, field test, and evaluation of the first-generation multi-function distribution class switchgear to be used to procure a manufacturer/developer for the remaining project phases. This chapter provides a detailed description of the possible phases for design and development of the chosen switchgear technology along with schedules, important milestones, and commercialization cycle for the development work in 2006–2010 and field testing and commercialization in 2011-2012

Chapter 5 provides EPRI's initial applications research plan for the ADA multi-function switchgear

Chapter 6 provides the procurement specification for selecting a contractor for subsequent phases. It contains generic specifications developed for the first generation multi-functional solid-state breakers for distribution applications. The material covered here uses appropriates materials from previous tasks for the purposes of RFP

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SUMMARY OF DESIGN WORKSHOP RESULTS

Objectives

A design workshop and project review meeting workshop in which sponsor input was received regarding the design and the multiyear project plan was conducted on July 12th, 2006. The focus of the meeting included the following:

- Present a conceptual design (Proposed functions, proposed technology solution, and communication interface) for the family of low-cost solid-state switchgear.
  - The conceptual design included a functional description of the multi-function switchgear with schematics and an initial list of components.
- Discussion and selection of functions to be designed into the product
  - Functions to be included in the product include (1) current interruption capability, (2) voltage and current sensing as a monitoring node as part of a larger real-time monitoring system in ADA, (3) a communication interface that conforms to IEC 61850 and is backwards compatible with major legacy architectures, and (4) a solid-state switching approach. Other functions namely fault current limitation and fault anticipation and location were identified as optional candidates. Following features were also discussed (1) Widespread system coverage, including distribution substations, feeders, and networks (2) Applicability to radial and networked distribution systems, (3) Coverage of overhead and underground systems, and (4) Integration with SCADA and utility operating systems,
- Provide an outline for the development plan, test and evaluation work to follow in future phases of the project
- Develop an outline for an applications research plan for future phases of the project
- Review the items described above and receive sponsor input regarding the design and the multiyear project plan

Meeting Minutes

The meeting minutes from this workshop is provided below.

Member Inputs

1. It was determined that the following functions would be given priority in future phases:
   - Current interruption

- Fault current limiting
- Use the device as a system monitoring node in ADA real-time monitoring system via communication link
- Support for switching functions needed to allow local islanding
- Transition switching to limit current inrush (capacitor switching).

2. It was agreed that submersibility would not be pursued in the first generation device, because of tight project budget and schedule expectations. It is a candidate for second generation.
3. Procurement package should allow either all solid-state or hybrid bids. But if it is a hybrid, the bidder must clearly show how it is a step toward eventually having an all solid-state approach
4. 1200 Amps should be minimum and not 600 Amps (feeder breakers and substations need 1200)
5. Coordinate with DFA developers to see if and when they will have a software product that could be embedded in the multi-function solid-state replacement for distribution switchgear. DFA is a possible function that could be embedded in this device, in the IUT, or in other devices, if sufficient funding becomes available and if DFA software (or an alternative from another source) becomes available for straightforward incorporation into programmable distribution equipment.
6. Use gate-controlled devices, not thyristors. GTO would be best choice of a device at this time for a hybrid design.
7. It was noted that the high-power switchgear project in the EPRI Substations Program is thyristor-based.
8. For hybrid bids, a bidder should include his migration schedule for moving the initial product to an all-solid-state approach in subsequent versions.
9. Cyberex was identified as a player in the switch field.
10. Some to consider in the bidders' list[3] could include:
    - Mistusbishi
    - Silicon Power
    - Cyberex
    - General Electric
    - ABB
    - Siemens
    - Invert Power (Ontario, Canda)
    - S&C Electric

[3] The list of candidate bidders identified here is not a final bidders' list and needs further screening

Specific Suggestions/Comments from Sponsors

- Device should have current limiting capability, especially with voltage sag. Multi-year plan should address how to integrate switchgear into system operations, e.g., coordination with feeder breaker above and fuses below.
- It was emphasized by several members that monitoring capabilities should be integrated into the device.
- One of the member suggested that he would like product option to add in fault current for another $30-50k with use of an energy storage device
- One of the member suggested that the device should support peer-to-peer communications in rapid fault isolation
- One of the member suggested that communications interface to be backwards compatible with DNP. Peer-to-peer communications would be supported if we integrate the new switching device's object model into IEC 61850
- It was emphasized that EPRI should consider both "all solid state" as well as "hybrid" bids and that if a hybrid bid is made, the path to all solid state in the long run must be shown by the bidder.

3
INITIAL DESIGN SPECIFICATION FOR THE SWITCHGEAR SYSTEM

This chapter addresses the following:

- Identifies the future needs for switchgear equipment (with multiple functions),
- Identifies current and expected future distribution switchgear applications
- Assess the desired characteristics for switchgear in these distribution system applications
- Identifies possible market drivers for this new device which is expected to provide a range of functionalities beyond that available with conventional switchgears by taking advantage of advances in power electronics and other related technologies. Functions that the switchgear needs to provide include: 1) current interruption, 2) current limiting, 3) fast fault clearing and detection, 4) distribution system condition monitoring, and 5) remote communication linkage with automated distribution operating systems

The initial conceptual design for the first generation of solid-state switchgear, presented here is aimed at distribution level applications in the 15KV-35KV class range. It is not intended for transmission level applications.

Need for a solid state switch module

While the potential benefits of power electronics based switchgear designs ("***all solid-state***" as well as "***hybrid***" designs) have long been apparent, potential high production costs have curtailed development efforts. Advances in high power solid-state components now make possible solid-state switchgear at a reasonable cost. In a recent study, EPRI conducted a comprehensive survey to assess utility needs and perceptivities with respect to power electronics based solid state switchgear that can limit fault currents. Some of the key findings that are relevant to the outcome of the economic assessment presented in this chapter include:

- Survey results indicate that up to 20% of utilities expecting to replace 5 to 10% of their circuit breakers in the next 10 years would use a fault current limiting devices that are priced at 1 to 5 times a circuit breaker
- Utilities having a greater expectation for circuit breaker replacement are even more likely to use a solid-state fault current limiter – the percentage increases to 30% of utilities when the range of circuit breaker replacement need expands to 5 to 30%
- Cases where breakers with the required ratings are not available, or where excessive fault current levels carry more than only cost of a breaker upgrade alone, 50% of the utilities value a solid-state fault current limiter at 2-5 times the cost of a breaker

Key Advantages of Solid-State ("All Solid-State" as well as "Hybrid" Designs) Switchgear

Solid-state switchgear offers a number of possibilities [2-6]:

- Repeated operations with high reliability and without wear-out.
- Reduced switching surges.
- Faster clearing reduces the impact of voltage sags on adjacent circuits.
- Faster clearing reduces stress on distribution equipment and reduces damage at the fault location.
- Limited inrush current (soft start), even for capacitive loads

Characteristics that can be attributed to the solid-state distribution class switchgear may include, but are not limited to, the following:

- Rapid Load Transfer Capabilities. Distribution solid-state switchgear can be used as solid-state transfer switches. The solid-state switchgear designs can be used to transfer the power supply of sensitive loads, from a "normal" supply system to an "alternate" supply system when a failure is detected in the "normal" supply. In one embodiment, this transfer is performed quickly (1/4 cycle) so that the load does not experience any power quality problem.
- Circuit Sectionalizing and Reconfiguration. Solid-state switches can eliminate momentary interruptions for the great majority of users on distribution systems when a fault occurs. Solid-state switches for reconfiguring systems can also allow for optimizing performance through reconfiguration without imposing momentary interruptions on users.
- Rapid Fault Current Solution Deployment. Solid-state switchgear designs can enable distribution entities/users to effectively deal with pressures to add new transmission capacity, provide open access for distributed and aggregate generation, and deal with the challenges presented by new fault current sources. Fault-current limiting is a characteristic that can be attributed to the subject solid-state switchgear. The following benefits can result from using solid-state switchgear that has fault-current limiting characteristics:
  - Failures. Cable thermal failures are less likely, and violent equipment failures are less likely.
  - Conductor burndowns. At the fault, the heat from the fault current arc may burn the conductor enough to break it, dropping it to the ground. Solid-state switchgear can provide faster clearing and lower magnitudes, therefore reducing the chance of burndowns.
  - Damage of inline equipment. A known problem is with inline hot-line clamps. If the connection is not good, high-current fault arcs across the contacts can burn the connection apart. Solid-state switchgear can provide faster clearing and lower magnitudes, therefore reducing the chances of such damage.
  - Evolving faults. Ground faults are more likely to become two- or three-phase faults with longer, higher-magnitude faults. Solid-state switchgear can provide current-limiting that may reduce this probability.

- Underbuilt. Faults on underbuilt distribution are less likely to cause faults on the transmission circuit above due to rising arc gases with fault-current limiting.
- Equipment ratings. Some distribution stations have fault current levels near the maximum ratings of existing switchgear; additional short-circuit current requires reconfigurations or new technology. Solid-state switchgear can provide fault-current limiting that can resolve this problem.
- Shocks. Step and touch potentials are less severe during faults.
- Conductor movement. Conductors move less during faults, providing more safety for workers in the vicinity of the line and making conductor slapping faults less likely).
- Voltage sags. Solid-state switchgear with fault-current limiting characteristics can reduce the depth of the voltage sag to customers/users on adjacent circuits.
- Coordination. Fuse coordination is easier. Fuse saving is more likely to work with lower fault currents.

• <u>Rapid Fault Isolation and Aid Power Quality Improvements</u>. With the flexibility of power electronic switching, the solid-state switchgear will achieve fault isolation and provide better network protection and take care of most of the distribution system situations that result in voltage sags, swells, and power outages.

• <u>Instantaneous Current Limiting</u>. Solid-state switchgear designs can provide instantaneous (sub-cycle) current limiting. Solid-state switchgear can alleviate the short circuit condition in both downstream and upstream devices by limiting fault currents coming from the sources of high short circuit capacity.

• <u>Faster Fault Clearing and Shorten Recloser Interval</u>. Solid-state switchgear designs may allow utilities/users to clear faults more quickly than current circuit breakers.

• <u>Mitigating the Effects of New Generation Within Distribution System</u> New technology will increase the available fault current of the network and may result in existing equipment not being adequately rated to handle the new ratings. Upgrading the system to accommodate the new fault current ratings may be expensive and create excessively high prices and barriers to new generation. The solid-state switchgear designs with current limiting capabilities can be used to mitigate this situation.

• <u>Interfaces with Distributed Generators</u>. Solid-state switches can facilitate implementation of local islanding schemes for distributed generators and allow connection and disconnection without concern for transients.

• <u>Repeated Operations With High Reliability and Without Wear-Out.</u> High fault currents are known to be a factor in reducing transformer life, so an advantage that can result from using solid-state switchgear is longer life with higher reliability for nearby transformers.

• <u>Curtail Mechanical Wear and Tear in Equipment</u>. Equipment in the fault current path will not experience the high asymmetrical and symmetrical fault currents that would be possible without the solid state switchgear.

• <u>Soft Start Capability</u>. Using solid-state switchgear can limit the inrush current for capacitive loads, by gradually phasing in the switching device rather than making an abrupt transition from an open to a closed position.

- Reduce Switching Surges. Solid-state switches can prevent transient voltages during capacitor switching and will allow capacitors to be switched in and out as often as needed. The result is better control of VAR flows, voltage, and flicker on the distribution system without causing unacceptable transient voltages.
- Standardization. Using solid-state switchgear can implement "standardized" designs and provide an alternative to large scale power system breaker upgrades. There are fixed and variable costs in maintaining an inventory of distribution switchgears. One of the possible characteristics for the solid-state switchgear design is standardization of product classes compared to the existing practice based on multiple voltages and current rating. Realization of this primary functional specification can result in significant reduction in inventory cost. It is possible to significantly reduce inventory costs by introducing "standardized" switchgear designs.
- Avoid Using Traditional (series reactor) Fault Current Limiting Solutions.
- Improved Operations and Asset Management. The operations-and-maintenance (O&M) cost reduction is potentially achievable with solid-state switchgears through significant reduction of size and weight and improved communication capabilities. In an embodiment, the solid-state switchgear adopts the IEC 61850 communication architecture.
- Minimize Environmental Impact. By minimizing the need for SF6 breakers, the solid-state switchgear designs will help diminish the environmental impacts of greenhouse gas and arced oil associated with breakers.
- Other Advanced Distribution Automation Functions. Solid-state switchgear can provide advanced distribution automation that can help develop new applications for condition monitoring and asset management purposes.
  - Act as a Smart Sensor. In one embodiment, the solid-state switchgear can act as a sensor of voltage, current, and power factor, and can perform other advanced distribution automation functions. Solid-state switchgear can be automated to record and transfer vital power quality and reliability information. The solid-state switchgear device is intended to act as part of the overall ADA (advanced distribution automation) monitoring system being developed in another EPRI ADA project. Some of the prospective functionalities of the monitoring system include, but are not limited to:
    - Solid-state switchgear is capable of providing real-time information about any combination of the following: voltage magnitude, current magnitude, power quality characteristics of the voltage and current, real and reactive power, temperature, energy use, harmonic distortion, and power factor.
    - Solid-state switchgear can provide alarming functions with intelligence for processing data and identifying conditions that require notification of a utility or utility automation system. These conditions could include any combination of the following: outages, power quality conditions outside of specified thresholds, excessive energy use, conditions characteristic of equipment problems, incipient fault detection, equipment problem identification, fault location, performance monitoring of protective systems, and harmonic resonance conditions.
    - Solid-state switchgear can provide real-time state estimation and predictive systems (including fault simulation modeling) to continuously assess the overall state of the

distribution system and predict future conditions. Solid-state switchgear can therefore provide the basis for system optimization.

- Solid-state switchgear can provide or assist information systems that can integrate meter data with overall information systems for optimizing system performance and responding to problems. These problems can include, but are not limited to: outage management, asset management, SCADA, loss analysis, and customer systems.
- Solid-state switchgear can integrate communications and control functions in order to optimize system performance.

– Open, Standardized Communication Architecture. The monitoring system and switchgear devices will all need to be conformed to IEC 61850. This will involve preparing an object model as part of the development phase and then working through an IEC working group to evolve it into a standard. IEC 61850 is the international standard document for substation automation systems developed under IEC Technical Committee (TC) 57. It defines the standards for communication architecture in the substation and the related system requirements. It supports all substation automation functions and their engineering. Different from that of earlier standards, the technical approach makes IEC 61850 flexible and future-proof. Additional parts of 61850 are currently under development by working groups of TC-57 to address standards for communications in the balance of the distribution system (feeder equipment).

Applications

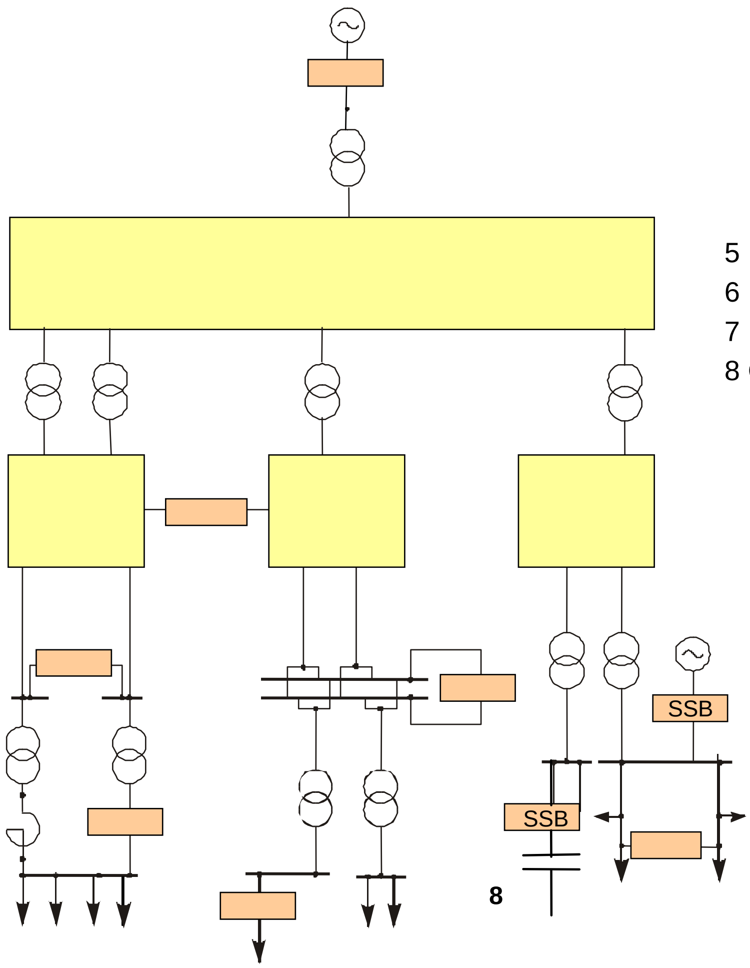
The need for solid-state switchgear must be based on clearly defined utility requirements to meet added functionalities and availability of power electronic technology. Therefore, utility requirements drive the need for the development and deployment of next-generation power electronics based solid-state switchgear.

The solid-state switchgear design has many features that are significantly different from conventional electromechanical circuit breakers, and will have a profound impact on present practices in both transmission and distribution systems. A non-limiting list of enhancements over a conventional mechanical breaker has been described in the previous section. Uses of the solid-state switchgear may include, but are not limited to, the following:

- Substation applications. Two functional characteristics that can be attributed to a solid-state switchgear are: current limiting and speed. Fault current limiting can allow the switchgear to be used in areas where fault current has (or will be) grown past the fault-current duty of existing circuit breakers. Fast switches and fault limiting can help reduce stress on distribution transformers and other distribution equipment. Solid state switches can also facilitate implementation of local islanding schemes for distributed generators and allow connection and disconnection without concern for transients.
- Custom applications to large customer services. Large customers/ consumers that use switchgears could use solid-state switchgears. They may have special needs that could be met by the subject solid-state switchgear including, but not limited to, fast transfer switching, sensitive equipment protection, and optionally voltage-sag correction. Solid state switches can prevent transient voltages during capacitor switching and will allow capacitors to be

switched in and out as often as needed. The result is better control of var flows, voltage, and flicker on the distribution system without causing unacceptable transient voltages.

- Feeder applications. One functional characteristic that can be attributed to the subject solid-state feeder switchgear is fast operation. Fault-current limiting is a characteristic that may not be needed as often (fault currents are generally lower). Solid-state feeder switchgear characteristics such as reliability and flexibility in control and operation can help gain acceptance and be advantageous in the commercial market. Competitive cost is another characteristic that can be attributed to the subject solid-state feeder switchgear. Circuit sectionalizing and reconfiguration is another application area as solid state switches have the potential to eliminate even momentary interruptions for the great majority of customers on distribution systems when a fault occurs. Solid state switches for reconfiguring systems can also allow for optimizing performance through reconfiguration without imposing momentary interruptions on customers. Solid state transfer switches are the primary application for distribution solid state switchgear at the present time.
- Industrial applications. Large industrial facilities are large consumers of medium-voltage switchgear and would benefit from fault-current limiting for cases with high short-circuit levels, provided by the subject solid-state switchgear at competitive cost.



5 Busbar connection / feeder
6 Coupling local generating units
7 Closing ring circuits
8 Capacitor Switches

Figure 3-1
Application of Solid State Switchgear at Distribution Voltage Levels

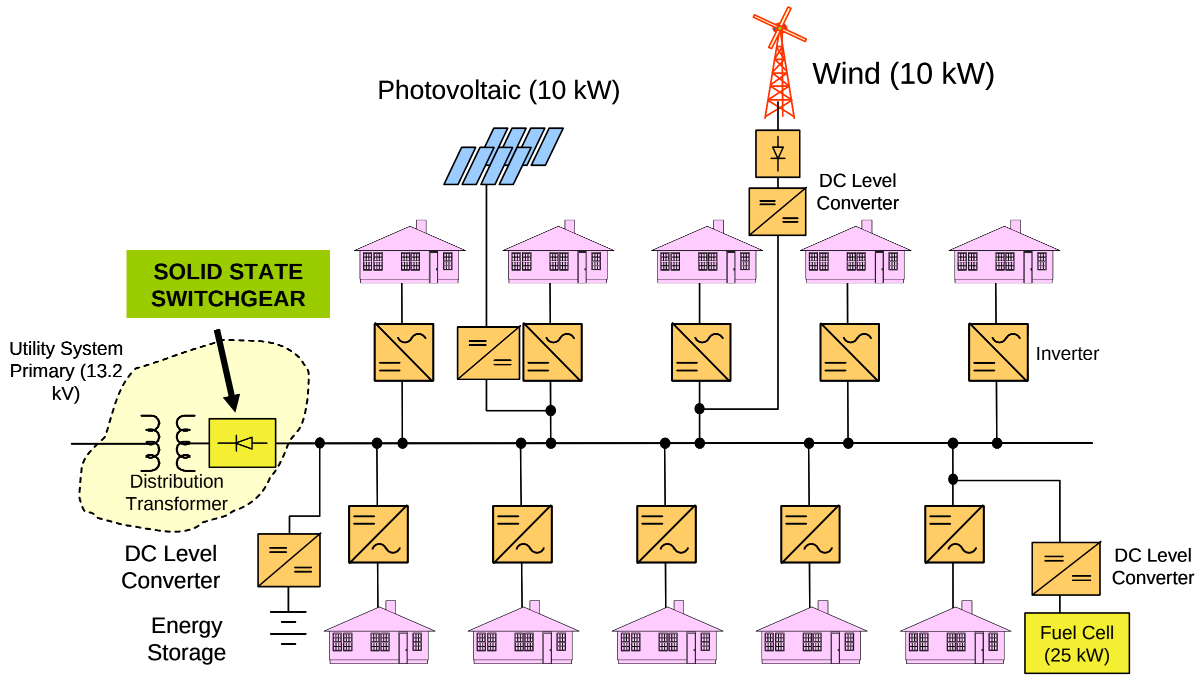


Figure 3-2
Application of Solid State Switchgear for Coupling New Generation

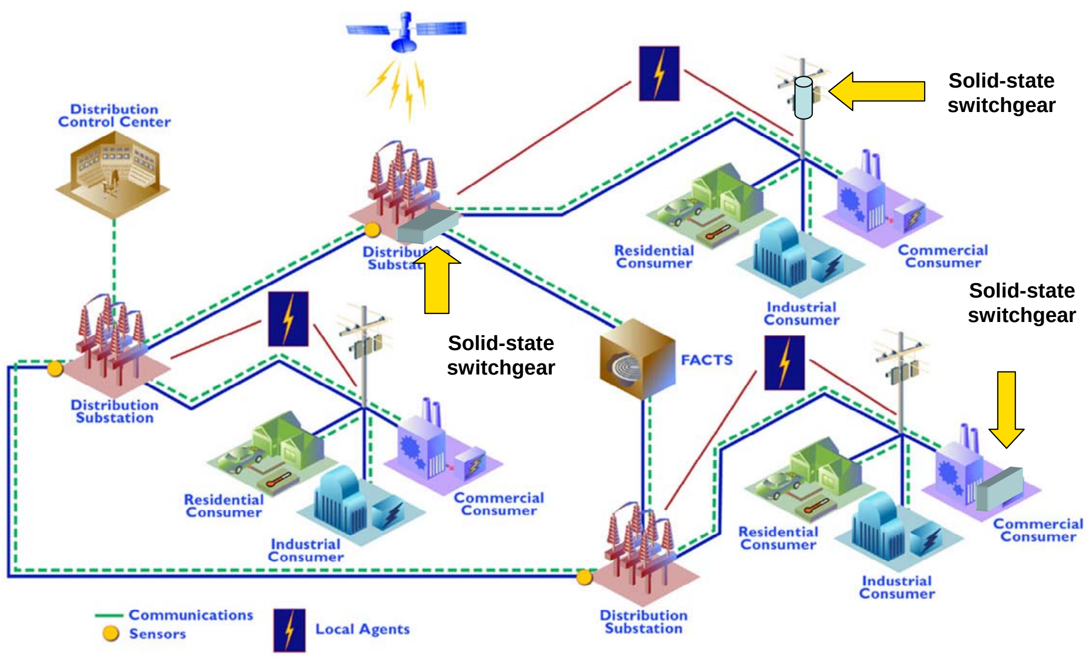


Figure 3-3
Solid-state Switchgear – A Cornerstone for Advanced Distribution Automation

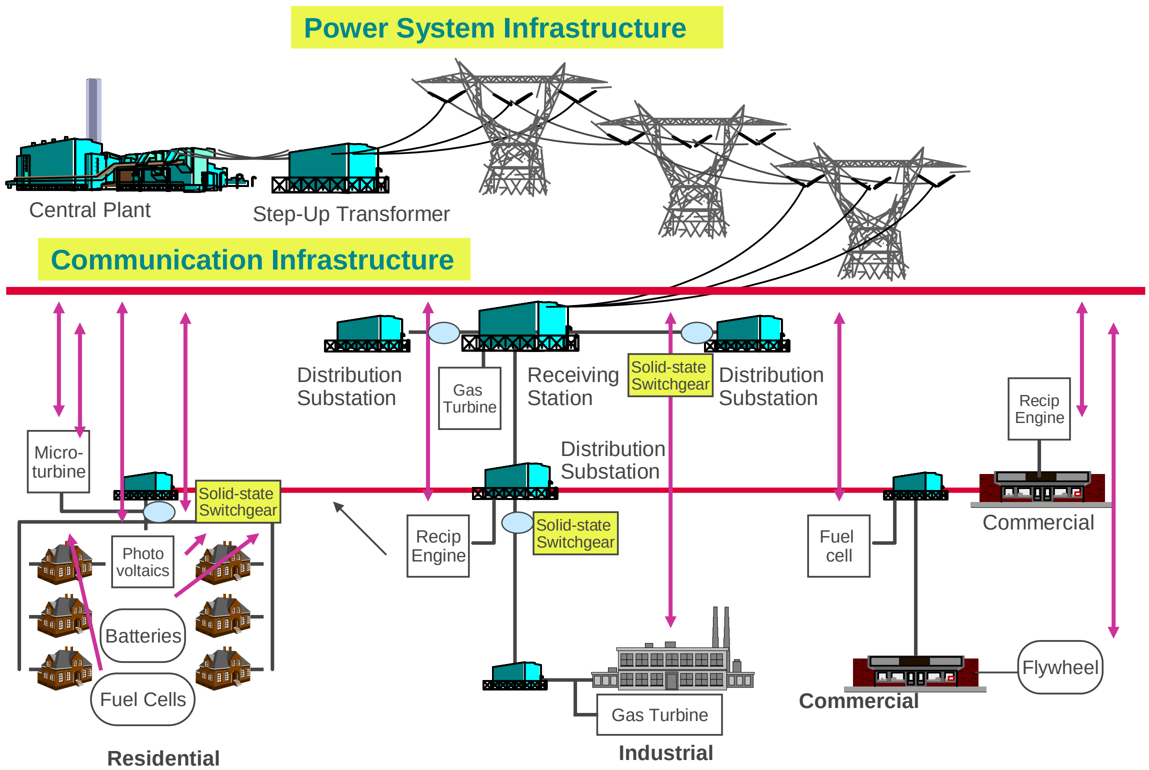


Figure 3-4
Realizing the Vision for Developing a Communication and Control Infrastructure for Advanced Monitoring

General concept and configuration

The first generation multi-functional solid-state switchgear should be innovative, scalable, reliable, and should offer multiple functions for multi-purpose distribution class circuit breaker and fault current limiting applications including: (1) current limiting of high magnitude fault currents, (2) faster clearing, (3) reduced maintenance, (4) reduced switching surges, and (5) high-speed load transfers. For the cost and reliability concerns, the circuit must be as simple as possible to avoid excessive bulky passive components.

Recently new designs of solid-state breakers ("***all solid-state***" as well as "***hybrid***" designs), transfer switches, and fault current limiters using modern power electronics have captured the attention of utilities as well as equipment producers. New designs for an intelligent "all solid-state" as well as "hybrid" distribution switchgears have resulted from the marriage of advanced power electronics and conventional switchgear technology. The general configuration is indicated in Figure 3-5 and Figure 3-6. Two types of designs can be used. One is an “all” solid-state based design other is “Hybrid” Solid State Circuit Breakers. Since a closed mechanical contact still exhibits the least amount of conduction losses amongst all “switching” elements in some designs an ultra-fast mechanical contacts are utilized for carrying the regular continuous operating current and solid-state switch for fault clearing and current limiting. This is referred as “hybrid” solid-state switchgear.

While the requirements for fault clearing, recloser, transfer switch, and current liming are different, the most difficult task is to turn the device off without going through zero crossing. Thus the first design criterion for a universally used switch is to be able to interrupt the current any time. Also, while the first design criteria must allow for all these functions as options, all the functionalities may not be required for all customers and applications.

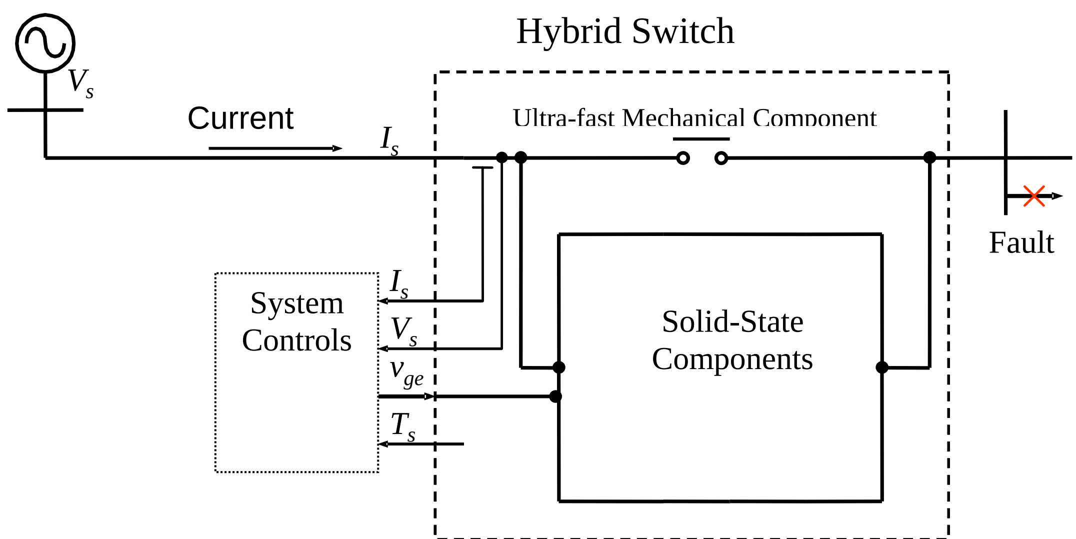


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Figure 3-5
A Hybrid Solid-State General Configuration

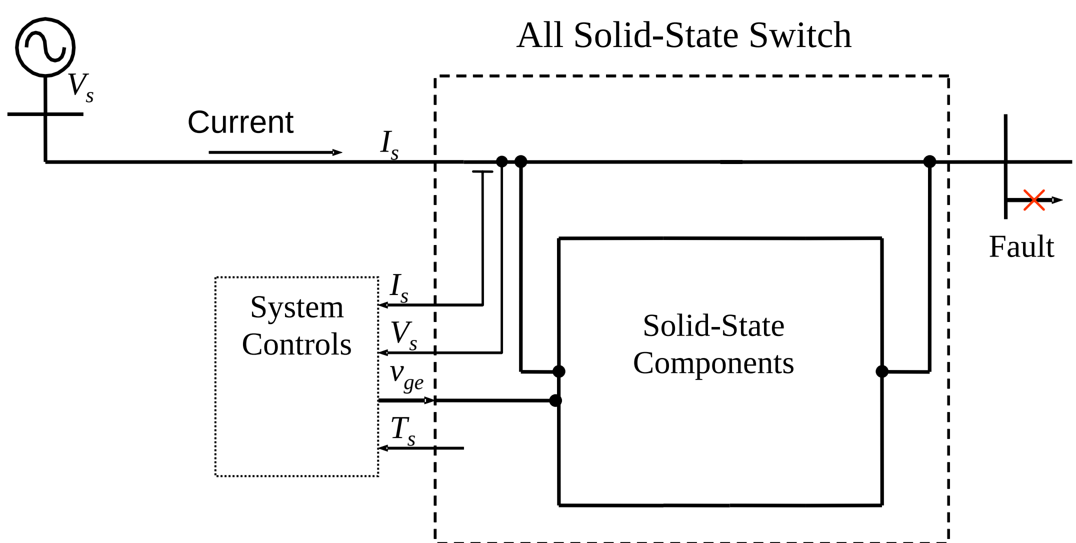

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Figure 3-6
"All" Solid-State General Configuration

Functional Requirements of the solid state switch module

Codes and Standards

The specification is intended to provide designers with a set of functionalities that are desirable in the context of solid-state switchgear rather than an exhaustive list of requirements. The functional specification is written in a technology-neutral manner so as to provide designers with maximum flexibility in achieving the desired functionalities. At a minimum, the functionality of the proposed design should meet the basic functionality of conventional distribution breakers and reclosers (for example for 15KV, 600A class).

The quality of the equipment and services supplied by the contractor should meet or exceed the relevant requirements for operating environment, structural design, insulation level, short circuit protection, surge withstand and other issues that are described in the C37 series of ANSI/IEEE standard for breakers and reclosers. Specific C37 series standards that are relevant to distribution switchgears are outlined below. Additional codes may apply to individual modules and equipment. In case of conflict, this specification shall govern, and the Contractor shall notify EPRI and the developer/vendor/contractor in writing of such conflicts as soon as they become known. EPRI and the developer/vendor/contractor will work together to get a host for the field development work

- ANSI C37.42-1989, American National Standard Specifications for Distribution Cutouts and Fuse Links.
- ANSI/IEEE C37.60-1981, IEEE Standard Requirements for Overhead, Pad Mounted, Dry Vault, and Submersible Automatic Circuit Reclosers and Fault Interrupters for AC Systems.
- Cooper Power Systems, "Comparison of Recloser and Breaker Standards," February, 1994.
- IEEE Working Group on Distribution Protection, "Distribution Line Protection Practices Industry Survey Results," IEEE Transactions on Power Delivery, vol. 10, no. 1, pp. 176-86, January 1995.
- ANSI C37.06-2000, AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis--Preferred Ratings and Related Required Capabilities.
- ANSI C37.42-1989, American National Standard Specifications for Distribution Cutouts and Fuse Links.
- ANSI/IEEE C37.60-1981, IEEE Standard Requirements for Overhead, Pad Mounted, Dry Vault, and Submersible Automatic Circuit Reclosers and Fault Interrupters for AC Systems.
- Cooper Power Systems, "Comparison of Recloser and Breaker Standards," February, 1994.
- IEEE Working Group on Distribution Protection, "Distribution Line Protection Practices Industry Survey Results," IEEE Transactions on Power Delivery, vol. 10, no. 1, pp. 176-86, January 1995.
- Westinghouse Electric Corporation, Applied Protective Relaying, 1982.
- ANSI/IEEE C37.90.1-IEEE Surge Withstand Capability (SWC) Test for Protective Relays and Relay Systems.

- ANSI/IEEE C37.90.2 - IEEE Standard Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers.
- Three phase and ground time over-current protection with timing in accordance with IEEE Std. C37.112 (Distribution Requirement)
- Hi-set instantaneous over-current protection (Distribution Requirement)
- Low-set instantaneous overcurrent protection, enabled/disabled by state of reclosing cycle (Distribution Requirement)
- Auto-reclosing function, settable for 0-3 reclosing attempts, 0-60 seconds adjustable delay per attempt, lockout after last attempt, 0-60 seconds reset delay after lockout reset (Distribution Requirement)
- Three-zone phase and ground distance protection (Transmission Requirement)
- Directional ground instantaneous and time overcurrent protection with timing per C37.112 (Transmission Requirement)
- Auto-reclosing function, as for distribution applications, but also with synchronism checking capability (Transmission Requirement)

If any equipment and components in the solid-state switchgear system are normally manufactured to non-U.S. standards, conformance of the equipment to the specified U.S. standards shall be certified by the Contractor. Further, individual solid-state switchgear installations shall comply with all applicable state and local codes in effect for each site on the date of the contract.

Design Considerations for Solid-State Current Limiters and Breakers

A thorough design and performance analysis should be conducted on any prospective design of solid-state switchgear to evaluate, which of the functional specifications can be achieved with the particular design and what will be tradeoff in cost, efficiency and reliability to achieve additional functionalities. It is feasible that many of the functionalities listed below can be programmed into the solid-state switchgear in different modes of operation. For example, transfer switch capabilities and fast fault clearing and instantaneous current limiting could be two different modes of operation that can be integrated within the same hardware platform and depending on the controller operating mode any one of the feature could be activated.

Basic Requirements/Specifications for a 15KV, 600/1200A Design for a Circuit-Breaker / Recloser / Current Limiter

- Steady-state current rating

  600/1200 A, continuous

- Emergency overload capability

  800/1400 A, 1 hour

700/1300 A, 8 hours

- Short-circuit current rating

    12.5/23 kA, symmetrical (for one second)[4]

- Voltage rating

    15.5 kV line to line

- Low-frequency withstand voltage

    50 kV, one minute

- BIL

    110 kV

- Losses

    Less than 10 kW

- Independent phase operation

    Each phase can open and close independently

- Speed

    Clears faults within 1/2 cycle

- Control connections

    The switch must have a connector to the controller. It is desirable to have an industry standard connection that could be used with other controllers (Schweitzer for example), but this setup may not be fast enough to achieve desired operational speeds. Another option is to have the controller built-in to the switch; then, an external connector must be available to communicate with the controller to program settings and download data.

- Controller capabilities

    The controller must provide standard functionality of digital relays, comparable to the SEL 351 relay.

- Powering and backup

    Should operate from a supplied external 120 V_{AC} source. Should operate for up to 8 hours on battery backup.

- Smart Sensor, Distribution Fault Anticipator, and Monitoring System
    - Develop a list of what parameters needs to be monitored. Some of these functionalities could include:

[4] 20KA peak 1/2 cycle rating

  - Capable of providing real time information about voltage magnitude, current magnitude, power quality characteristics of the voltage and current, real and reactive power, temperature, energy use, harmonic distortion, power factor, etc..
  - Alarming functions with intelligence for processing data and identifying conditions that require notification of the utility or utility automation system. These could include outages, power quality conditions outside of specified thresholds, excessive energy use, conditions characteristic of equipment problems, incipient fault detection, equipment problem identification, fault location, performance monitoring of protective systems, harmonic resonance conditions, etc.
  - Real time state estimation and predictive systems (including fault simulation modeling) to continuously assess the overall state of the distribution system and predict future conditions, providing the basis for system optimization.
  - Information systems that can integrate meter data with overall information systems for optimizing system performance and responding to problems (outage management, asset management, SCADA, loss analysis, customer systems, etc.)
  - Integrate communications and control functions in order to optimize system performance
  - Capable of providing real time information about voltage magnitude, current magnitude, power quality characteristics of the voltage and current, real and reactive power, temperature, energy use, harmonic distortion, power factor, etc.
- – Determine the type of sensor equipment and support equipment for the sensors

- Communication and Control Infrastructure[5]
  - – Develop an object model for the multi-functional switchgear based on use cases
  - – Work with IEC working group to develop into a part of IEC 61850
  - – The procedures include:
    - Determine functional requirements
    - Determine the communication system requirements to support these functions
    - Identify IEC61850 logical nodes for each switchgear function, each application module, and each sensor
    - Develop IEC61850 data exchanges within the solid-state switchgear
    - Develop IEC61850 data exchanges with external systems

[5] As the distribution system becomes more automated, opportunities exist to improve the utilization of distribution switchgears. More sophisticated automation integrated with solid-state switchgear can serve as an outage notification and outage management device, remotely control the different mode of the functionality of the breaker and monitor condition of the breaker and the power system in real time. The proposed design should evaluate centralized control, decentralized control, and combination approaches for automation. Realizing the full potential of an solid-state switchgear will require more sophisticated communication architectures. A promising platform is the IEC 61850 architecture that is an open industry standard developed from EPRI's Utility Communications Architecture (UCA). A wide variety of equipment can plug into this architecture. The proposed design should provide the flexibility to integrate the IEC 61859 architecture within the switchgear.

    - Specify conformance testing
    - Specify IEC61850 configuration tools
  - Communication infrastructure for integrating customer meter data with a real time system data manager. This might involve local concentrators and data processing depending on the specific architecture and design.

- Enclosure

  Must fit in enclosures for overhead pole mounting (like a recloser), padmounted application, and installation in draw-out metal-clad switchgear. This requires a size of approximately: 28”W × 32”H × 14”D

- Insulation

  It could be oil, SF_6, or solid insulation.

- Price

  Manufacturing cost should be compared with US$20,000 (three-phase) for a conventional breaker

Optional Features (Scalable Implementation)

- Current limiting Threshold

  For example, for short circuits to 50 kA, limit current to 10 kA peak. The ability of power electronic based switchgear to limit the magnitude of fault currents is one of its most valuable features.

  Maximum fault currents on electric power systems tend to grow over time because of reinforcement of the system to handle larger loads. Switchgear designs which can limit maximum fault currents, may avoid the need to replace large amounts of expensive equipment whose fault current capability has been outgrown. Typical distribution system fault currents range from 20KA to 64KA. Having a current-limiting threshold that can be adjustable, rather than fixed, might be desirable.

- Voltage

  25 and 35 kV models

- Gang operation

  It is desirable that the switches can be applied in modules in parallel or series to increase voltage and/or current ratings.

Relay Requirements/Specifications for Solid State Switchgear in Current Limiting Application

Solid state switchgear will have many features that are significantly different from today's electromechanical circuit breakers. For example it can be expected to have:

- Ability to clear faults in a time frame of 1/4 cycle from fault inception.
- Current limiting of high magnitude fault currents.
- Reclosing as rapidly as 1/2 cycle after clearing a fault.
- Soft reclosing by limiting current to the circuit until it has demonstrated to have returned to normal integrity

The next section provides some of the relaying issues and potential concerns that would need to be investigated. The Contactor shall need to revise some of the issues raised here will have to be revisited in more details as development of solid-state switchgear application progresses and as potential users provide real world examples for study.

Relaying of the Solid-State Switch

As a solid state device, the solid state switchgear will have controls that will self protect. Designing the solid state switchgear to respond properly to system abnormal conditions may allow these controls to be integrated with conventional protective and relaying practices for improved performance, thus promoting early acceptance of the new technology. Relaying requirements of the solid state designs and adjustments that will have to be made include:

- Evaluate the benefit of having all relaying contained in the solid-state switchgear controls versus the concern for a common mode failure.
  - Determine the required minimum characteristics of a fully functional and testable microprocessor relay package integral to the solid-state switchgear. This may be a removable card or leads to a test connector.
  - Quantify the requirements for independent, redundant relays to operate the solid-state switchgear.
- Evaluate the need and feasibility for an adjustable threshold for current limiting action.
  - Determine the range of current limiting settings between solid-state switchgear needs and power system needs to minimize circuit interruptions.
  - Examine the restrictions on dI/dt detection, such as high frequency switching currents cause by capacitor banks.
- Examine new features that may be required to gain full advantage of the high-speed reclose capability.
  - Explore testing for circuit integrity before full reclose.
  - Explore testing for and establishing a re-synchronized reclose.
  - Examine feasibility of non-trip current limiting for back-to-back capacitor switching.

- Evaluate the impact on existing protective devices with an solid-state switchgear functioning in the fault current limiting mode.
  - Determine at what level fault current limiting will slow fault clearing of devices in adjacent protection zones.
  - Explore how adjacent zone devices will respond to non-sinusoidal currents caused by the SSCL in the fault current limiting mode.
- Evaluate the impact of using the inherent single pole tripping capability of the solid-state switchgear.
  - Explore feeder conditions and time windows where expanded possibilities may exist such as lateral fuse saving.
  - Establish limitations on single pole tripping such as downstream three phase transformer connections.
- Evaluate coordination with high speed reclosing capabilities of the solid-state switchgear.
  - Explore how gradual reclosing, if feasible, will impact arc extinction.
  - Estimate the possibility of coordinating rapid re-synchronizing with intentional distributed generation (DG) islands.
- Evaluate coordination/utilization of ultra high-speed fault clearing.
  - Evaluate the tie breaker application.
  - Evaluate application of DG on network service.

4
PROJECT PLAN FOR DEVELOPMENT AND TESTING OF MULTI-FUNCTION SWITCHGEAR SYSTEM

EPRI has undertaken the development of a family of power electronics based switchgear applications at ***distribution*** class voltages. This chapter covers the real R&D (from prototype stage through initial testing) associated with developing a solid-state switch technology for ***distribution*** level applications in the 15KV-35KV class range.

In 2005 EPRI project work, a comprehensive requirements definition was described in *EPRI Family of Multi-Functional Low Cost Solid State Switchgear: Requirements Definition Phase* (EPRI, Palo Alto, CA: 2006 TR1010666) to assess the requirements for first generation multi-functional ***distribution voltage*** solid-state switchgears. This preliminary research was the first step before embarking on development of the hardware and associated controls for development of a family of low-cost multifunctional solid-state switchgear for a range of distribution applications.

The overall objective of this chapter is to lay the foundation for EPRI's long term technology roadmap for the development and commercialization cycle for the next-generation solid-state switchgear family in distribution applications. It builds on the work done in 2005 to assess the feasibility of replacing current distribution class switchgears with a more sophisticated device, a family of low-cost multifunctional solid-state switchgear. Key elements covered (as a part of EPRI's multifunction solid-state switchgear program) in this chapter include:

- Incremental plan with stage gates to allow flexibility to align with actual revenues received
- Straw-man schedule for the development of a family of low-cost multifunctional solid-state switchgear
- Refined description of the possible phases for design and development (lab prototype, field prototype) of the switchgear technology along with the important milestones
- Refined description of selection of test hosts, preparation of test plan, execution of the test plan, and field testing
- Refinement of switchgear system into commercial-ready form

The intent in this report is not to make recommendations for a specific design or a specific semiconductor device. This decision will have to be made by the manufactures to come up with other innovative designs that will meet the specification or through a competitive procurement process to select a vendor/developer/partner. Based on the preliminary results and on-going research in these areas, "***all solid-state***" based switchgear designs as well as "***hybrid***" designs have the potential to offer a myriad of advantages that prospective purchasers may find attractive and may make them successful in the marketplace. EPRI will consider both "all solid state" as well as “hybrid” bids and that if a hybrid bid is made, the path to all solid state in the long run must be shown by the bidder. These designs will guide the development of the smart solid-state switchgear.

Following the General Trends to Support the Vision Direction

One approach, commonly known as the stage-gateTM model, whose chief characteristic is a hierarchical flow of possible milestones that would have to be realized during the various phases for the development of any new technology is shown in Figure 4-1. Stage gate breaks the innovation process into a predetermined set of stages, each consisting of prescribed, multifunctional, and parallel activities. Many leading companies and research organizations have developed a systematic stage-gate process for moving a new product through the various steps from “idea” to “launch.” Most importantly, they have built the key lessons into the roadmap for new product success in order to improve the effectiveness and timeliness of their product.

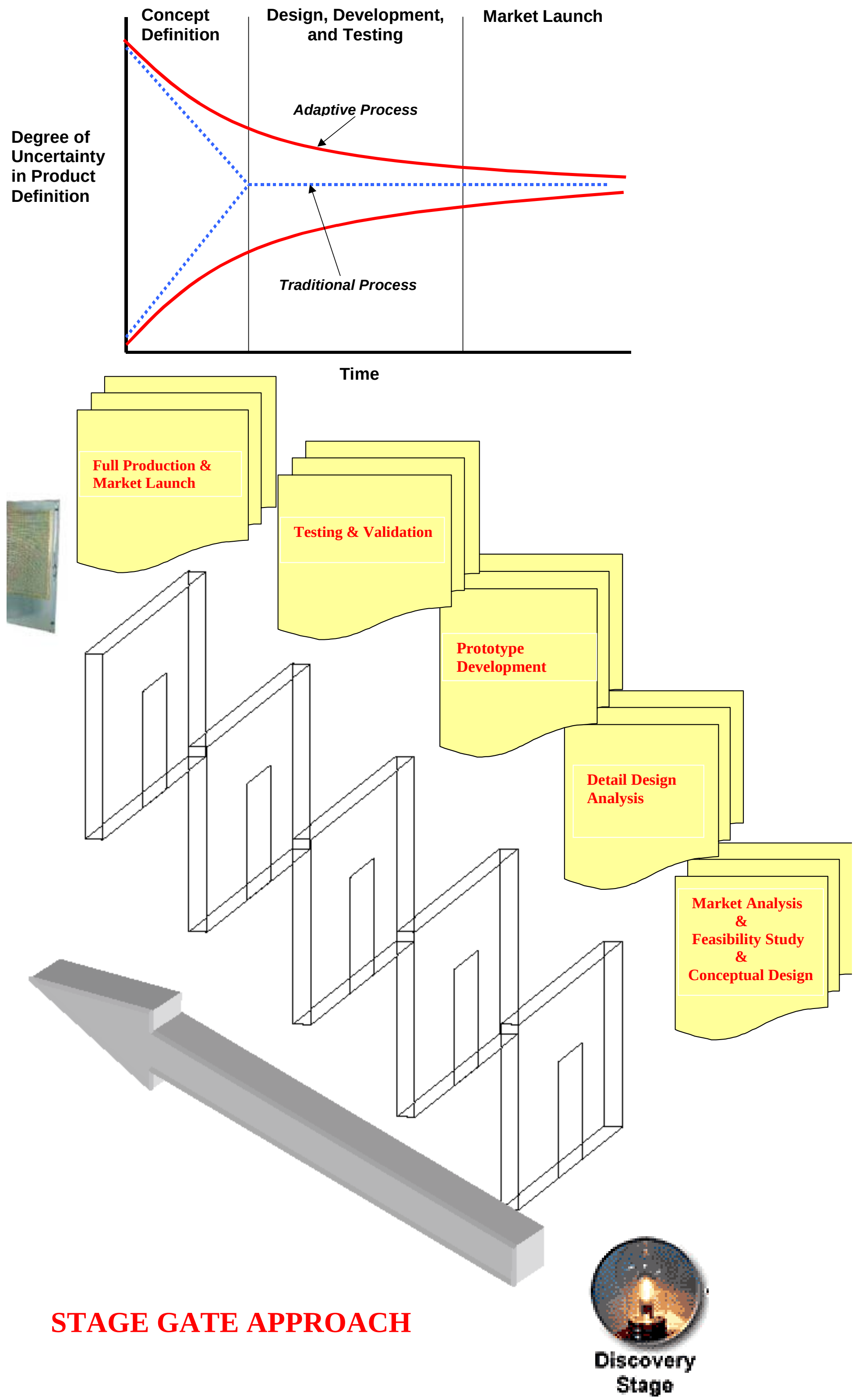

Figure 4-1
A Stage-Gate Approach for New Product Development

Traditional stage-gate or PACE® processes (shown on the left in Figure 4-1 where the gates are "transparent") assume that there is little uncertainty associated with the technologies to be utilized for product development. The gates can be identified, clearly defined, and planned for, and their outcomes are known right from the beginning of the development process. In simple terms, the product development team can "see" all the deliverables at the gates, because most of product-development stages are predictable. It should be noted that even though this curve varies with individual application areas and technologies, it does convey a trend relative to the effects of realizing the ultimate vision.

Incremental Plan with Stage Gates

The distribution system has been identified to be the next major target for first generation multi-functional solid-state power conversion. The overall objective of this study is to lay the foundation for EPRI's multifunction solid-state switchgear program and outline the incremental plan with stage gates of the possible phases for design and development of the switchgear technology along with schedules, important milestones, and commercialization cycle for the development work, field testing and commercialization. The development effort has been broken down into two distinct product families; namely:

- ***Generation 1:*** ***15KV Class Distribution Switchgear Development*** (Basic Features and Requirements include: Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch)
  - Detailed design analysis and functionality verification (2007)
  - Bench model development and testing (2007-2008)
  - Field prototype development and deployment (2009-2010))
  - Field testing and debugging of field prototype (2009-2010)
  - Finalization of design, packaging and preparation of product family specification and subsequent commercialization (2011)
- ***Generation 2:*** ***35KV Class Distribution Switchgear Development*** (Basic Features and Requirements include: Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch)
  - Bench model development and testing (2012)
  - Field prototype development and deployment (2013-2014)
  - Finalization of design, packaging and preparation of product family specification and subsequent commercialization (2014)

Straw-man Schedule for the Development of EPRI's Multi-functional Solid-State Switchgear – How to Realize the Vision in the Future

History indicates that the success of a semiconductor device is heavily dependent on the success of the application. In most cases, power electronics researchers have to choose off-the-shelf power devices with the specifications that best fit their applications. They usually do not have a say about how they would like the device parameters to be changed. On the other hand, materials and device researchers build switching devices for the power electronics researchers to use in their circuits, but they rarely know how and where the devices are going to be used. Also, the availability of the semiconductor device dictates the circuit development.

As represented in Figure 4-2, a “barrier” still exists between the people who design and build power devices and the people who use them in their circuits and systems. Close interaction between the both sides of the barrier is needed to obtain the most performance for devices and systems. With this interaction, the design loop will be closed and the possibility for building optimal application-specific power devices will arise.

EPRI’s multifunction solid-state switchgear program is designed to address this need, namely

- Assess key application areas for this product
- Identify development options[6] that can give us the flexibility to align with funding received
- Initiate competitive procurement process to select vendors who are best suited to implement the solid-state switch technology
- Identify development process in the laboratory and field
- Interface closely with program sponsors over the program life cycle
- Work and interact with other utilities over the program life cycle
- Work and interface closely with multiple vendors on implementation of solid-state switch technology throughout the development cycle, laboratory testing, field demonstration and after development during early commercialization
- Select test hosts for demonstrating the product and its applications
- Addresses customer engagement in applications research during the latter stages of development and after development during early commercialization
- Address key integration issues and additional refinements to take advantage of the new technology

This will help us to close the design loop, move the technology from prototypes and early products to widespread applications as well as tie this to the application research plan (see Figure 4-3). With the recent advances in power electronics, especially in the areas of high-voltage power electronics (see Figure 4-4); solid-state-based switchgear designs are well within the realm of possibility.

[6] For example, the minimum system developed could be a current interruption device with a communication interface that enables it to be used as a monitoring node in ADA and that allows remote control of the switch. Other functions, like fault current limiting or use in fault anticipation/location schemes, can be options added to the minimum system, if funding allows.

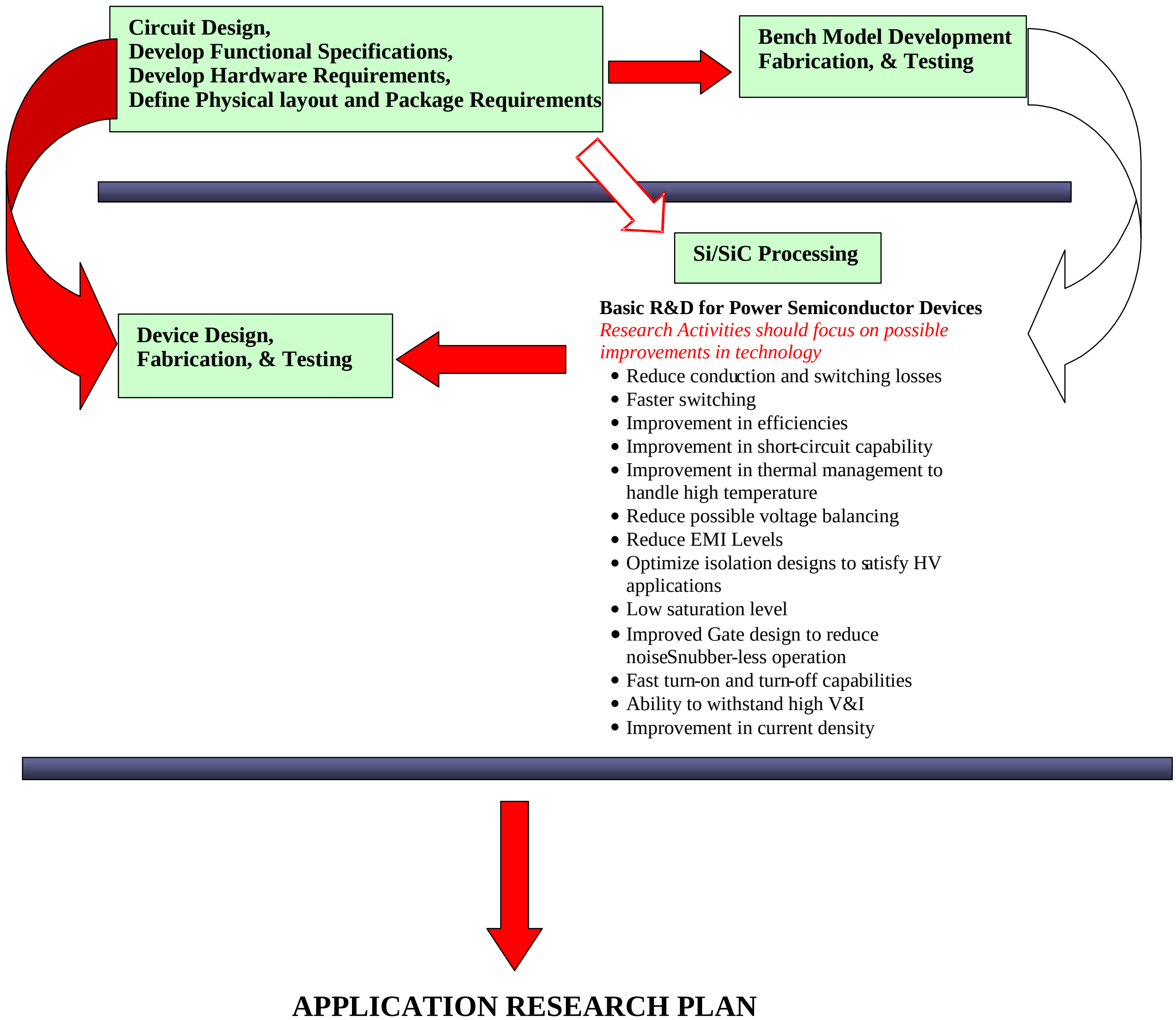

Figure 4-2
Closing the Device Design Loop – A Key for Building Optimal Application-Specific Power Devices

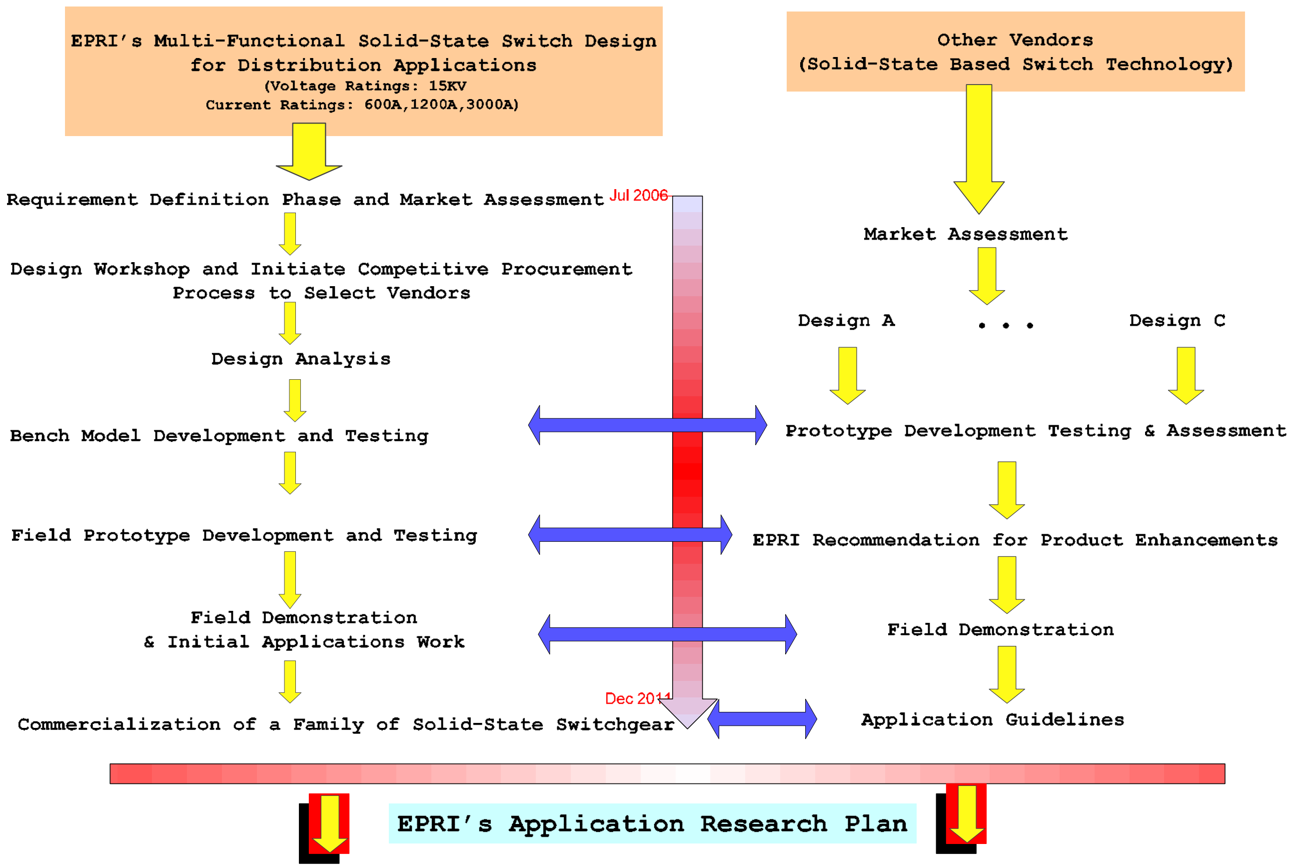

Figure 4-3
Project Plan for Development, Testing, and Commercializing of Multi-Functional Switchgear System

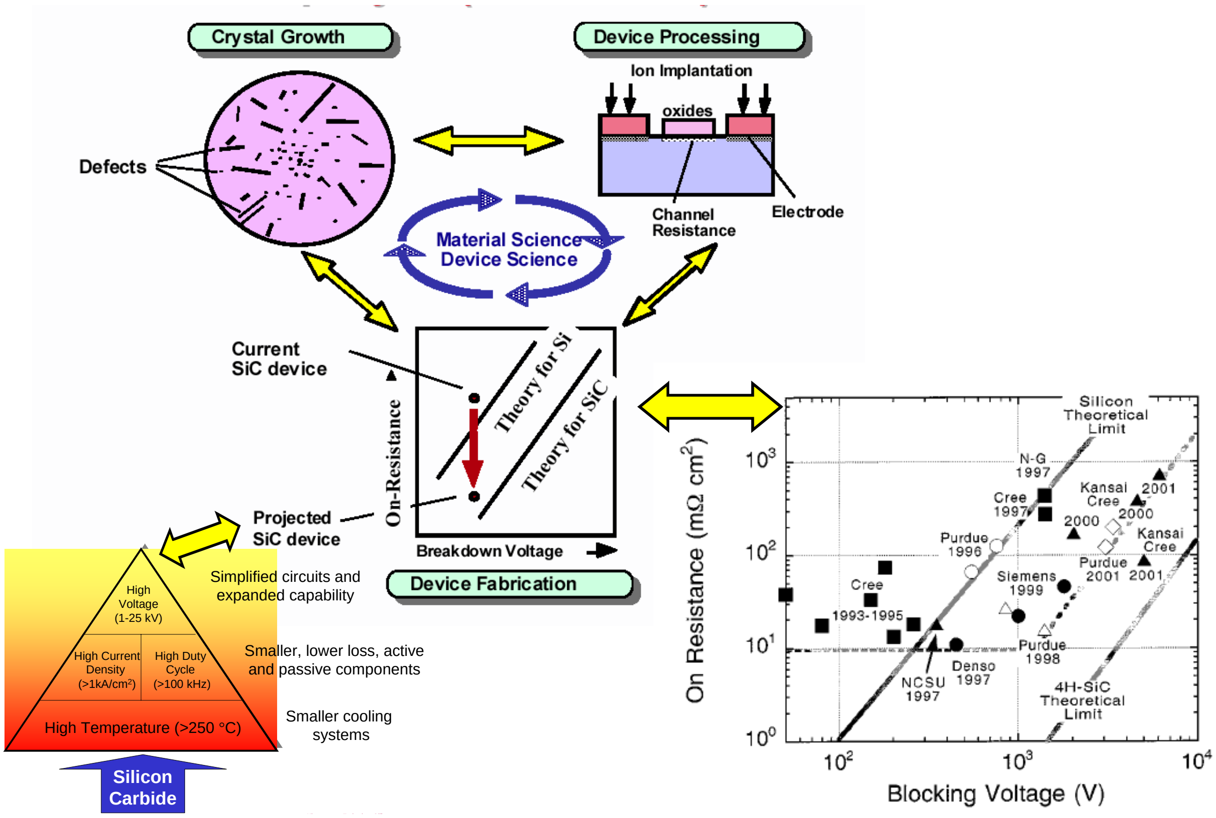

Figure 4-4
Trends in Semiconductor Device Advancement [DARPA HPE Program[7]]

[7] The Defense Advanced Research Projects Agency (DARPA) under Department of Defense wide bandgap semiconductor technology (WBST) high power electronics (HPE) program started in 2002. The objective of the program is to revolutionize high power electrical energy control, conversion, and distribution by establishing a new class of solid state power switching transistors employing wide bandgap semiconductor materials.

Roadmap	Technology Watch
Short-Term	**Technology:** Electronics (solid-state/hybrid) based Switch Design **Level:** Distribution System **Ratings:** 15KVclass 600A / 1200A / 3000A **Maturity:** Concept stage; Risk - Low **Product Development:** 1-5 years **Field Application:** 5 years **Potential Market Drivers:** Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch
Mid-Term	**Technology:** Electronics (solid-state/hybrid) based Switch Design **Level:** Distribution System **Ratings:** 35KV class 600A / 1200A / 3000A **Maturity:** Concept stage; Risk - Intermediate **Product Development:** 5-8 years **Field Application:** 8 years **Potential Market Drivers:** Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch

Figure 4-5
A Generic Technology Roadmap to Realize a Family of Power Electronics Based Switchgear Designs in Distribution Applications

The next section adopts the traditional stage-gate approach to provide a more refined EPRI long-term roadmap for the development of the chosen switchgear designs and schedule for the development work, field testing, and commercialization. The overall technology roadmap characteristics, as shown in Figure 4-5, provide a consolidated summary of the key technology metrics that are required to realize the development of any "all-solid-state" and "hybrid[8]" based switchgear designs.

EPRI's Long-Term Roadmap

The distribution system has been identified to be the next major target for solid-state power conversion. Lack of strong initiative and proper long-term research plan has always been a barrier in new technology development. EPRI, as the leading research institute in the power industry, is ideally suited to take the first step to initiate the research in this direction based on a long-term research plan targeting the development of medium and high voltage, high-power semiconductor switches and parallel development of circuit topology, controller, and prototype of solid-state distribution switchgear. The following research plan provides a brief description of the possible different phases of a family of low-cost multifunctional solid-state switchgear development effort with estimated time and milestones.

This section adopts the traditional stage-gate approach discussed earlier and provides a detailed description of the possible phases (shown in Figure 4-6) for design and development of the solid-state switchgear technology along with schedules and important milestones (see Figure 4-7) for the development work, field testing, and commercialization. Distribution switchgear

[8] For Distribution applications, hybrid design is only an option it is not a requirement for a family of first generation multi-functional solid-state switches

development effort has been broken down into two distinct product families as indicated before. The two product families and possible phases (schedule dependent on funding availability) for development, testing, and commercialization include:

- ***Generation 1:*** ***15KV Class Distribution Switchgear Development*** (Basic Features and Requirements include: Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch)
  - **Phase I**: Detailed design analysis and functionality verification of family of either "all solid-state" OR "hybrid" technology (Voltage Ratings: 15KV & Current Ratings: 600A, 1200A, 3000A) which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2007)
  - **Phase II**: Bench model development and testing of 15KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2007-2008)
  - **Phase III**: Field prototype development, deployment, and testing of 15KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2009-2010)
  - **Phase IV**: Field testing and debugging of field prototype (2009-2010)
  - **Phase V**: Finalization of design, packaging and preparation of product family specification and subsequent commercialization (2011)
- ***Generation 2:*** ***35KV Class Distribution Switchgear Development*** (Basic Features and Requirements include: Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch)
  - **Phase I**: Bench model development and testing of 35KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2012)
  - **Phase II**: Field prototype development, deployment, field testing and debugging (2013-2014)
  - **Phase III**: Finalization of design, packaging and preparation of product family specification and subsequent commercialization (2014)

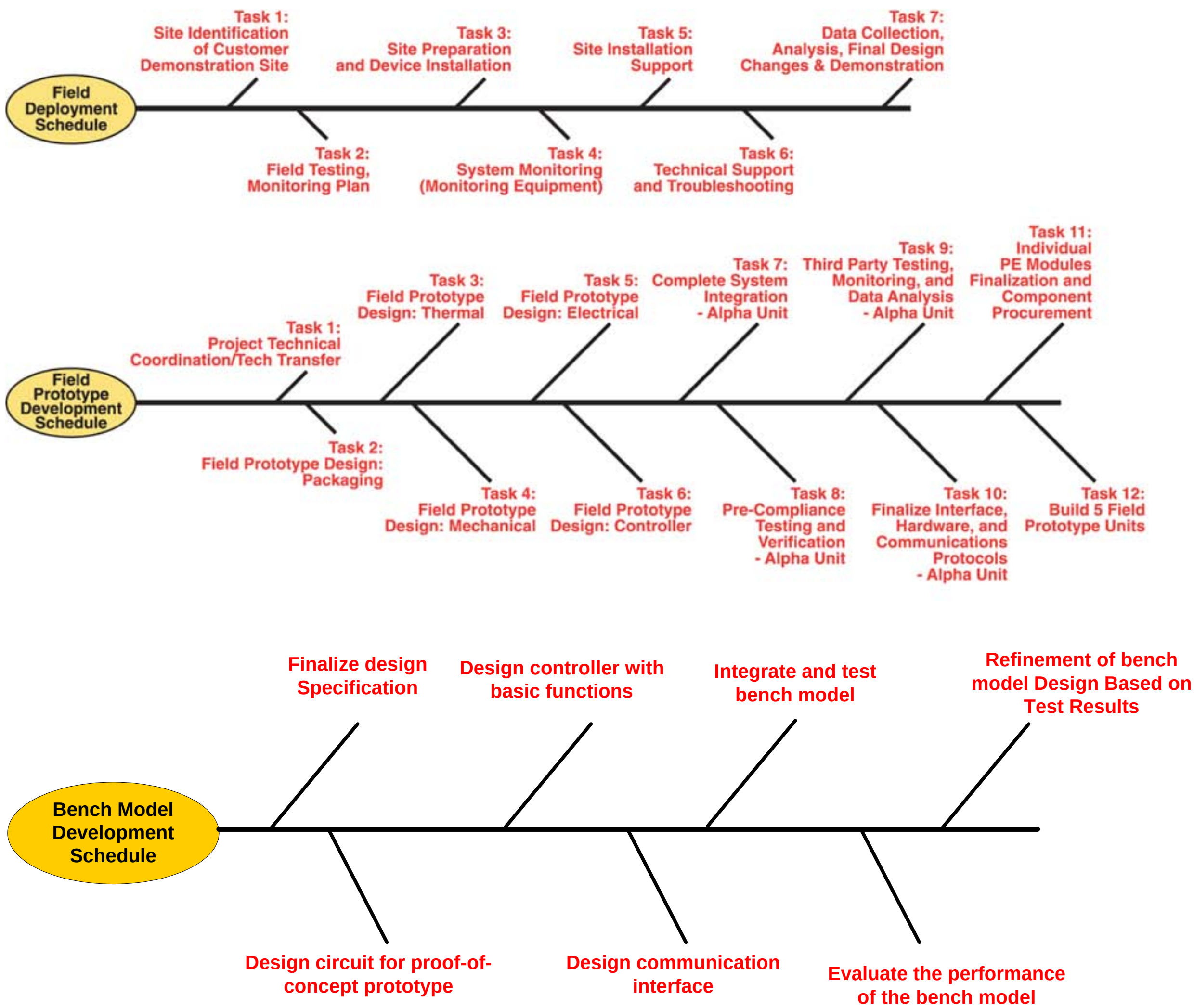

Figure 4-6
Projections of Possible Phases and Individual Tasks for Design and Development (2007–2011)

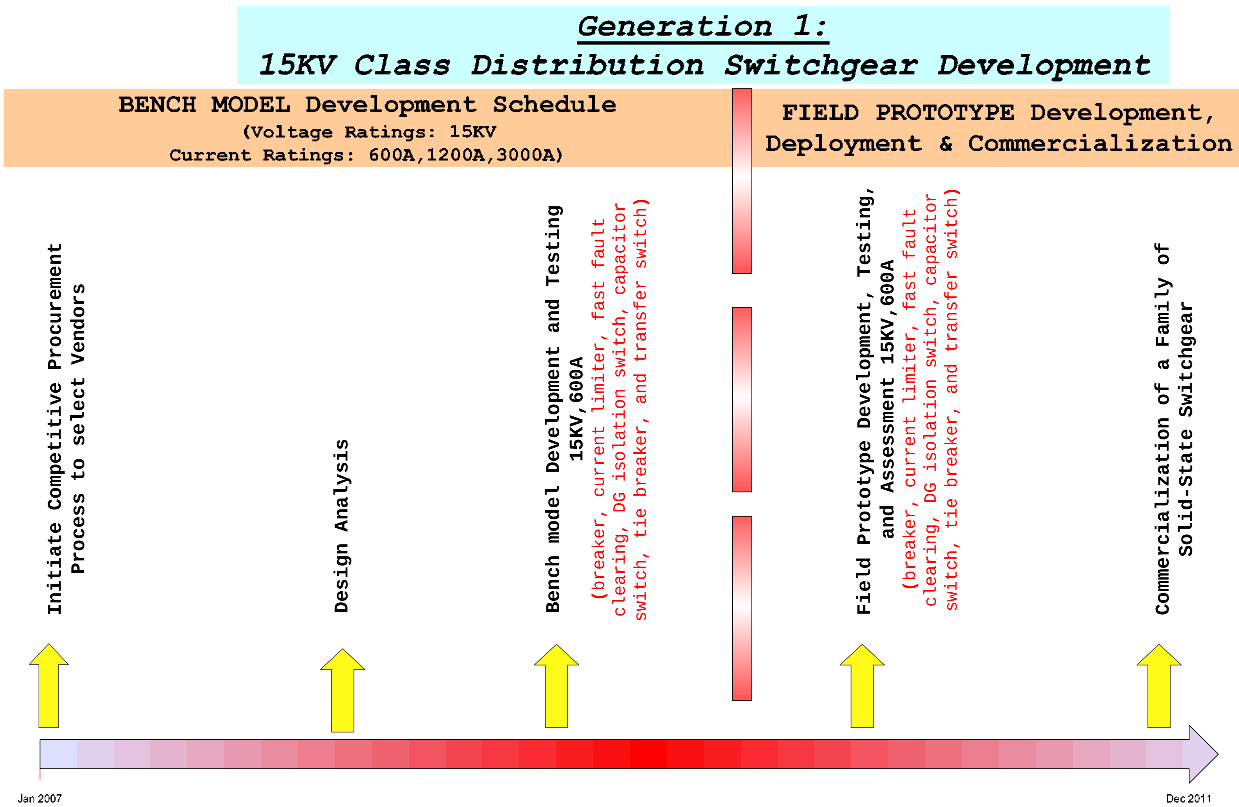

Figure 4-7
EPRI's Long-Term Roadmap for the Proposed First Generation Distribution Voltage Solid-State Switchgear – Development Schedules and Important Milestones

Generation 1: 15KV Class Distribution Switchgear Development

Phase I: Proof of Concept Design Analysis of family of Switchgear Topologies (Voltage Ratings: 15KV& Current Ratings: 600A, 1200A, 3000A)–Year of Performance: 2007

The first phase of the research should include a comprehensive design analysis to verify the functionality that can be achieved with the conceptual design and estimation of efficiency, cost and reliability of such a proposed design. This is the most critical stage since the commitment to a certain design topology will ultimately lead to hardware and controller development and lab prototype. Critical issues that should be addressed during the design analysis include:

- Selection of the circuit topology for designs with can be used as a switchgear that can be used as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker;
- Selection of the circuit topology for designs with can be used as a switchgear that can be used as a transfer switch;
- Selection of active devices and passive components and calculation for semiconductor device voltage and current ratings;

- Simulation of the performance using industry accepted design packages for power electronics design analysis;
- Estimation of the cost of the proposed system based on existing component costs and estimated component cost for different degrees of market penetration;
- Determination of design packaging and thermal management systems.
- Evaluation of the design with respect to its ability to meet the different desired functionalities that are addressed in the generic functional specification

Phase II: Bench Model Development and Testing of 15KV 1200A Distribution Switchgear–Year of Performance: 2007-2008

The second phase of the research will proceed after selection of the preferred design topology and semiconductor device based on Phase I design analysis. The Phase II research will lead to development of the hardware, controller and packaging of a laboratory prototype (Bench model) of 15KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, a current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker and transfer switch. It is suggested that the first generation of the bench model be based on 15-kV system so that the existing device can be used and high-voltage experience can be gained. The successful rate of concept proofing is much higher. Once the switchgear is fully designed and proven to be working, the high-voltage SiC device or an HV-IGBT or an HV- Super-GTO can be used to move the voltage level higher. The bench model serves a number of purposes, including determining that the product will work. The prototype also serves to highlight design flaws and defects that need to be resolved. Key research tasks that should be accomplished during this phase include:

- ***Design circuit for proof-of-concept laboratory bench model (2007)***

  The complete switchgear including devices, active and passive components, heat sink, sensors, and bus bar should be designed and packaged for laboratory demonstration. Gate drivers and auxiliary power supplies need to be designed with proper isolation and minimum noise susceptibility. It is desirable to have the device protection at the gate-drive level to ensure highly reliable operation. Voltage and current and heat sink temperature should be monitored for both control and protection purposes.

- ***Design controller with basic functions (2007-2008)***

  The controller will likely be designed with a digital signal processor (DSP) for digital control. Hardware should include sufficient PWM and analog-to-digital (A/D) and digital-to-analog (D/A) channels. The interface from PWM channels to the gate drivers would preferably be isolated by optical fibers. Software should be designed to perform basic control functions such as voltage balance and power transfer.

- ***Design communication interface (2007-2008)***

  The bench model shall be designed for easy mapping to open architecture communication standards for distribution switchgear, when they become available in the IEC 61850 series. It is not known at this time when those IEC standards will be written. However, the product development shall include a communication interface with a non-proprietary object model for the device, which can be provided to IEC to aid in development of a standard

- ***Integrate and test the laboratory bench model (2007-2008)***

  The entire power circuit and controller should be integrated for laboratory testing. Hydro-Québec built a distribution test feeder (see Figure 4-8) to test equipment, control cabinet, software for advanced distribution system which could be used for the purpose of laboratory testing.

- ***Evaluate the performance of the proof-of-concept bench model (2008)***

  The performance such as load current interruption, fault current limiting capabilities, ability to clear fault instantaneously, operation as a tie breaker, provide DG isolation, ability to provide soft start capability, ability to reduce switching surges, system efficiency over entire power range, heat sink temperature, total harmonic distortion (THD) of voltage and current, power factor, and so forth need to be evaluated.

- ***Refinement of Design Based on Test Results (2008)***

  Based on initial test results the prototype design should be modified and retested in order to verify the performance of the proof-of-concept prototype. The results from the lab testing should be compared with Phase I design analysis results and any discrepancies should be accounted for before moving to the next stage of field demonstration.

Figure 4-8
Distribution Test Feeder at Hydro Quebec

Phase III & IV: Field prototype development and testing of 15KV 1200A distribution switchgear–Year of Performance: 2009-2010

The fourth phase of the research will lead to development of 15KV, 1200A field demonstration unit to obtain real life field experience and verification of the performance. The field demonstration units need to be designed and packaged to address the entire range of environmental and operational scenarios that may be encountered in a distribution system. Refinement of the lab prototype should address these operational and environmental issues before developing field prototypes. Utility demonstration sites will be selected and identified through competitive bids. Field demonstration prototype will be built and delivered to the selected demonstration sites for field-testing. Hydro-Québec built a distribution test feeder (see Figure 4-8) to test equipment, control cabinet, software for advanced distribution system which could be used for the purpose of laboratory field testing.

The basic performance such as load current interruption, fault current limiting capabilities, ability to clear fault instantaneously, operation as a tie breaker, provide DG isolation, ability to provide soft start capability, ability to reduce switching surges, operation as transfer switch, system efficiency over entire power range, heat sink temperature, total harmonic distortion (THD) of voltage and current, power factor, and so forth need to be evaluated. Reliability and performance information will be recorded during the demonstration period for product improvement. Key issues that need to be addressed during this stage of the development effort include:

- ***Package the power circuit and component. (2009)***
- ***Design controller with advanced functions (2009)***
- ***Design communication interface (2009-2010)***
- ***Integrate and test the field demonstration prototype (2009-2010)***
- ***Demonstrate and test in selected sites (2009-2010)***

Phase V: Commercialization of a Family of Solid-State Switchgear Year of Performance: 2011

The final phase is technology commercialization. EPRI will work with the developer, manufacturer, and utilities for large-quantity manufacturing and commercialization. Development of a commercialization plan will be the initial step in this phase. The commercialization plan will address the strategies for transferring this technology to the marketplace and development of a business plan centered on specific application areas. The commercialization plan will also identify the important characteristics required for successful commercialization. For example, the commercialization plan will identify essential manufacturing capabilities required to build the transformer and optimal channels to market and distribution strategies. It is anticipated that the initial phases of the research will be conducted by EPRI with cost sharing from organizations involved in the development of the hardware and field demonstration units. These organizations will also play a key role with EPRI and member utilities in identifying the best strategy for commercialization of the family of solid-state switchgears that are capable of interrupting load or fault currents in critical load applications or be applied as a transfer switch, tie breaker, or fault current interrupter.

5
EPRI'S INITIAL APPLICATIONS RESEARCH PLAN

Motivation

Application of an EPRI-developed technology is the final step in a project life cycle. Application of the results of the development phase of a project is the final measure of project success. It is desirable to EPRI and its technical staff to have a high level of involvement in applications and to plan from project initiation and continuing throughout a project life cycle for applications work.

Projects should not be seen as ending with the delivery of development results, but as continuing through the planned applications phase of the project. The applications work can occur after the product is delivered or, in some cases, during the latter stages of development. A major motivation for the project manager is the opportunity this provides for expanding the business created for EPRI and for the individual project manager involved. EPRI can perform applications work to validate a product in specific applications and determine whether it is commercially viable or needs more development work. However, mass commercialization should be done outside of EPRI. The applications work can take many forms, such as utility trial use in new applications, training programs, and expert assistance for utilities, among others. These are activities which can help keep the project manager's workload stable and prevent a work shortage. Increased applications work is also in keeping with EPRI's goal to move to fewer, larger activities.

Limits of EPRI's Applications Work

EPRI is limited by charter from engaging in commercialization work. It has been disconcerting to EPRI technical staff in the past to have to pass the product to a manufacturer without the opportunity to stay involved in applications work. The opportunity to do applications work now exists! It is important to discuss the applications work early and often with the customers, program sponsors, other utilities, and multiple vendors over the life cycle of EPRI's multifunction solid-state switchgear program. This is because ultimately they will make the choice on whether or not to fund an applications phase. It serves as a vehicle for getting customer input to the applications phase planning and execution are noted throughout this document.

Objectives

EPRI applications research on a specific product can be done via two basic mechanisms:

- As tasks within the scope of the same project as that in which the product was developed.
- As a separate project.

In the first case, the project description field in the project planning template should contain a description of the tasks for the applications research, as well as the development work. It is imperative to give the clients a view of the full intended scope of the project from the outset, because they will be the ones deciding on whether or not to fund it. The applications research tasks, like the development tasks, can be updated year by year as the project unfolds to reflect what is being learned in the project. Clients should be actively engaged in the process of updating the project plan from year to year. In summary, for the first case, applications research tasks are treated just like development tasks in the template and in the interaction with clients to develop the project scope. Either the clients want something included in the scope or they do not. EPRI does those development and application activities that the clients are willing to fund. The applications plan field in the template can state that applications research is planned and is described in the project description field. It can also explain the expected teaming with utilities and vendors that may be needed for the applications research.

In the second case, a separate project is set up just for the applications research activities on a specific product. There is no material difference from the first case on how this would be handled, except that a separate project planning template is needed just for the applications phase of the work in the second case. Development would be done in one project and applications research in another. The handling of the content in the project description field and the applications plan field would be the same. Work to be performed by EPRI would be described in the project description field. Again, actual execution of the work depends on willingness of clients to fund it.

This chapter provides EPRI's initial applications research plan for applications research for the first-generation multi-function switchgear. One of the key objectives for the initial application research plan should address the ***best practices*** for engagement of the customers, program sponsors, other utilities, and multiple vendors and an application plan over the life cycle of EPRI's multifunction solid-state switchgear program. Some of the materials presented here were obtained from EPRI's WorkSmart report on Applications [61].

As illustrated in Figure 5-1, normally, the initial applications research will begin in the latter part of the development cycle and continue into the early stages of commercialization.

Types of application activities considered here include the following:

- Addresses customer engagement in applications research during the latter stages of development and after development during early commercialization
- Interface closely with program sponsors over the program life cycle
- Work and interact with other utilities over the program life cycle
- Work and interface closely with multiple vendors on implementation of solid-state switch technology throughout the development cycle, laboratory testing, field demonstration and after development during early commercialization

- Perform technical application studies/guides on opportunities to use the multifunction switchgear technology
- Work with potential vendors, program sponsors, and other utilities to select a host site to test and demonstrate the product and its key applications
- Perform trial applications of the multi-function switchgear in major types of distribution system environment
- Conduct experience evaluation and documentation for major application types to aid prospective users in adoption.
- User group, workshops, subscription support services, as may be specified in the applications research plan.
- Address key integration issues and additional refinements to take advantage of the new technology

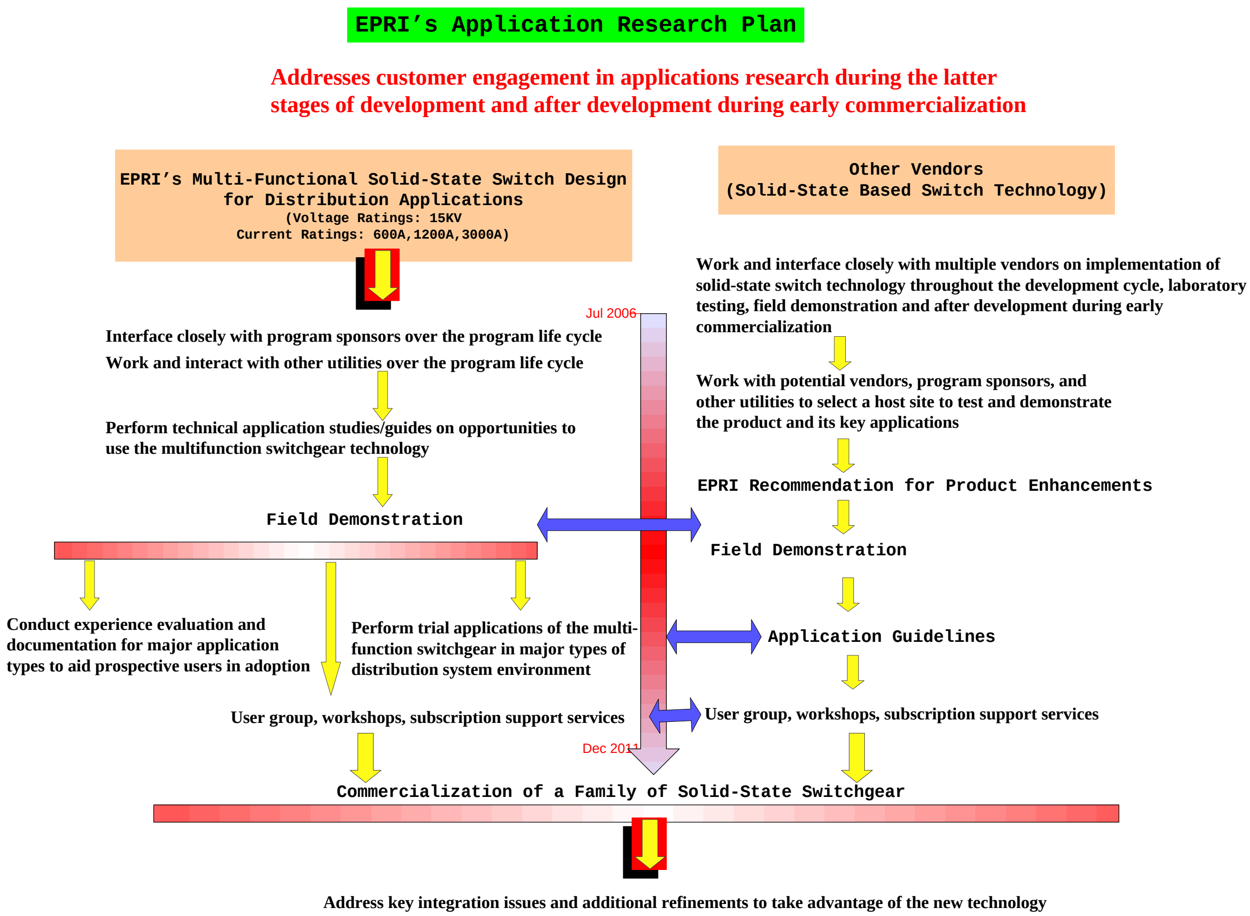

Figure 5-1
Initial Application Research Guide

Address Customer Engagement Activities During EPRI's Multifunction Solid-State Switchgear Program

It is important that customers (program sponsors and other utilities) have input to and understand the full scope of EPRI's multifunction solid-state switchgear program during latter part of the development cycle and continue into the early stages of commercialization. This includes the applications phase for projects which will have one. The goal is to have the customers embrace the full program scope and be willing to make commitments to stay with the project to completion, including any applications phase.

Engagement Activities During Project's Development Phase

During solid-state switch technology development, the customers should be involved to get their inputs to tailor the product to their needs so that they can derive maximum benefits from it. Also they should be engaged for providing refinement of the project's multi-year plan for development and applications research plan. This involvement will help avoid problems with the product after commercial release. This involvement will also give them a chance to aid in the annual update to the project's multi-year plan and to begin final alignment of the applications plan with the actual final product characteristics that are emerging.

Table 5-1 provides representative activities.

Table 5-1
Engagement Activities During Project's Development Phase [61]

Activity	Description	When/Participants
Project kickoff meeting	A kickoff meeting will be held with the program sponsors, other utilities and contractor to review the work plan and get customer input providing refinement of the project's multi-year plan for development and applications research plan. A face-to-face meeting is preferred, but a web-cast can be used if project funding is thin and/or customer travel budgets are thin. During these reviews, the impact of results to date on future project plans, including the applications phase should be considered.	Soon after contact execution, allowing enough time for technical manager and contractor to develop the necessary presentation materials • Technical manager • Program sponsors • Multiple vendors • Contractor(s)
Engagement of customers in project review meetings	Depending on the length and complexity of the project, one or more project review meetings could be held at times in the project where there are some interim results to critique and/or key project decisions to be made. Face-to-face meetings are preferred, but web-casts can be used, if project funding is thin and/or customer travel budgets are thin. These reviews give the customer an opportunity to shape a product and increase the chances of their having a high level of satisfaction.	Synchronized to major project milestones or on an ad-hoc when a problem arises. • Technical Manager • Program sponsors • Multiple vendors Contractor(s)
Engagement of customer in product development	For bench and field prototype development, this would include direct customer participation in pre-commercial field prototypes. For software, DSP controls, and communication protocols and functions, this would include direct customer participation in pre-commercial beta testing. This would include direct customer participation in reviewing (and in some cases co-writing) a report, paper or other paper product. Involvement with other utilities and multiple vendors are also needed so that they may also be a partner in the testing and application verification phase.	During product development • Technical manager • Program sponsors • Multiple vendors
Engagement of customers in annual update to the project plan, including applications phase	Solicit customer inputs in writing the revised application research plan for the project, R&D roadmaps, and the description of it that will go in the supplemental funding opportunity notice, whichever applies. It is desirable to continually engage the customer in the planning of the applications work so they will understand the full project scope and be prepared to fund it through the completion of the applications phase.	Anytime by e-mail and telephone and at advisory committee meetings • Technical manager • Program sponsors • Multiple vendors

Engagement Activities During Project's Applications Phase

As discussed in the previous section, for this program the applications research phase should begin prior to the release of a family of low cost multifunction solid-state switchgear and continue after the release. Even when a product is delivered by a vendor/manufacturer, an EPRI applications plan should exist that involves EPRI, the customers, and the vendor/manufacturer in a process for follow-through on applications. The applications work should help encourage customer use of the product help introduce the product into all major applications that have been identified for the product, evaluate the experiences with the product in these applications, and provide feedback to aid in product improvement or development of a next-generation product. Table 4 provides representative activities.

Table 5-2
Engagement Activities during Project's Initial Research Applications Plan [61]

Activity	Description	When/Participants
Applications field experience assessment	Conduct applications workshops with project sponsors, utilities, and multiple vendors to examine experience with applications for the product, possible new applications for the product, and issues for improving the product or developing a next-generation product. Work and interface closely with multiple vendors on implementation of solid-state switch technology during the latter stages of the development cycle and conduct field demonstration	After commercial product release • Technical manager • Program sponsors • Other utilities • Multiple vendors
Training forums	Conduct forums (face-to-face, webcast, video, web training, etc.) to introduce prospective users to a product and/or train their staff on procedures for adoption and maintenance. The training may include basic familiarization with the core technologies as well as the product. Training can begin in advance of the product release and continue after product release.	During development and after commercial product release • Technical managers • Program sponsors • Multiple vendors
Periodic technology transfer workshops	Workshops in which the only topics are recent EPRI products (not industry issues, or vendors). These aren't training courses, per se, but there is enough detail to provide an appreciation for the technology. These would typically be done for an entire program or higher level grouping of products, rather than an individual product.	Periodic, e.g., annually or biennially, depending on number of products coming out in a given area • Technical managers • Program sponsors • Multiple vendors
Customer site coordinators	Select customer staff members as site coordinators. Part of their job is to encourage use of the EPRI product within the customer's organization.	During development and after commercial product release • Technical manager • Program sponsors • Multiple vendors
Subscriber-requested assistance as part of base program	A provision that allow use of a small percentage of base program funding to have EPRI staff visit sites who need help implementing EPRI technology. It is a quick way to start including implementation into the base program, but it is prompted by a customer calling EPRI.	After commercial product release • Program sponsors • Multiple vendors
Webcasts following product release	Increased emphasis on webcasts following product release. Significant resources are invested in preparing and giving these webcasts for each maintenance guide they produce. Participation is very strong, particularly by plant staff (end-users)	After commercial product release • Program sponsors • Multiple vendors

	that never travel to EPRI meetings.	
Testimonials and documentation of applications experience	Tools that can be used are Testimonials, EPRI Innovators, Success Stories, EPRI Journal articles, EPRI annual report, and the Applications Scorecard. These are most often done after a product exits, but there are situations in which testimonials and success stories can be documented with customer input during the development phase of a project (for example to celebrate and recognize a key interim deliverable being achieved).	Whenever a customer has valuable experience to share • Technical manager • Program sponsors • Multiple vendors
Applications workshops	Conduct applications workshops with customers and, in some cases, vendors to examine experience with applications for the product, possible new applications for the product, and issues for improving the product or developing a next-generation product.	After commercial product release • Technical manager • Program sponsors • Multiple vendors

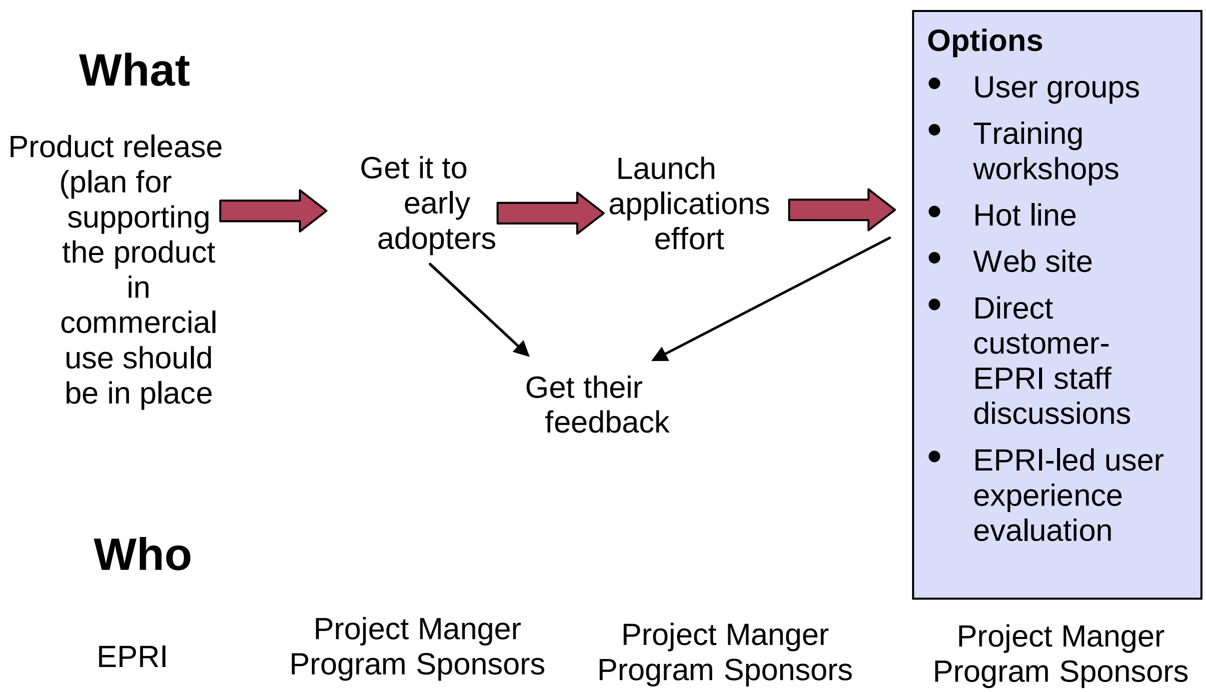

Figure 5-2
Engagement During Project's Application Plan [61]

6 PROCUREMENT SPECIFICATION FOR SELECTING A CONTRACTOR FOR SUBSEQUENT PHASES

General

This chapter outlines a detailed procurement specification for future project phases of EPRI's multifunction solid-state switchgear program. The procurement specification was developed using the design specification, the development and test plan, and the applications research plan from the prior tasks. The design specification section contains preliminary generic specifications that are developed for the first generation multi-functional solid-state breakers for distribution applications. This specification is intended to delineate the concepts and functional requirements for the power electronics based 15KV class distribution switchgear development. The specification is developed as a functional specification so as not to be unduly restrictive on designs and thereby allow equipment suppliers to offer reliable solutions to users' problems at the lowest possible cost.

The intent here is not to make recommendations for a specific design or a specific semiconductor device. The question is, "Is there a possibility that other designs may evolve that might meet the need"? This decision will have to be made by the manufactures to come up with other innovative designs that will meet the specification or through a competitive procurement process to select a vendor/developer/partner.

Based on the preliminary results and on-going research in these areas, "***all solid-state***" based switchgear designs as well as "***hybrid***" designs have the potential to offer a myriad of advantages that prospective purchasers may find attractive and may make them successful in the marketplace. It was emphasized that EPRI should consider both "all solid state" as well as "hybrid" bids and that if a hybrid bid is made, the path to all solid state in the long run must be shown by the bidder. These designs will guide the development of the smart solid-state switchgear.

The procurement specification is aligned with the project's multiyear plan in the EPRI base portfolio. In particular, the project's broad tasks, as outlined here, from the multi-year plan for Program 124 are as follows:

- **Requirements Definition** (completed in 2005).
  - Assess the needed characteristics for switchgear in current and future distribution system applications (from prior EPRI work and current literature).
  - Study the current state-of-the-art in conventional and solid-state switchgear and identify the technology gaps that must be filled to meet the needs.

- Conduct a conceptual design and cost/benefit analysis of a few candidate solid-state switch concepts for the prospective family.
- Identify candidate functions to be included in the switchgear products.
- Conduct a feasibility assessment for developing the chosen concept.

- **Development of Initial Design and Plans for Testing and Evaluation, Commercialization, and Applications Research**
  - Proceed in 2006 with detailed design for a specific low-cost multi-function switchgear concept
  - Proceed in 2006 and develop a plan for development, test and evaluation, and applications research phases of the project.
  - Proceed in 2006 and assess key application areas for this product
  - Proceed in 2006 and identify development options[9] that can give us the flexibility to align with funding received
  - Proceed in 2007 and initiate competitive procurement process to select vendors who are best suited to implement the solid-state switch technology
  - Proceed in 2007 and develop design drawings.
  - Proceed in 2007 and develop technical specifications for the component technologies (electronic and communications)
  - Proceed in 2007 and update the cost/benefit analysis for the switchgear family
  - Proceed in 2007 and determine the communication architecture needs for the switchgear, building on existing standards and legacy systems.
- **Development of Multi-Function Switchgear Family**
  - Conduct laboratory bench model development and then field prototyping of the chosen concept. The product would be designed for easy mapping to open architecture communication standards for distribution switchgear, when they become available in the IEC 61850 series. It is not known at this time when those IEC (International Electrotechnical Commission) standards will be written. However, the product development will include a communication interface with a nonproprietary object model for the device, which can be provided to IEC to aid in development of a standard.
  - Update cost/benefit analysis and plans for future phases based on the results of development work in this task.
  - Develop specifications for the commercial products.
  - Conform the switchgear family to open-systems-based communication architecture standards, with backwards compatibility with major legacy communication systems. In particular, EPRI will seek to harmonize this product with IEC 61850 standards and part

[9] For example, the minimum system developed could be a current interruption device with a communication interface that enables it to be used as a monitoring node in ADA and that allows remote control of the switch. Other functions, like fault current limiting or use in fault anticipation/location schemes, can be options added to the minimum system, if funding allows.

of the project resources will therefore be used for active participation in the IEC standards development.

  – Develop specifications for the commercial switchgear family. Identify shortcomings and technology gaps that may be addressed in other project work and/or a second-generation family.

- **Test and Evaluation**
  – Select test hosts for demonstrating the product and its applications
  – Field test switchgear in one or more actual utility systems, depending on availability of willing utility partners who are able to provide funding for purchase and installation of the equipment.
  – Document test results to aid in final product specification.
  – Update cost/benefit analysis and plans for future phases based on the results of system testing and evaluation.

- **Finalization of Design and Packaging for Commercial Release**
  – Correct problems identified in field testing.
  – Design packaging.
  – Transition results to vendor(s) for commercialization.

- **Applications Research**
  – Perform technical application studies on opportunities to use the multifunction switchgear technology.
  – Conduct experience evaluation and documentation for major application types to aid prospective users in adoption.
  – User group, workshops, subscription support services, as may be specified in the applications research plan.
  – Interface closely with program sponsors over the program life cycle
  – Work and interact with other utilities over the program life cycle
  – Work and interface closely with multiple vendors on implementation of solid-state switch technology throughout the development cycle, laboratory testing, field demonstration and after development during early commercialization
  – Address key integration issues and additional refinements to take advantage of the new technology
  – Addresses customer engagement in applications research during the latter stages of development and after development during early commercialization

The material covered here uses appropriates materials from Chapter 2, 3, 4, and 5 for the purposes of RFP.

Objectives of this Solicitation

EPRI has undertaken the development of a family of power electronics based switchgear applications at ***distribution*** class voltages. Because this technology is relatively new, there is a still lack of standards and procedures. The overall objective of this multi-year project is to develop and commercialize a family of low-cost, multifunctional, solid-state switchgear for ***distribution*** applications.

Solid-state switchgear ("***all solid-state***" as well as "***hybrid***" designs) will have many features that are significantly different from today's electromechanical circuit breakers and is certain to have a profound impact on present practices in distribution systems. It is essential to carefully examine application areas, understand what parts of a system might be sensitive and possibly to develop a detailed definition of the requirements for product development for the new device.

The Electric Power Research Institute (EPRI) is seeking to procure a first generation multi-functional and modular 15KV, 1200A class solid-state breakers. This specification covers the development of a generic design for the solid-state switchgear products of multiple ratings and the procurement of the first site-specific (field prototype) solid-state switchgear.

The initial conceptual design for the first generation of solid-state switchgear present in the previous chapter is aimed at distribution level applications in the 15KV-35KV class range. It is ***NOT*** intended for transmission level applications.

It is the intent of this specification to describe required and desired features of the solid-state switch technology and establish interface requirements. It is not meant to unduly restrict design variations and innovations that can reliably provide the features desired at the lowest possible cost. Throughout this document:

- EPRI shall mean the Electric Power Research Institute,

- Owner/Host shall mean the entity at whose site the solid-state switchgear will be installed,

- Bidder shall mean the entities submitting a proposal to this RFP, and

- Contractor shall mean the successful Bidder selected to develop the first generation multi-functional solid-state switchgear.

It is planned that the solid-state switchgear be developed by a single Contractor (i.e., the successful bidder). Bidders will need to demonstrate appropriate skills in the areas of power electronics, communications, and standards, and other needed disciplines. Bidders are encouraged to engage partners, subcontractors and/or suppliers to provide all capabilities and equipment necessary to supply a fully functional integrated system. However, the Contractor will have overall responsibility for ensuring that the solid-state switchgear performs as specified and provide a warranty.

Background

With the growth of the electricity demand, utilities have been upgrading their systems continuously for higher power transfer capability and, consequently, for higher fault current handling capability. There are growing instances in utility distribution systems wherein the fault current levels are exceeding the interrupting capability of existing substation circuit breakers. This increase in fault current level either requires the replacement of a large number of substation breakers or the development of some means to limit the fault current. Also, many mechanical circuit breakers are operating much more than originally intended in applications such as capacitor switching. This continual use of mechanical breakers requires intensive maintenance to be performed or periodic replacement of the whole breaker. Also, the process of replacing circuit breakers of adequately high fault current interruption capability can become an expensive affair. Environmental problems are also on the horizon with the use of both SF6 gas and oil within mechanical breakers, which may pose long term problems for many utilities.

Recently new designs of solid-state breakers ("***all solid-state***" as well as "***hybrid***" designs), transfer switches, and fault current limiters using modern power electronics have captured the attention of utilities as well as equipment producers. New designs for an intelligent "all solid-state" as well as "hybrid" distribution switchgears have resulted from the marriage of advanced power electronics and conventional switchgear technology. The operating characteristic of solid-state switchgear is primarily dictated by the capabilities of the semiconductor devices used. Voltage and current ratings of the breaker define the number of power semiconductors required and, consequently, the cost and the operating losses of the breaker.

In 2005 EPRI project work a comprehensive requirements definition was described in *EPRI Family of Multi-Functional Low Cost Solid State Switchgear: Requirements Definition Phase* (EPRI, Palo Alto, CA: 2006. TR1010666) to assess the requirements for first generation multi-functional distribution voltage solid-state switchgears, identify the application areas, and evaluate the economic and technical considerations for different technologies and design options. This preliminary research was the first step before embarking on development of the hardware and associated controls for development of a family of low-cost multifunctional solid-state switchgear for a range of distribution applications.

Need for a solid state switch module

While the potential benefits of power electronics based switchgear designs ("***all solid-state***" as well as "***hybrid***" designs) have long been apparent, potential high production costs have curtailed development efforts. Advances in high power solid-state components now make possible solid-state switchgear at a reasonable cost. In a recent study, EPRI conducted a comprehensive survey to assess utility needs and perceptivities with respect to power electronics based solid state switchgear that can limit fault currents. Some of the key findings that are relevant to the outcome of the economic assessment presented in this chapter include:

- Survey results indicate that up to 20% of utilities expecting to replace 5 to 10% of their circuit breakers in the next 10 years would use a fault current limiting devices that are priced at 1 to 5 times a circuit breaker

- Utilities having a greater expectation for circuit breaker replacement are even more likely to use a solid-state fault current limiter – the percentage increases to 30% of utilities when the range of circuit breaker replacement need expands to 5 to 30%
- Cases where breakers with the required ratings are not available, or where excessive fault current levels carry more than only cost of a breaker upgrade alone, 50% of the utilities value a solid-state fault current limiter at 2-5 times the cost of a breaker

Characteristics that can be attributed to the solid-state distribution class switchgear may include, but are not limited to, the following:

- Rapid Load Transfer Capabilities. Distribution solid-state switchgear can be used as solid-state transfer switches. The solid-state switchgear designs can be used to transfer the power supply of sensitive loads, from a "normal" supply system to an "alternate" supply system when a failure is detected in the "normal" supply. In one embodiment, this transfer is performed quickly (1/4 cycle) so that the load does not experience any power quality problem.
- Circuit Sectionalizing and Reconfiguration. Solid-state switches can eliminate momentary interruptions for the great majority of users on distribution systems when a fault occurs. Solid-state switches for reconfiguring systems can also allow for optimizing performance through reconfiguration without imposing momentary interruptions on users.
- Rapid Fault Current Solution Deployment. Solid-state switchgear designs can enable distribution entities/users to effectively deal with pressures to add new transmission capacity, provide open access for distributed and aggregate generation, and deal with the challenges presented by new fault current sources. Fault-current limiting is a characteristic that can be attributed to the subject solid-state switchgear. The following benefits can result from using solid-state switchgear that has fault-current limiting characteristics:
  - Failures. Cable thermal failures are less likely, and violent equipment failures are less likely.
  - Conductor burndowns. At the fault, the heat from the fault current arc may burn the conductor enough to break it, dropping it to the ground. Solid-state switchgear can provide faster clearing and lower magnitudes, therefore reducing the chance of burndowns.
  - Damage of inline equipment. A known problem is with inline hot-line clamps. If the connection is not good, high-current fault arcs across the contacts can burn the connection apart. Solid-state switchgear can provide faster clearing and lower magnitudes, therefore reducing the chances of such damage.
  - Evolving faults. Ground faults are more likely to become two- or three-phase faults with longer, higher-magnitude faults. Solid-state switchgear can provide current-limiting that may reduce this probability.
  - Underbuilt. Faults on underbuilt distribution are less likely to cause faults on the transmission circuit above due to rising arc gases with fault-current limiting.
  - Equipment ratings. Some distribution stations have fault current levels near the maximum ratings of existing switchgear; additional short-circuit current requires

reconfigurations or new technology. Solid-state switchgear can provide fault-current limiting that can resolve this problem.

  – Shocks. Step and touch potentials are less severe during faults.
  – Conductor movement. Conductors move less during faults, providing more safety for workers in the vicinity of the line and making conductor slapping faults less likely).
  – Voltage sags. Solid-state switchgear with fault-current limiting characteristics can reduce the depth of the voltage sag to customers/users on adjacent circuits.
  – Coordination. Fuse coordination is easier. Fuse saving is more likely to work with lower fault currents.

- <u>Rapid Fault Isolation and Aid Power Quality Improvements</u>. With the flexibility of power electronic switching, the solid-state switchgear will achieve fault isolation and provide better network protection and take care of most of the distribution system situations that result in voltage sags, swells, and power outages.
- <u>Instantaneous Current Limiting</u>. Solid-state switchgear designs can provide instantaneous (sub-cycle) current limiting. Solid-state switchgear can alleviate the short circuit condition in both downstream and upstream devices by limiting fault currents coming from the sources of high short circuit capacity.
- <u>Faster Fault Clearing and Shorten Recloser Interval</u>. Solid-state switchgear designs may allow utilities/users to clear faults more quickly than current circuit breakers.
- <u>Mitigating the Effects of New Generation Within Distribution System</u> New technology will increase the available fault current of the network and may result in existing equipment not being adequately rated to handle the new ratings. Upgrading the system to accommodate the new fault current ratings may be expensive and create excessively high prices and barriers to new generation. The solid-state switchgear designs with current limiting capabilities can be used to mitigate this situation.
- <u>Interfaces with Distributed Generators</u>. Solid-state switches can facilitate implementation of local islanding schemes for distributed generators and allow connection and disconnection without concern for transients.
- <u>Repeated Operations With High Reliability and Without Wear-Out</u>. High fault currents are known to be a factor in reducing transformer life, so an advantage that can result from using solid-state switchgear is longer life with higher reliability for nearby transformers.
- <u>Curtail Mechanical Wear and Tear in Equipment</u>. Equipment in the fault current path will not experience the high asymmetrical and symmetrical fault currents that would be possible without the solid state switchgear.
- <u>Soft Start Capability</u>. Using solid-state switchgear can limit the inrush current for capacitive loads, by gradually phasing in the switching device rather than making an abrupt transition from an open to a closed position.
- <u>Reduce Switching Surges</u>. Solid-state switches can prevent transient voltages during capacitor switching and will allow capacitors to be switched in and out as often as needed. The result is better control of VAR flows, voltage, and flicker on the distribution system without causing unacceptable transient voltages.

- Standardization. Using solid-state switchgear can implement “standardized” designs and provide an alternative to large scale power system breaker upgrades. There are fixed and variable costs in maintaining an inventory of distribution switchgears. One of the possible characteristics for the solid-state switchgear design is standardization of product classes compared to the existing practice based on multiple voltages and current rating. Realization of this primary functional specification can result in significant reduction in inventory cost. It is possible to significantly reduce inventory costs by introducing “standardized” switchgear designs.
- Avoid Using Traditional (series reactor) Fault Current Limiting Solutions.
- Improved Operations and Asset Management. The operations-and-maintenance (O&M) cost reduction is potentially achievable with solid-state switchgears through significant reduction of size and weight and improved communication capabilities. In an embodiment, the solid-state switchgear adopts the IEC 61850 communication architecture.
- Minimize Environmental Impact. By minimizing the need for SF6 breakers, the solid-state switchgear designs will help diminish the environmental impacts of greenhouse gas and arced oil associated with breakers.
- Other Advanced Distribution Automation Functions. Solid-state switchgear can provide advanced distribution automation that can help develop new applications for condition monitoring and asset management purposes.
    - Act as a Smart Sensor. In one embodiment, the solid-state switchgear can act as a sensor of voltage, current, and power factor, and can perform other advanced distribution automation functions. Solid-state switchgear can be automated to record and transfer vital power quality and reliability information. The solid-state switchgear device is intended to act as part of the overall ADA (advanced distribution automation) monitoring system being developed in another EPRI ADA project. Some of the prospective functionalities of the monitoring system include, but are not limited to:
        - Solid-state switchgear is capable of providing real-time information about any combination of the following: voltage magnitude, current magnitude, power quality characteristics of the voltage and current, real and reactive power, temperature, energy use, harmonic distortion, and power factor.
        - Solid-state switchgear can provide alarming functions with intelligence for processing data and identifying conditions that require notification of a utility or utility automation system. These conditions could include any combination of the following: outages, power quality conditions outside of specified thresholds, excessive energy use, conditions characteristic of equipment problems, incipient fault detection, equipment problem identification, fault location, performance monitoring of protective systems, and harmonic resonance conditions.
        - Solid-state switchgear can provide real-time state estimation and predictive systems (including fault simulation modeling) to continuously assess the overall state of the distribution system and predict future conditions. Solid-state switchgear can therefore provide the basis for system optimization.
        - Solid-state switchgear can provide or assist information systems that can integrate meter data with overall information systems for optimizing system performance and

responding to problems. These problems can include, but are not limited to: outage management, asset management, SCADA, loss analysis, and customer systems.

- Solid-state switchgear can integrate communications and control functions in order to optimize system performance.

- Open, Standardized Communication Architecture. The monitoring system and switchgear devices will all need to be conformed to IEC 61850. This will involve preparing an object model as part of the development phase and then working through an IEC working group to evolve it into a standard. IEC 61850 is the international standard document for substation automation systems developed under IEC Technical Committee (TC) 57. It defines the standards for communication architecture in the substation and the related system requirements. It supports all substation automation functions and their engineering. Different from that of earlier standards, the technical approach makes IEC 61850 flexible and future-proof. Additional parts of 61850 are currently under development by working groups of TC-57 to address standards for communications in the balance of the distribution system (feeder equipment).

Applications

Utility requirements drive the need for the development and deployment of next-generation power electronics based solid-state switchgear. The solid-state switchgear design has many features that are significantly different from conventional electromechanical circuit breakers, and will have a profound impact on present practices in distribution systems. A non-limiting list of enhancements over a conventional mechanical breaker has been described in the previous section. Uses of the solid-state switchgear may include, but are not limited to, the following:

- Substation applications. Two functional characteristics that can be attributed to a solid-state switchgear are: current limiting and speed. Fault current limiting can allow the switchgear to be used in areas where fault current has (or will be) grown past the fault-current duty of existing circuit breakers. Fast switches and fault limiting can help reduce stress on distribution transformers and other distribution equipment. Solid state switches can also facilitate implementation of local islanding schemes for distributed generators and allow connection and disconnection without concern for transients.
- Custom applications to large customer services. Large customers/ consumers that use switchgears could use solid-state switchgears. They may have special needs that could be met by the subject solid-state switchgear including, but not limited to, fast transfer switching, sensitive equipment protection, and optionally voltage-sag correction. Solid state switches can prevent transient voltages during capacitor switching and will allow capacitors to be switched in and out as often as needed. The result is better control of var flows, voltage, and flicker on the distribution system without causing unacceptable transient voltages.
- Feeder applications. One functional characteristic that can be attributed to the subject solid-state feeder switchgear is fast operation. Fault-current limiting is a characteristic that may not be needed as often (fault currents are generally lower). Solid-state feeder switchgear characteristics such as reliability and flexibility in control and operation can help gain acceptance and be advantageous in the commercial market. Competitive cost is another characteristic that can be attributed to the subject solid-state feeder switchgear. Circuit sectionalizing and reconfiguration is another application area as solid state switches have the

potential to eliminate even momentary interruptions for the great majority of customers on distribution systems when a fault occurs. Solid state switches for reconfiguring systems can also allow for optimizing performance through reconfiguration without imposing momentary interruptions on customers. Solid state transfer switches are the primary application for distribution solid state switchgear at the present time.

- Industrial applications. Large industrial facilities are large consumers of medium-voltage switchgear and would benefit from fault-current limiting for cases with high short-circuit levels, provided by the subject solid-state switchgear at competitive cost.

General concept and configuration

The first generation multi-functional solid-state switchgear should be innovative, scalable, reliable, and should offer multiple functions for multi-purpose distribution class circuit breaker and fault current limiting applications including: (1) current limiting of high magnitude fault currents, (2) faster clearing, (3) reduced maintenance, (4) reduced switching surges, and (5) high-speed load transfers. For the cost and reliability concerns, the circuit must be as simple as possible to avoid excessive bulky passive components.

Recently new designs of solid-state breakers ("***all solid-state***" as well as "***hybrid***" designs), transfer switches, and fault current limiters using modern power electronics have captured the attention of utilities as well as equipment producers. New designs for an intelligent "all solid-state" as well as "hybrid" distribution switchgears have resulted from the marriage of advanced power electronics and conventional switchgear technology. The general configuration is indicated in Figure 6-1 and Figure 6-2. Two types of designs can be used. One is an “all” solid-state based design other is “Hybrid” Solid State Circuit Breakers. Since a closed mechanical contact still exhibits the least amount of conduction losses amongst all “switching” elements in some designs an ultra-fast mechanical contacts are utilized for carrying the regular continuous operating current and solid-state switch for fault clearing and current limiting. This is referred as “hybrid” solid-state switchgear.

While the requirements for fault clearing, recloser, transfer switch, and current liming are different, the most difficult task is to turn the device off without going through zero crossing. Thus the first design criterion for a universally used switch is to be able to interrupt the current any time. Also, while the first design criteria must allow for all these functions as options, all the functionalities may not be required for all customers and applications.

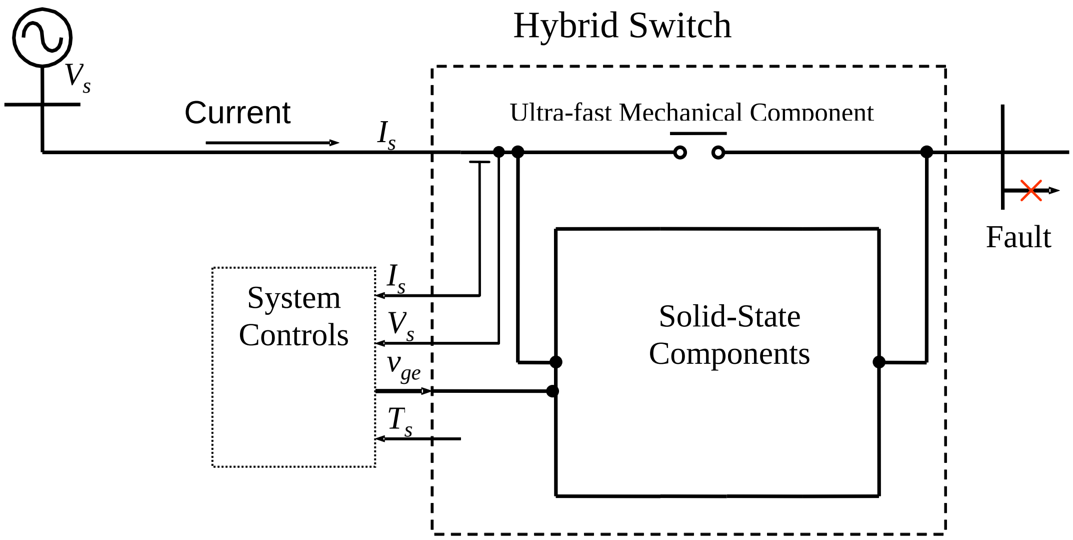

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Figure 6-1
A Hybrid Solid-State General Configuration

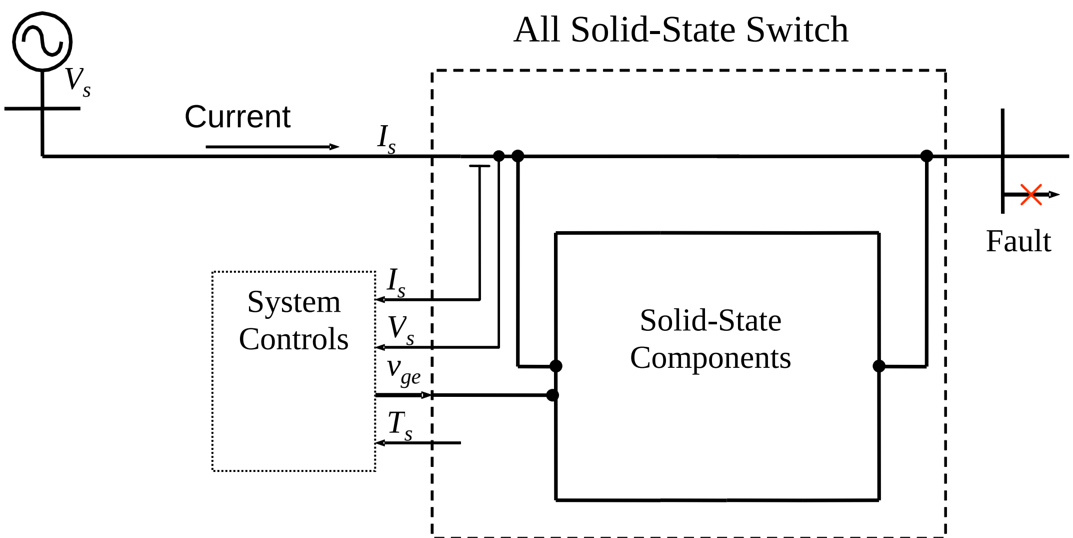

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Figure 6-2
"All" Solid-State General Configuration

Functional requirements of the solid state switch module

Codes and Standards

The specification is intended to provide designers with a set of functionalities that are desirable in the context of solid-state switchgear rather than an exhaustive list of requirements. The functional specification is written in a technology-neutral manner so as to provide designers with maximum flexibility in achieving the desired functionalities. At a minimum, the functionality of the proposed design should meet the basic functionality of conventional distribution breakers and reclosers (for example for 15KV, 600A class).

The quality of the equipment and services supplied by the contractor should meet or exceed the relevant requirements for operating environment, structural design, insulation level, short circuit protection, surge withstand and other issues that are described in the C37 series of ANSI/IEEE standard for breakers and reclosers. Specific C37 series standards that are relevant to distribution switchgears are outlined below. Additional codes may apply to individual modules and equipment. In case of conflict, this specification shall govern, and the Contractor shall notify EPRI and the developer/vendor/contractor in writing of such conflicts as soon as they become known. EPRI and the developer/vendor/contractor will work together to get a host for the field development work

- ANSI C37.42-1989, American National Standard Specifications for Distribution Cutouts and Fuse Links.
- ANSI/IEEE C37.60-1981, IEEE Standard Requirements for Overhead, Pad Mounted, Dry Vault, and Submersible Automatic Circuit Reclosers and Fault Interrupters for AC Systems.
- Cooper Power Systems, "Comparison of Recloser and Breaker Standards," February, 1994.
- IEEE Working Group on Distribution Protection, "Distribution Line Protection Practices Industry Survey Results," IEEE Transactions on Power Delivery, vol. 10, no. 1, pp. 176-86, January 1995.
- ANSI C37.06-2000, AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis--Preferred Ratings and Related Required Capabilities.
- ANSI C37.42-1989, American National Standard Specifications for Distribution Cutouts and Fuse Links.
- ANSI/IEEE C37.60-1981, IEEE Standard Requirements for Overhead, Pad Mounted, Dry Vault, and Submersible Automatic Circuit Reclosers and Fault Interrupters for AC Systems.
- Cooper Power Systems, "Comparison of Recloser and Breaker Standards," February, 1994.
- IEEE Working Group on Distribution Protection, "Distribution Line Protection Practices Industry Survey Results," IEEE Transactions on Power Delivery, vol. 10, no. 1, pp. 176-86, January 1995.
- Westinghouse Electric Corporation, Applied Protective Relaying, 1982.
- ANSI/IEEE C37.90.1-IEEE Surge Withstand Capability (SWC) Test for Protective Relays and Relay Systems.

- ANSI/IEEE C37.90.2 - IEEE Standard Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers.
- Three phase and ground time over-current protection with timing in accordance with IEEE Std. C37.112 (Distribution Requirement)
- Hi-set instantaneous over-current protection (Distribution Requirement)
- Low-set instantaneous overcurrent protection, enabled/disabled by state of reclosing cycle (Distribution Requirement)
- Auto-reclosing function, settable for 0-3 reclosing attempts, 0-60 seconds adjustable delay per attempt, lockout after last attempt, 0-60 seconds reset delay after lockout reset (Distribution Requirement)
- Three-zone phase and ground distance protection (Transmission Requirement)
- Directional ground instantaneous and time overcurrent protection with timing per C37.112 (Transmission Requirement)
- Auto-reclosing function, as for distribution applications, but also with synchronism checking capability (Transmission Requirement)

If any equipment and components in the solid-state switchgear system are normally manufactured to non-U.S. standards, conformance of the equipment to the specified U.S. standards shall be certified by the Contractor. Further, individual solid-state switchgear installations shall comply with all applicable state and local codes in effect for each site on the date of the contract.

Design Considerations for Solid-State Current Limiters and Breakers

A thorough design and performance analysis should be conducted on any prospective design of solid-state switchgear to evaluate, which of the functional specifications can be achieved with the particular design and what will be tradeoff in cost, efficiency and reliability to achieve additional functionalities. It is feasible that many of the functionalities listed below can be programmed into the solid-state switchgear in different modes of operation. For example, transfer switch capabilities and fast fault clearing and instantaneous current limiting could be two different modes of operation that can be integrated within the same hardware platform and depending on the controller operating mode any one of the feature could be activated.

Basic Requirements/Specifications for a 15KV, 600/1200A Design for a Circuit-Breaker / Recloser / Current Limiter

- Steady-state current rating

    600/1200 A, continuous

- Emergency overload capability

    800/1400 A, 1 hour

700/1300 A, 8 hours

- Short-circuit current rating

  12.5/23 kA, symmetrical (for one second)[10]

- Voltage rating

  15.5 kV line to line

- Low-frequency withstand voltage

  50 kV, one minute

- BIL

  110 kV

- Losses

  Less than 10 kW

- Independent phase operation

  Each phase can open and close independently

- Speed

  Clears faults within 1/2 cycle

- Control connections

  The switch must have a connector to the controller. It is desirable to have an industry standard connection that could be used with other controllers (Schweitzer for example), but this setup may not be fast enough to achieve desired operational speeds. Another option is to have the controller built-in to the switch; then, an external connector must be available to communicate with the controller to program settings and download data.

- Controller capabilities

  The controller must provide standard functionality of digital relays, comparable to the SEL 351 relay.

- Powering and backup

  Should operate from a supplied external 120 V_{AC} source. Should operate for up to 8 hours on battery backup.

- Smart Sensor, Distribution Fault Anticipator, and Monitoring System
  - Develop a list of what parameters needs to be monitored. Some of these functionalities could include:

[10] 20KA peak 1/2 cycle rating

        - Capable of providing real time information about voltage magnitude, current magnitude, power quality characteristics of the voltage and current, real and reactive power, temperature, energy use, harmonic distortion, power factor, etc..
        - Alarming functions with intelligence for processing data and identifying conditions that require notification of the utility or utility automation system. These could include outages, power quality conditions outside of specified thresholds, excessive energy use, conditions characteristic of equipment problems, incipient fault detection, equipment problem identification, fault location, performance monitoring of protective systems, harmonic resonance conditions, etc.
        - Real time state estimation and predictive systems (including fault simulation modeling) to continuously assess the overall state of the distribution system and predict future conditions, providing the basis for system optimization.
        - Information systems that can integrate meter data with overall information systems for optimizing system performance and responding to problems (outage management, asset management, SCADA, loss analysis, customer systems, etc.)
        - Integrate communications and control functions in order to optimize system performance
        - Capable of providing real time information about voltage magnitude, current magnitude, power quality characteristics of the voltage and current, real and reactive power, temperature, energy use, harmonic distortion, power factor, etc.
    - Determine the type of sensor equipment and support equipment for the sensors

- Communication and Control Infrastructure[11]
    - Develop an object model for the multi-functional switchgear based on use cases
    - Work with IEC working group to develop into a part of IEC 61850
    - The procedures include:
        - Determine functional requirements
        - Determine the communication system requirements to support these functions
        - Identify IEC61850 logical nodes for each switchgear function, each application module, and each sensor
        - Develop IEC61850 data exchanges within the solid-state switchgear
        - Develop IEC61850 data exchanges with external systems

[11] As the distribution system becomes more automated, opportunities exist to improve the utilization of distribution switchgears. More sophisticated automation integrated with solid-state switchgear can serve as an outage notification and outage management device, remotely control the different mode of the functionality of the breaker and monitor condition of the breaker and the power system in real time. The proposed design should evaluate centralized control, decentralized control, and combination approaches for automation. Realizing the full potential of an solid-state switchgear will require more sophisticated communication architectures. A promising platform is the IEC 61850 architecture that is an open industry standard developed from EPRI's Utility Communications Architecture (UCA). A wide variety of equipment can plug into this architecture. The proposed design should provide the flexibility to integrate the IEC 61859 architecture within the switchgear.

    - Specify conformance testing
    - Specify IEC61850 configuration tools
  - Communication infrastructure for integrating customer meter data with a real time system data manager. This might involve local concentrators and data processing depending on the specific architecture and design.

- Enclosure

  Must fit in enclosures for overhead pole mounting (like a recloser), padmounted application, and installation in draw-out metal-clad switchgear. This requires a size of approximately: 28"W × 32"H × 14"D

- Insulation

  It could be oil, SF_6, or solid insulation.

- Price

  Manufacturing cost should be compared with US$20,000 (three-phase) for a conventional breaker

Optional Features (Scalable Implementation)

- Current limiting Threshold

  For example, for short circuits to 50 kA, limit current to 10 kA peak. The ability of power electronic based switchgear to limit the magnitude of fault currents is one of its most valuable features.

  Maximum fault currents on electric power systems tend to grow over time because of reinforcement of the system to handle larger loads. Switchgear designs which can limit maximum fault currents, may avoid the need to replace large amounts of expensive equipment whose fault current capability has been outgrown. Typical distribution system fault currents range from 20KA to 64KA. Having a current-limiting threshold that can be adjustable, rather than fixed, might be desirable.

- Voltage

  25 and 35 kV models

- Gang operation

  It is desirable that the switches can be applied in modules in parallel or series to increase voltage and/or current ratings.

Relay Requirements/Specifications for Solid State Switchgear in Current Limiting Application

Solid state switchgear will have many features that are significantly different from today's electromechanical circuit breakers. For example it can be expected to have:

- Ability to clear faults in a time frame of 1/4 cycle from fault inception.
- Current limiting of high magnitude fault currents.
- Reclosing as rapidly as 1/2 cycle after clearing a fault.
- Soft reclosing by limiting current to the circuit until it has demonstrated to have returned to normal integrity

The next section provides some of the relaying issues and potential concerns that would need to be investigated. The Contactor shall need to revise some of the issues raised here will have to be revisited in more details as development of solid-state switchgear application progresses and as potential users provide real world examples for study.

Relaying of the Solid-State Switch

As a solid state device, the solid state switchgear will have controls that will self protect. Designing the solid state switchgear to respond properly to system abnormal conditions may allow these controls to be integrated with conventional protective and relaying practices for improved performance, thus promoting early acceptance of the new technology. Relaying requirements of the solid state designs and adjustments that will have to be made include:

- Evaluate the benefit of having all relaying contained in the solid-state switchgear controls versus the concern for a common mode failure.
  - Determine the required minimum characteristics of a fully functional and testable microprocessor relay package integral to the solid-state switchgear. This may be a removable card or leads to a test connector.
  - Quantify the requirements for independent, redundant relays to operate the solid-state switchgear.
- Evaluate the need and feasibility for an adjustable threshold for current limiting action.
  - Determine the range of current limiting settings between solid-state switchgear needs and power system needs to minimize circuit interruptions.
  - Examine the restrictions on dI/dt detection, such as high frequency switching currents cause by capacitor banks.
- Examine new features that may be required to gain full advantage of the high-speed reclose capability.
  - Explore testing for circuit integrity before full reclose.
  - Explore testing for and establishing a re-synchronized reclose.
  - Examine feasibility of non-trip current limiting for back-to-back capacitor switching.

- Evaluate the impact on existing protective devices with an solid-state switchgear functioning in the fault current limiting mode.
  - Determine at what level fault current limiting will slow fault clearing of devices in adjacent protection zones.
  - Explore how adjacent zone devices will respond to non-sinusoidal currents caused by the SSCL in the fault current limiting mode.
- Evaluate the impact of using the inherent single pole tripping capability of the solid-state switchgear.
  - Explore feeder conditions and time windows where expanded possibilities may exist such as lateral fuse saving.
  - Establish limitations on single pole tripping such as downstream three phase transformer connections.
- Evaluate coordination with high speed reclosing capabilities of the solid-state switchgear.
  - Explore how gradual reclosing, if feasible, will impact arc extinction.
  - Estimate the possibility of coordinating rapid re-synchronizing with intentional distributed generation (DG) islands.
- Evaluate coordination/utilization of ultra high-speed fault clearing.
  - Evaluate the tie breaker application.
  - Evaluate application of DG on network service.

Site Conditions

The Contractor shall design the solid-state switchgear to be suitable for all climate zones. The baseline design for the solid-state switchgear should be for outdoor installation and should abide by the specifications of distribution circuit-breakers as set forth in the ANS, IEEE, NEMA, NEC, and OSHA standards

Prospective Configuration

A "hybrid" mechanical/electronics based approach was proposed in the EPRI report, *EPRI Family of Multi-Functional Low Cost Solid State Switchgear: Requirements Definition Phase* (EPRI, Palo Alto, CA: 2006 TR1010666), for the first generation solid-state switchgear designs to limit the on-state losses and to minimize the cooling requirements of the semiconductor switches. Since a closed mechanical contact still exhibits the least amount of conduction losses amongst all "switching" elements in some designs an ultra-fast mechanical contacts can be utilized for carrying the regular continuous operating current and solid-state switch for fault clearing and current limiting. The use of a hybrid approach allows the semiconductor junction to operate from a lower starting temperature and allows the interruption of higher fault currents than a completely solid state unit. The solid-state switch works in transient fault condition and is controlled with pulse-width modulation to limit the fault current. A fast mechanical works in steady state to allow low-loss operation and to avoid unreliable bulky and thermal management system.

It should be again emphasized that the intent is not to make recommendations for a specific design or a specific semiconductor device. This decision will have to be made by the manufactures to come up with other innovative designs that will meet the specification or through a competitive procurement process to select a vendor/developer/partner. It was emphasized that EPRI should consider both "all solid state" as well as "hybrid" bids and that if a hybrid bid is made, the path to all solid state in the long run must be shown by the bidder. These designs will guide the development of the smart solid-state switchgear.

Operating under Steady-State Conduction Mode

A fast-action mechanical switch is turned on in steady state to bypass the current and to avoid overheating the solid-state switch, which tends to have higher loss and higher associated heat generation. When a fault current is detected, the mechanical switch can be quickly turned off, and the current can be transferred to the solid-state switch for fault current limiting and clearing operations.

Operating under Fault Limiting Conditions

Figure 6-3 shows the circuit diagram and basic operation waveform of the prospective universal hybrid switch (PHS) under fault current limiting condition. The switch consists of a fast mechanical switch S_m and a solid-state switch S_{ss}. The solid-state switch S_{ss} consists of a diode bridge and a PWM controlled IGBT or other gate-turn-off device to form a bidirectional switch. When the fault occurs, S_m is turned off, and S_{ss} is turned on to allow current flowing through the bidirectional switch. This fault current magnitude can be controlled by the PWM switching.

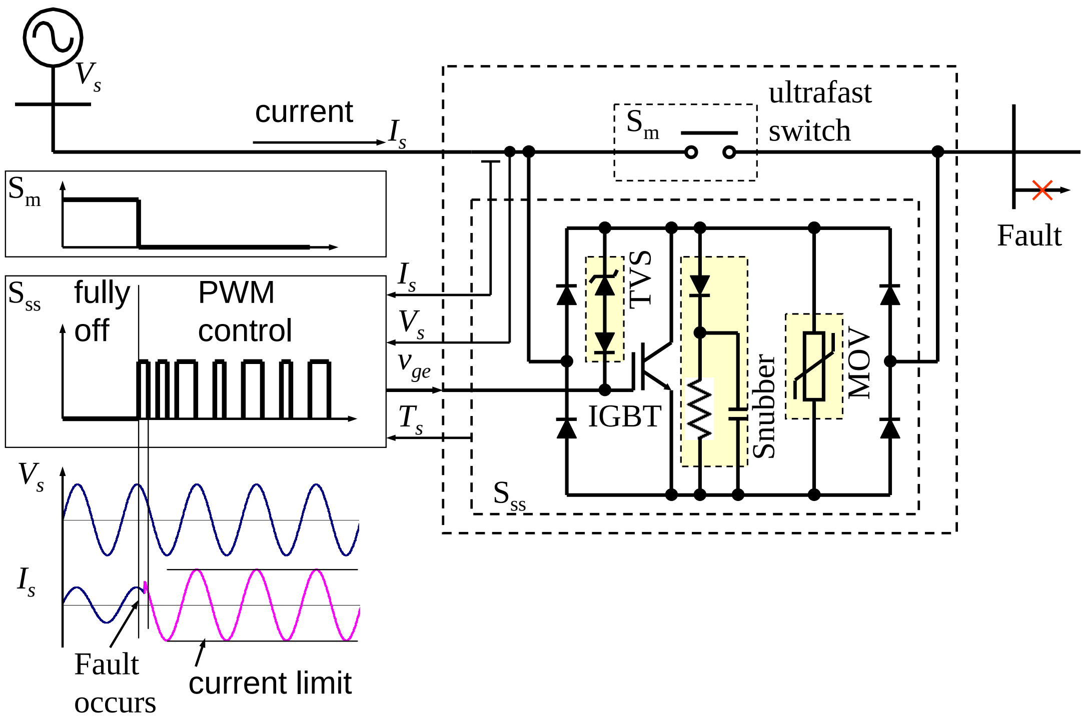

Figure 6-3
Circuit Diagram and Basic Operation Waveform of the Prospective Hybrid Switch

The proposed switch has current and voltage sensors, I_s and V_s, that can also serve as the monitoring purpose. A temperature sensor T_s is also fed back to the controller for device protection. The gate-drive circuit has a transient-voltage suppressor (TVS) to allow gate triggered under over-voltage condition to protect the device from instantaneous over-voltage failure. A metal-oxide-varistor (MOV) is also added to absorb transient over voltage coming from the system. When the switch is operating in PWM condition, the snubber circuit serves as the energy buffer that allows current magnitude to be regulated.

Operating under Fault Clearing Mode

The fault clearing mode can be controlled by simply turning off the switch without PWM operation. Figure 6-4 shows the PHS associated waveform under fault clearing mode operation. When the fault occurs, the mechanical switch S_m turns off, and the solid-state switch S_{ss} turns on to avoid the arc. Once the current is flowing in S_{ss}, then it can be turned off any time to clear the fault. Similar operating procedure can also be applied to static transfer switch operation. In that case, two PHS's are needed.

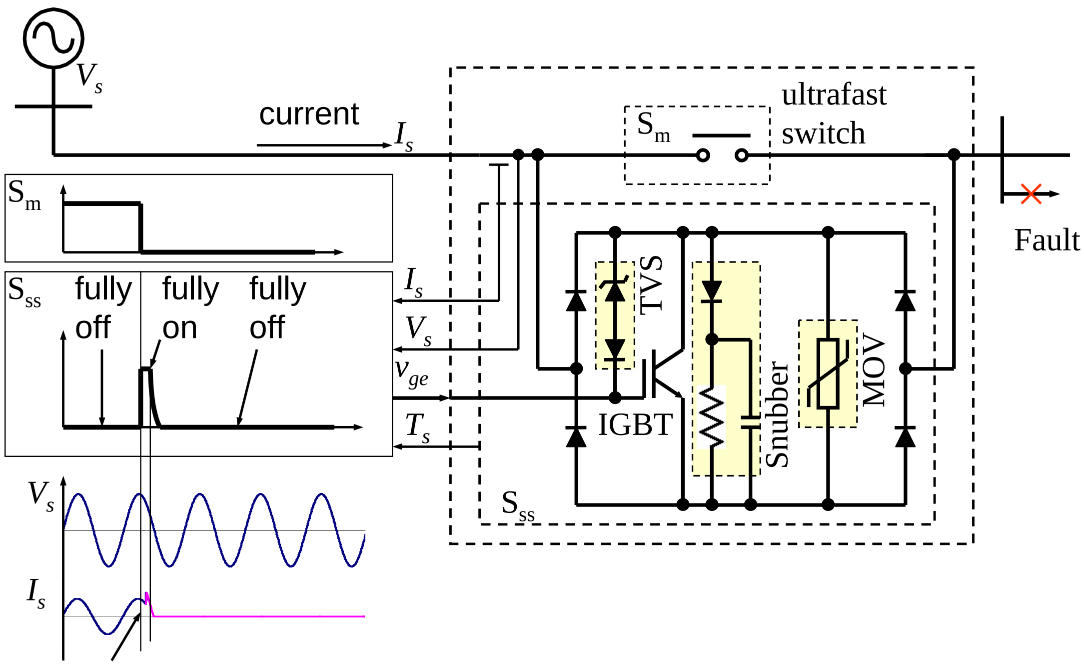

Figure 6-4
Prospective Hybrid Switch: Operating Under Fault Clearing Mode

Operating under Linear Region

The fault current limiting mode can also be controlled by operating the device in linear region without PWM operation. The operation is simply to reduce the gate drive voltage so that the device goes into high impedance mode. Figure 6-5 shows the waveform associated with linear mode current limiting operation. In this case, a large amount of power needs to be consumed in the device, and the temperature can shoot high very quickly. Thus this mode of operation is not recommended for a long-term current limiting condition. It would require the temperature feedback to ensure device junction temperature stays below the limit.

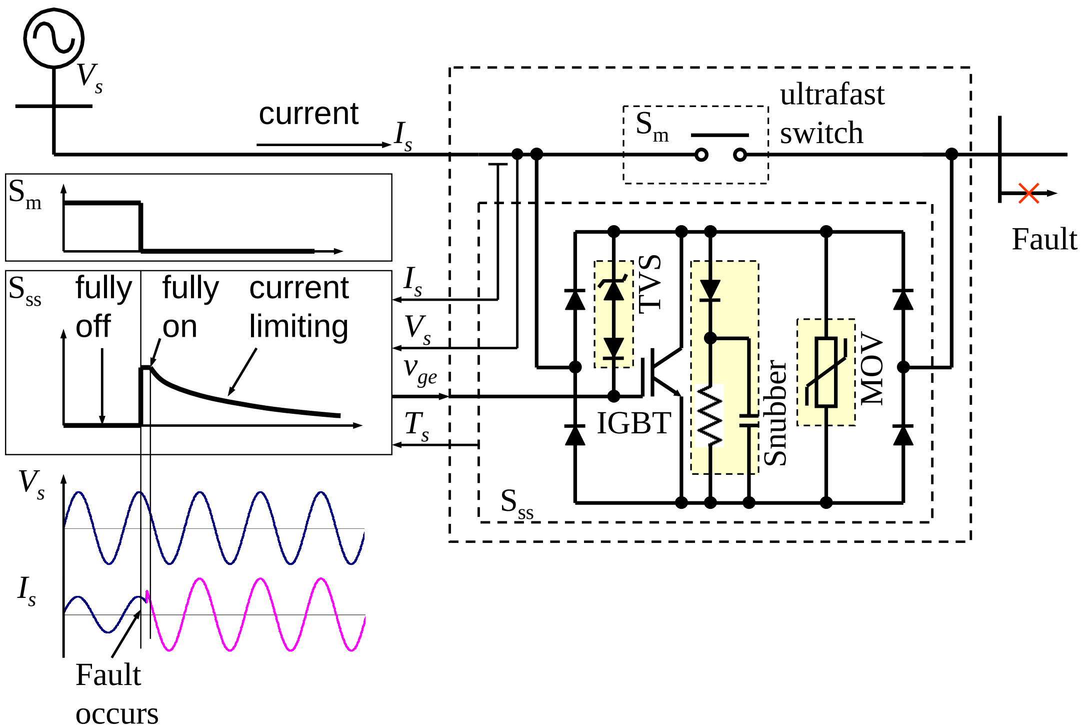

Figure 6-5 Prospective Hybrid Switch: Operating Under Linear Region for Fault Current Limiting

Note that the linear region operation cannot be achieved with all thyristor devices because they are the latch-on devices. However, the GTO and GTO (ETO, Super-GTO) derives devices can all be used in PWM operation with a lower switching frequency. Figure 6-6 shows the circuit diagram and associated PWM waveform using GTO or GTO-derived devices for current limiting operation. The use of GTO does not have over-voltage protection function provided by the gate drive circuit, but the same function can be performed with MOV. The voltage snubber is needed for the energy buffer as well as the dv/dt protection. The current snubber function may be obtained by the line inductance.

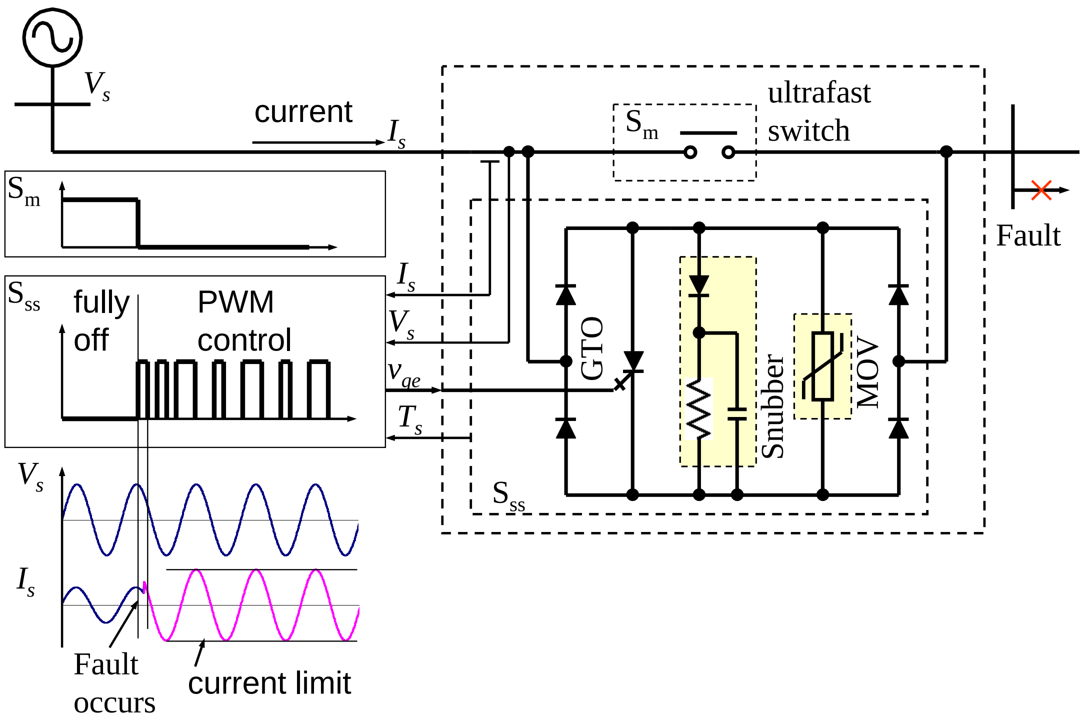

Figure 6-6
Prospective Hybrid Switch: Adopting GTO or GTO-Derived Device as the Switching Device for PWM Operation

Justification

This design is useful in a family of low-cost solid-state distribution switchgear that can expand the capabilities of existing distribution switchgears to a modular “integrated electrical interface” and create new service opportunities to meet the customers' requirement. The disclosed approach is a multi-functional, modular, hybrid design of power electronics based switchgear which will offer important advantages during design, testing, manufacturing and service stages namely:

- Design is simplified because within the module one is dealing with comparatively low voltages
- Testing is also simplified because of the reduced voltage level.
- The same modules can be applied to many different voltage ratings and applications
- One can use the same modules for different voltage breakers by stacking the appropriate number of modules depending on the voltage level of the breaker. This way we reap the benefits of mass production even further by:
- Having the same building block for different voltage breakers, thus simplifying manufacturing, testing and repair costs.

The proposed design has many features that are significantly different from conventional electromechanical circuit breakers, and will have a profound impact on present practices in distribution systems. A non-limiting list of enhancements over a conventional mechanical breaker includes: (1) current limiting of high magnitude fault currents, (2) faster clearing, (3) reduced maintenance, (4) reduced switching surges, and (5) high-speed load transfers. This design provides one or more improvements over the prior art.

Although the requirements for fault clearing, recloser, transfer switch, and current liming are different, the most difficult task is to turn the device off without going through zero crossing. Thus the first design criterion for a universally used switch is to be able to interrupt the current any time. In this case the gate controlled device is the best choice. For the cost and reliability concerns, the circuit must be as simple as possible to avoid excessive bulky passive components. In this case the pure silicon controlled rectifiers (SCR) based switch needs to be excluded. Even though SCR can be force-turned off by external commutation circuits for fault current limiting, the added components are simply not justifiable. Unfortunately all gate-controlled switches have high voltage drop that significantly degrades the efficiency. Thus the proposed switch is a hybrid version that utilizes fast mechanical switch for regular conducting and gate-controlled switch for fault clearing and current limiting.

Advantages of this design include:

- Sub-cycle operation
- Long Breaker cost life and Reduced Maintenance Costs
- SF6, is not required
- Lower Losses
- Less Expensive than "All solid-state" designs
- Cooling not required
- Reduced Switching Transients
- Current Limiting Capabilities

Project Plan for Development and Testing of Multi-Function Switchgear System

EPRI's multifunction solid-state switchgear program is designed to address this need, namely

- Assess key application areas for this product
- Identify development options[12] that can give us the flexibility to align with funding received
- Initiate competitive procurement process to select vendors who are best suited to implement the solid-state switch technology
- Identify development process in the laboratory and field
- Interface closely with program sponsors over the program life cycle

[12] For example, the minimum system developed could be a current interruption device with a communication interface that enables it to be used as a monitoring node in ADA and that allows remote control of the switch. Other functions, like fault current limiting or use in fault anticipation/location schemes, can be options added to the minimum system, if funding allows.

- Work and interact with other utilities over the program life cycle
- Work and interface closely with multiple vendors on implementation of solid-state switch technology throughout the development cycle, laboratory testing, field demonstration and after development during early commercialization
- Select test hosts for demonstrating the product and its applications
- Address key integration issues and additional refinements to take advantage of the new technology
- Addresses customer engagement in applications research during the latter stages of development and after development during early commercialization

This will help us to close the design loop, move the technology from prototypes and early products to widespread applications as well as tie this to the application research plan (see Figure 6-7). With the recent advances in power electronics, especially in the areas of high-voltage power electronics; solid-state-based switchgear designs are well within the realm of possibility.

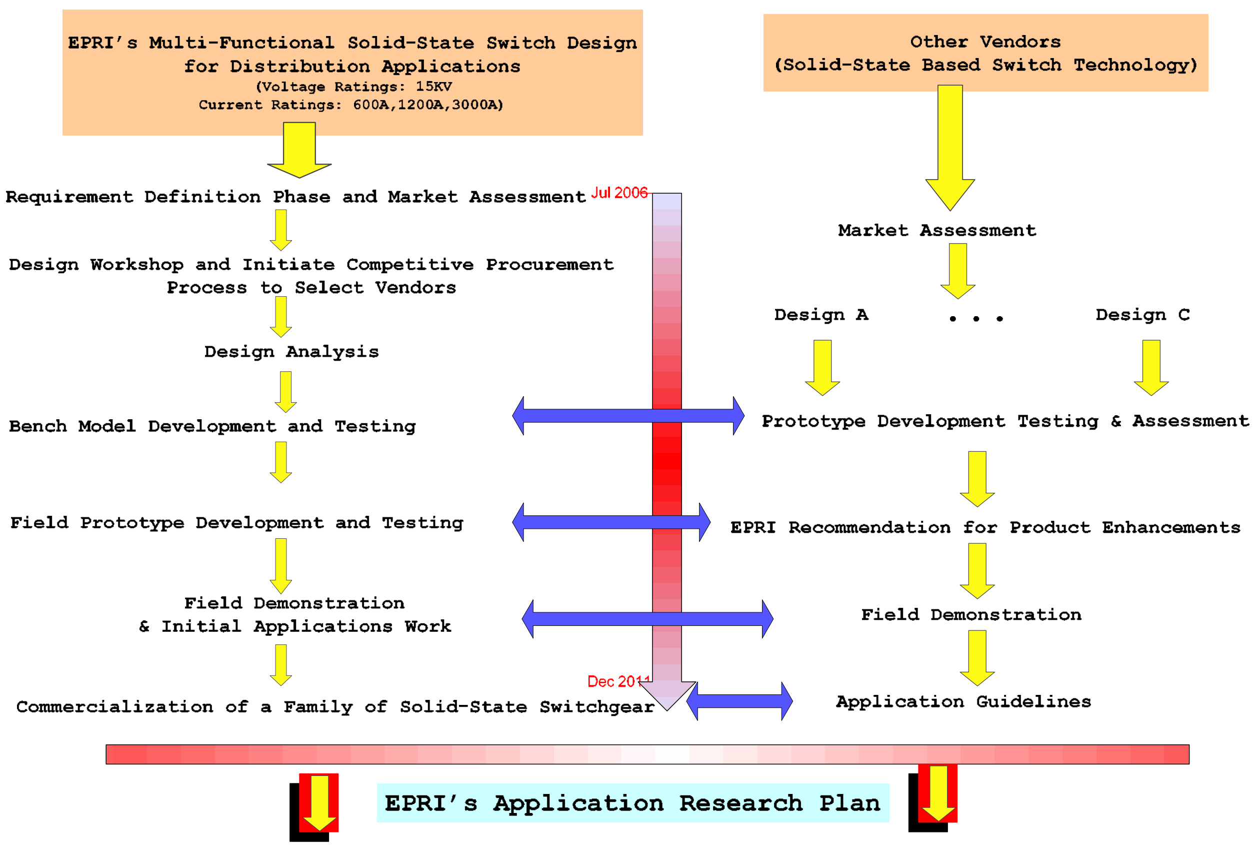

Figure 6-7
Project Plan for Development, Testing, and Commercializing of Multi-Functional Switchgear System

This section adopts the traditional stage-gate approach discussed earlier and provides a detailed description of the possible phases (shown in Figure 6-8) for design and development of the solid-state switchgear technology along with schedules and important milestones (see Figure 6-9) for the development work, field testing, and commercialization. Distribution switchgear development effort has been broken down into two distinct product families as indicated before. The two product families and possible phases (schedule dependent on funding availability) for development, testing, and commercialization include:

- ***Generation 1:*** ***15KV Class Distribution Switchgear Development*** (Basic Features and Requirements include: Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch)
  - **Phase I**: Detailed design analysis and functionality verification of family of either "all solid-state" OR "hybrid" technology (Voltage Ratings: 15KV & Current Ratings: 600A, 1200A, 3000A) which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2007)
  - **Phase II**: Bench model development and testing of 15KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2007-2008)
  - **Phase III**: Field prototype development, deployment, and testing of 15KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2009-2010)
  - **Phase IV**: Field testing and debugging of field prototype (2009-2010)
  - **Phase V**: Finalization of design, packaging and preparation of product family specification and subsequent commercialization (2011)
- ***Generation 2:*** ***35KV Class Distribution Switchgear Development*** (Basic Features and Requirements include: Act as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker, and transfer switch)
  - **Phase I**: Bench model development and testing of 35KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, current limiter, DG isolation switch, capacitor switch, tie breaker, and transfer switch (2012)
  - **Phase II**: Field prototype development, deployment, field testing and debugging (2013-2014)
  - **Phase III**: Finalization of design, packaging and preparation of product family specification and subsequent commercialization (2014)

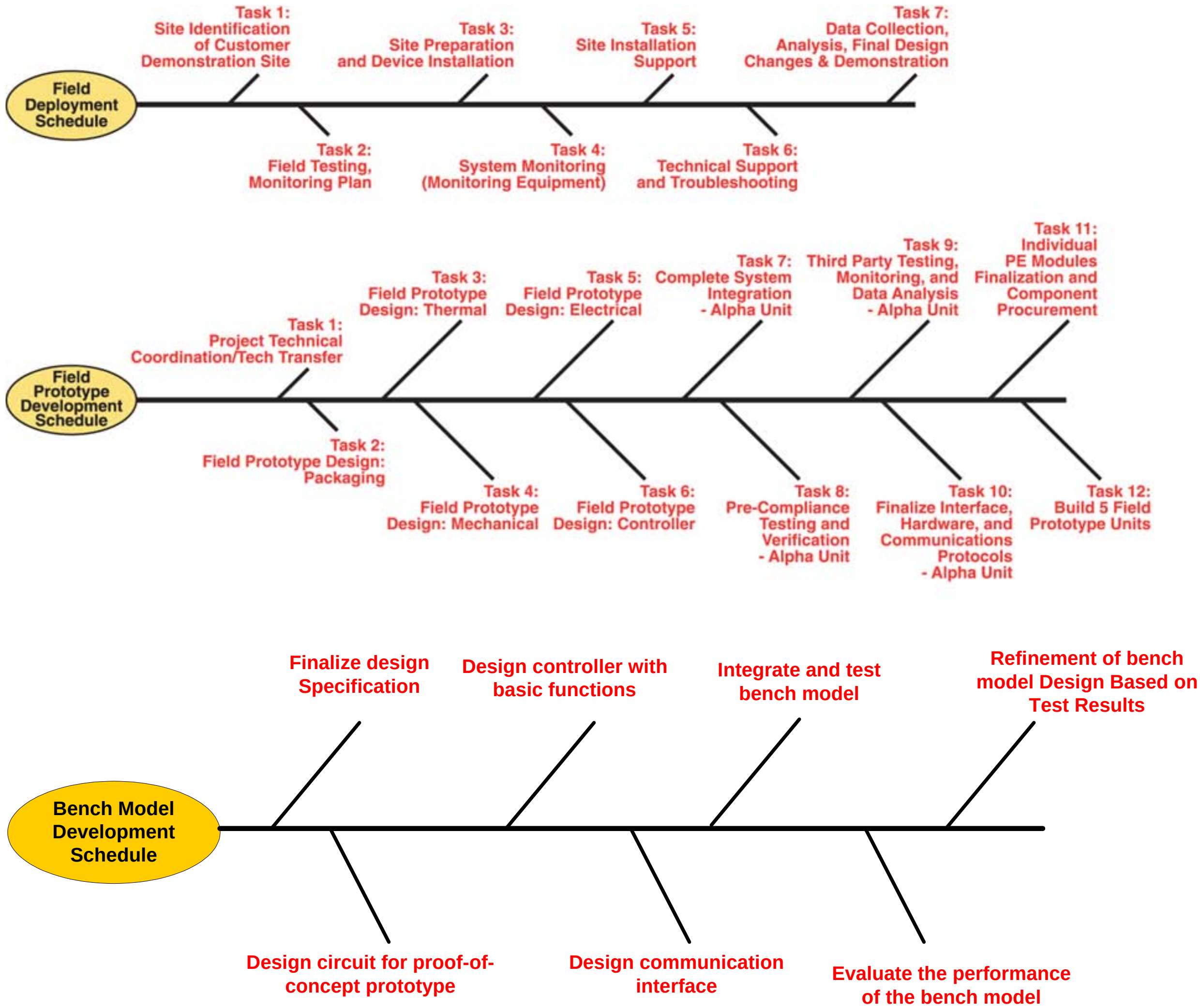

Figure 6-8
Projections of Possible Phases and Individual Tasks for Design and Development (2007–2011)

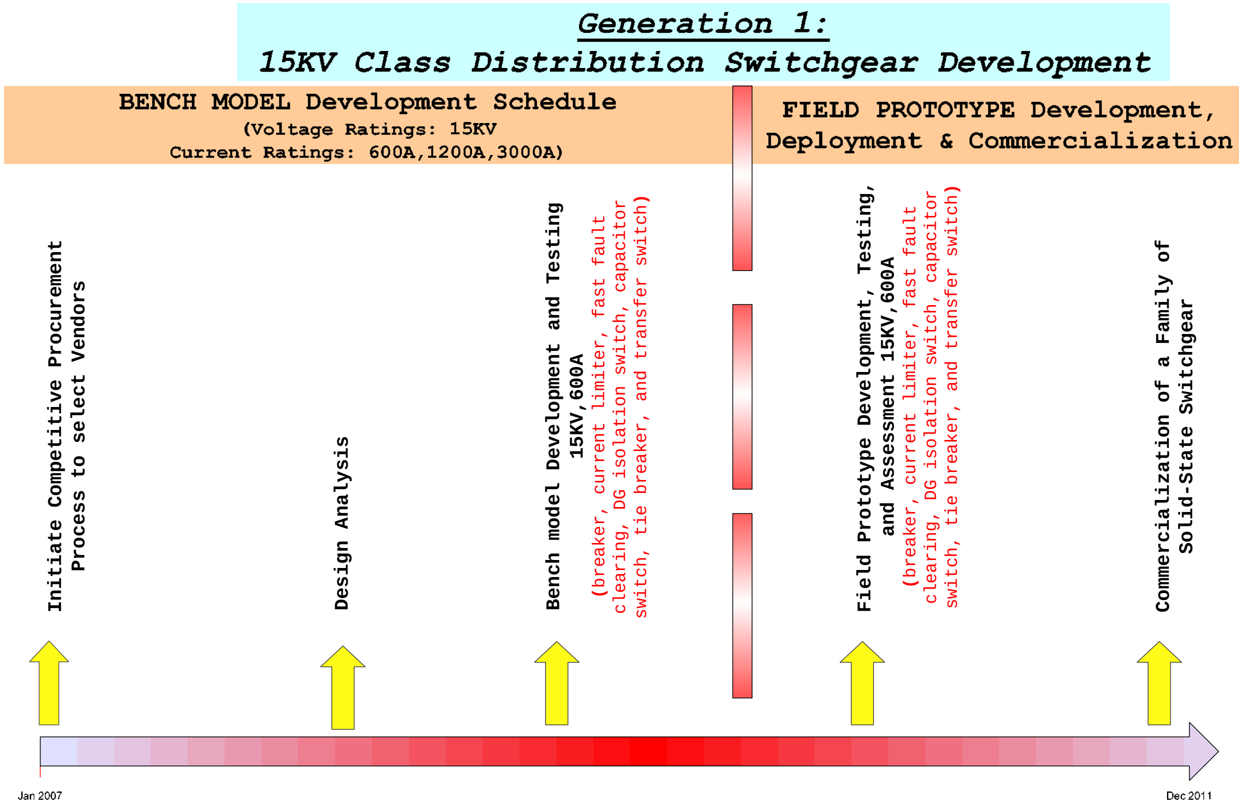

Figure 6-9
EPRI's Long-Term Roadmap for the Proposed First Generation Distribution Voltage Solid-State Switchgear – Development Schedules and Important Milestones

Generation 1: 15KV Class Distribution Switchgear Development

Phase I: Proof of Concept Design Analysis of family of Switchgear Topologies (Voltage Ratings: 15KV& Current Ratings: 600A, 1200A, 3000A)–Year of Performance: 2007

The first phase of the research should include a comprehensive design analysis to verify the functionality that can be achieved with the conceptual design and estimation of efficiency, cost and reliability of such a proposed design. This is the most critical stage since the commitment to a certain design topology will ultimately lead to hardware and controller development and lab prototype. Critical issues that should be addressed during the design analysis include:

- Selection of the circuit topology for designs with can be used as a switchgear that can be used as a breaker, current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker;
- Selection of the circuit topology for designs with can be used as a switchgear that can be used as a transfer switch;
- Selection of active devices and passive components and calculation for semiconductor device voltage and current ratings;

- Simulation of the performance using industry accepted design packages for power electronics design analysis;
- Estimation of the cost of the proposed system based on existing component costs and estimated component cost for different degrees of market penetration;
- Determination of design packaging and thermal management systems.
- Evaluation of the design with respect to its ability to meet the different desired functionalities that are addressed in the generic functional specification

Phase II: Bench model Development and Testing of 15KV 1200A Distribution Switchgear
Year of Performance: 2007-2008

The second phase of the research will proceed after selection of the preferred design topology and semiconductor device based on Phase I design analysis. The Phase II research will lead to development of the hardware, controller and packaging of a laboratory prototype (Bench model) of 15KV 1200A distribution switchgear using either "all solid-state" OR "hybrid" technology which can be used as a breaker, a current limiter, fast fault clearing, DG isolation switch, capacitor switch, tie breaker and transfer switch. It is suggested that the first generation of the bench model be based on 15-kV system so that the existing device can be used and high-voltage experience can be gained. The successful rate of concept proofing is much higher. Once the switchgear is fully designed and proven to be working, the high-voltage SiC device or an HV-IGBT or an HV- Super-GTO can be used to move the voltage level higher. The bench model serves a number of purposes, including determining that the product will work. The prototype also serves to highlight design flaws and defects that need to be resolved. Key research tasks that should be accomplished during this phase include:

- ***Design circuit for proof-of-concept laboratory bench model (2007)***

  The complete switchgear including devices, active and passive components, heat sink, sensors, and bus bar should be designed and packaged for laboratory demonstration. Gate drivers and auxiliary power supplies need to be designed with proper isolation and minimum noise susceptibility. It is desirable to have the device protection at the gate-drive level to ensure highly reliable operation. Voltage and current and heat sink temperature should be monitored for both control and protection purposes.

- ***Design controller with basic functions (2007-2008)***

  The controller will likely be designed with a digital signal processor (DSP) for digital control. Hardware should include sufficient PWM and analog-to-digital (A/D) and digital-to-analog (D/A) channels. The interface from PWM channels to the gate drivers would preferably be isolated by optical fibers. Software should be designed to perform basic control functions such as voltage balance and power transfer.

- ***Design communication interface (2007-2008)***

  The bench model shall be designed for easy mapping to open architecture communication standards for distribution switchgear, when they become available in the IEC 61850 series. It is not known at this time when those IEC standards will be written. However, the product development shall include a communication interface with a non-proprietary object model for the device, which can be provided to IEC to aid in development of a standard

- ***Integrate and test the laboratory bench model (2007-2008)***

  The entire power circuit and controller should be integrated for laboratory testing. Hydro-Québec built a distribution test feeder (see Figure 4-8) to test equipment, control cabinet, software for advanced distribution system which could be used for the purpose of laboratory testing.

- ***Evaluate the performance of the proof-of-concept bench model (2008)***

  The performance such as load current interruption, fault current limiting capabilities, ability to clear fault instantaneously, operation as a tie breaker, provide DG isolation, ability to provide soft start capability, ability to reduce switching surges, system efficiency over entire power range, heat sink temperature, total harmonic distortion (THD) of voltage and current, power factor, and so forth need to be evaluated.

- ***Refinement of Design Based on Test Results (2008)***

  Based on initial test results the prototype design should be modified and retested in order to verify the performance of the proof-of-concept prototype. The results from the lab testing should be compared with Phase I design analysis results and any discrepancies should be accounted for before moving to the next stage of field demonstration.

Figure 6-10
Distribution Test Feeder at Hydro Quebec

Phase III & IV: Field prototype development and testing of 15KV 1200A distribution switchgear

Year of Performance: 2009-2010

The fourth phase of the research will lead to development of 15KV, 1200A field demonstration unit to obtain real life field experience and verification of the performance. The field demonstration units need to be designed and packaged to address the entire range of environmental and operational scenarios that may be encountered in a distribution system. Refinement of the lab prototype should address these operational and environmental issues before developing field prototypes. Utility demonstration sites will be selected and identified through competitive bids. Field demonstration prototype will be built and delivered to the selected demonstration sites for field-testing. Hydro-Québec built a distribution test feeder (see Figure 6-10) to test equipment, control cabinet, software for advanced distribution system which could be used for the purpose of laboratory field testing.

The basic performance such as load current interruption, fault current limiting capabilities, ability to clear fault instantaneously, operation as a tie breaker, provide DG isolation, ability to provide soft start capability, ability to reduce switching surges, operation as transfer switch, system efficiency over entire power range, heat sink temperature, total harmonic distortion (THD) of voltage and current, power factor, and so forth need to be evaluated. Reliability and performance information will be recorded during the demonstration period for product improvement. Key issues that need to be addressed during this stage of the development effort include:

- ***Package the power circuit and component. (2009)***
- ***Design controller with advanced functions (2009)***
- ***Design communication interface (2009-2010)***
- ***Integrate and test the field demonstration prototype (2009-2010)***
- ***Demonstrate and test in selected sites (2009-2010)***

Phase V: Commercialization of a Family of Solid-State Switchgear

Year of Performance: 2011

The final phase is technology commercialization. EPRI will work with the developer, manufacturer, and utilities for large-quantity manufacturing and commercialization. Development of a commercialization plan will be the initial step in this phase. The commercialization plan will address the strategies for transferring this technology to the marketplace and development of a business plan centered on specific application areas. The commercialization plan will also identify the important characteristics required for successful commercialization. For example, the commercialization plan will identify essential manufacturing capabilities required to build the transformer and optimal channels to market and distribution strategies. It is anticipated that the initial phases of the research will be conducted by EPRI with cost sharing from organizations involved in the development of the hardware and field demonstration units. These organizations will also play a key role with EPRI and member utilities in identifying the best strategy for commercialization of the family of solid-state switchgears that are capable of interrupting load or fault currents in critical load applications or be applied as a transfer switch, tie breaker, or fault current interrupter.

Design Review

The intent here is not to make recommendations for a specific design or a specific semiconductor device. The question is, "Is there a possibility that other designs may evolve that might meet the need"? This decision will have to be made by the manufactures to come up with other innovative designs that will meet the specification or through a competitive procurement process to select a vendor/developer/partner.

Based on the preliminary results and on-going research in these areas, "***all solid-state***" based switchgear designs as well as "***hybrid***" designs have the potential to offer a myriad of advantages that prospective purchasers may find attractive and may make them successful in the marketplace. It was emphasized that EPRI should consider both "all solid state" as well as "hybrid" bids and that if a hybrid bid is made, the path to all solid state in the long run must be shown by the bidder. These designs will guide the development of the smart solid-state switchgear. The contractor shall:

- Develop a generic design that includes equipment options and a plan or strategy to meet the range of voltage and power levels delineated herein.
- Conduct up to three design review meetings at the EPRI's facilities at Palo Alto, CA.
- Prepare and submit a report, accompanied by drawings and cost estimates, describing the generic design and options

Requirements for Test Site

The Contractor shall:

- Work with the EPRI to determine the relevant characteristics of the host site.
- Develop a final design, fabricate, assemble, test, ship, install at the designated site, start up and perform the acceptance testing of fully functional turnkey solid-state switchgear that meets the requirements delineated herein and the particular requirements of the host's installation.

The Contractor shall also design, supply, install and test:

- Power ac wiring in conduit between the switchgear terminals and the host's site incoming ac and critical loads.
- Connection to the grounding system at the host's site.
- Communications links to the host's control system, protective relaying and similar equipment.
- The Contractor shall review specifications and design drawings for the host's equipment, and ensure compatibility with the Contractor's design.

Installation support

The Contractor shall:

- Obtain all permits necessary to install or construct the unit at the host's site
- Provide a training class for host's engineers, technicians and/or maintenance personnel at the Host's site.
- Supply any special equipment and tools required for maintenance
- Supply an initial complement of spare parts
- Provide a warranty for the entire switch and its constituent equipment.
- Submit documents, drawings, reports, data and other submittals, as required herein.

Submittals To EPRI

The following items shall be submitted to EPRI of the solid-state switchgear:

- A schedule showing the chronology of major activities required to design, fabricate, assemble, test, ship, install and start up the first unit. The schedule shall use a bar chart, critical path diagram or similar methods to show the relationship among the required activities, and their start and completion dates. Major milestones shall be listed in a table. The Contractor shall develop a submittal schedule for documents that require EPRI as well as host's approval before permission to proceed is granted. The documents and drawings shall, as a minimum, include those listed below:
  - Schematic diagrams and operational write-up
  - Electrical single line, protective relaying diagrams and equipment grounding drawings
  - Control logic diagrams
- Progress Reports shall be submitted by the fifth working day of each month. These reports should be concise letter reports of 1 to 2 pages and shall include schedule updates, illustrating the baseline and current status for the project activities. Also, they shall include the status of sub-tier contractor activities and construction progress photographs. The reports shall briefly describe project activities during the previous month, milestones attained and activities planned for the next reporting period. The reports also shall include details of problems encountered and the solutions applied. EPRI reserves the right to verify contents of the Progress Reports through visits to Contractor facilities or sub-tier contractor facilities with or without prior notice.
- Certified factory test reports on equipment qualification tests.
- Detailed testing and acceptance testing plan for review and approval two months prior to startup.
- A Final Report with startup data and documentation of the Acceptance Testing
- An Operation and Maintenance (O&M) manual for the solid-state switch and its component parts. An initial review copy shall be provided two months prior to startup. Four copies of the final O&M manual shall be provided within one month of acceptance of the unit by EPRI.

- Final design including any field changes made during installation/construction, startup or acceptance testing.

All submittals shall be clean, legible and be submitted with document or drawing numbers, checker signature, approval signature, date, revision number and brief description of changes since the previous revision.

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A

EXAMPLE OF A PROSPECTIVE HYBRID SWITCH DESIGN

A “hybrid” mechanical/electronics based approach was proposed in the EPRI report, *EPRI Family of Multi-Functional Low Cost Solid State Switchgear: Requirements Definition Phase* (EPRI, Palo Alto, CA: 2006 TR1010666), for the first generation solid-state switchgear designs to limit the on-state losses and to minimize the cooling requirements of the semiconductor switches. Since a closed mechanical contact still exhibits the least amount of conduction losses amongst all “switching” elements in some designs an ultra-fast mechanical contacts can be utilized for carrying the regular continuous operating current and solid-state switch for fault clearing and current limiting. The use of a hybrid approach allows the semiconductor junction to operate from a lower starting temperature and allows the interruption of higher fault currents than a completely solid state unit. The solid-state switch works in transient fault condition and is controlled with pulse-width modulation to limit the fault current. A fast mechanical works in steady state to allow low-loss operation and to avoid unreliable bulky and thermal management system.

Operating under Steady-State Conduction Mode

A fast-action mechanical switch is turned on in steady state to bypass the current and to avoid overheating the solid-state switch, which tends to have higher loss and higher associated heat generation. When a fault current is detected, the mechanical switch can be quickly turned off, and the current can be transferred to the solid-state switch for fault current limiting and clearing operations.

Operating under Fault Limiting Conditions

Figure A-1 shows the circuit diagram and basic operation waveform of the proposed universal hybrid switch (PHS) under fault current limiting condition. The switch consists of a fast mechanical switch S_m and a solid-state switch S_{ss}. The solid-state switch S_{ss} consists of a diode bridge and a PWM controlled IGBT or other gate-turn-off device to form a bidirectional switch. When the fault occurs, S_m is turned off, and S_{ss} is turned on to allow current flowing through the bidirectional switch. This fault current magnitude can be controlled by the PWM switching.

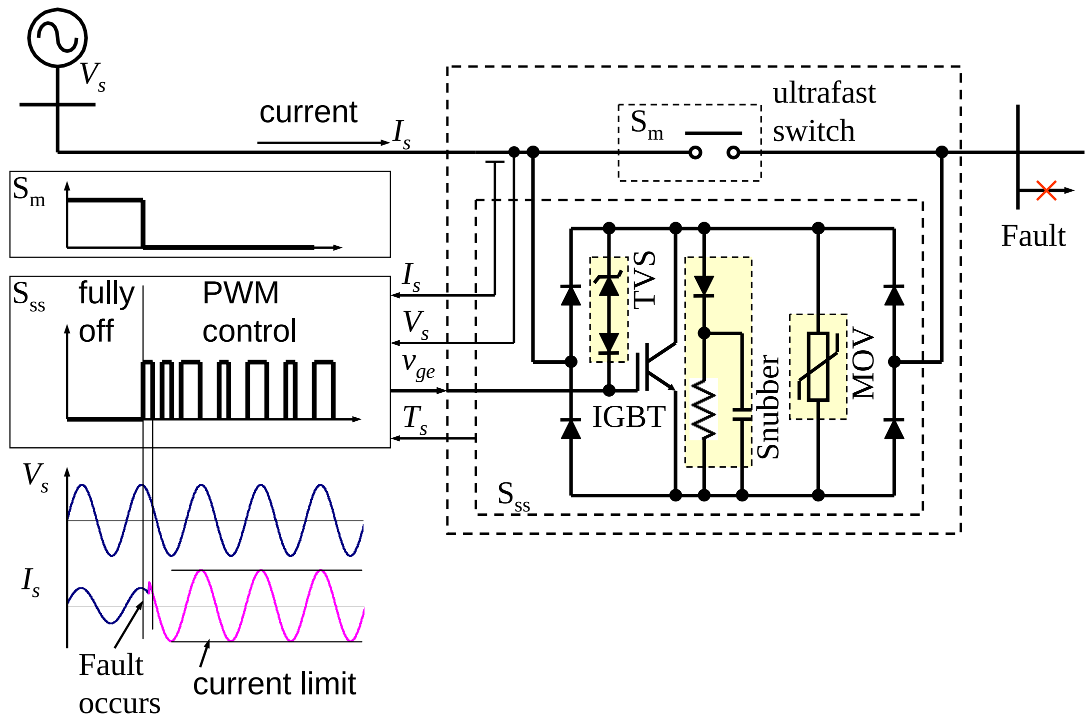

Figure A-1
Circuit Diagram and Basic Operation Waveform of the Prospective Hybrid Switch

The proposed switch has current and voltage sensors, I_s and V_s, that can also serve as the monitoring purpose. A temperature sensor T_s is also fed back to the controller for device protection. The gate-drive circuit has a transient-voltage suppressor (TVS) to allow gate triggered under over-voltage condition to protect the device from instantaneous over-voltage failure. A metal-oxide-varistor (MOV) is also added to absorb transient over voltage coming from the system. When the switch is operating in PWM condition, the snubber circuit serves as the energy buffer that allows current magnitude to be regulated.

Operating under Fault Clearing Mode

The fault clearing mode can be controlled by simply turning off the switch without PWM operation. Figure A-2 shows the PHS associated waveform under fault clearing mode operation. When the fault occurs, the mechanical switch S_m turns off, and the solid-state switch S_{ss} turns on to avoid the arc. Once the current is flowing in S_{ss}, then it can be turned off any time to clear the fault. Similar operating procedure can also be applied to static transfer switch operation. In that case, two PHS's are needed.

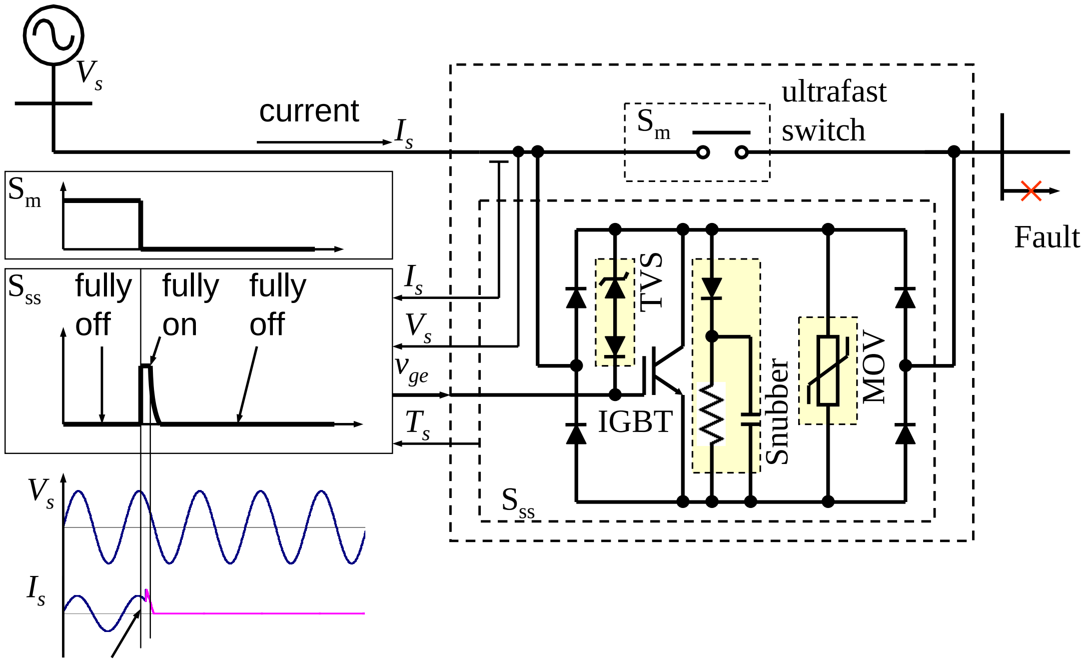

Figure A-2
Prospective Hybrid Switch: Operating Under Fault Clearing Mode

Operating under Linear Region

The fault current limiting mode can also be controlled by operating the device in linear region without PWM operation. The operation is simply to reduce the gate drive voltage so that the device goes into high impedance mode. Figure A-3 shows the waveform associated with linear mode current limiting operation. In this case, a large amount of power needs to be consumed in the device, and the temperature can shoot high very quickly. Thus this mode of operation is not recommended for a long-term current limiting condition. It would require the temperature feedback to ensure device junction temperature stays below the limit.

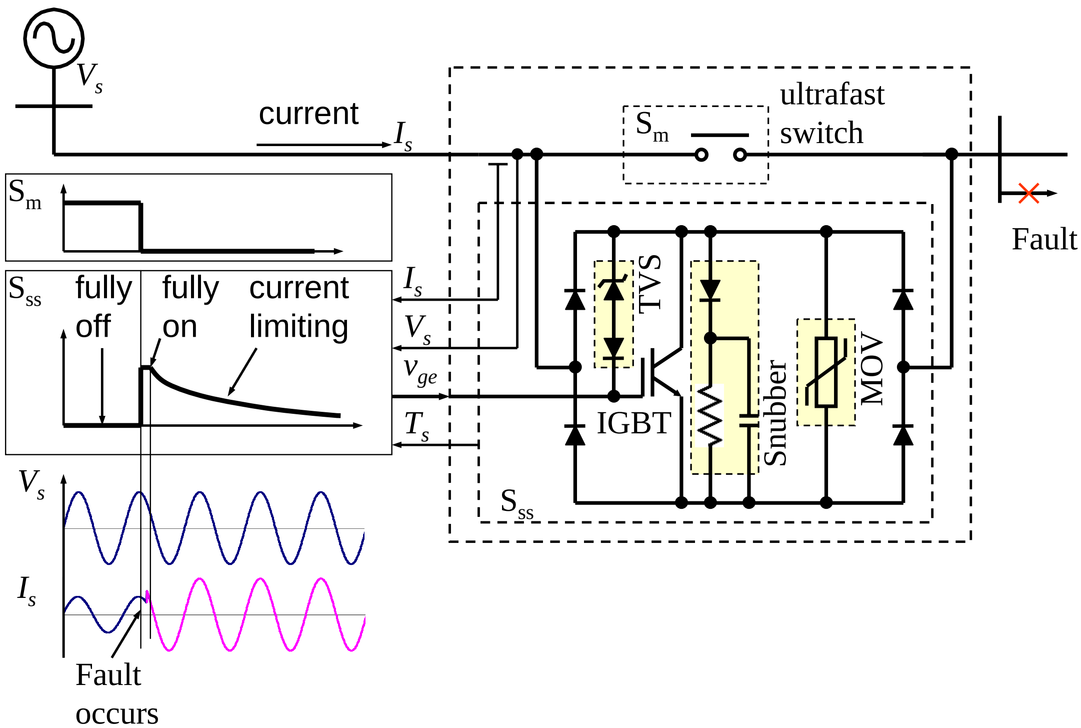

Figure A-3:
Prospective Hybrid Switch: Operating Under Linear Region for Fault Current Limiting

Note that the linear region operation cannot be achieved with all thyristor devices because they are the latch-on devices. However, the GTO and GTO (ETO, Super-GTO) derives devices can all be used in PWM operation with a lower switching frequency. Figure A-4 shows the circuit diagram and associated PWM waveform using GTO or GTO-derived devices for current limiting operation. The use of GTO does not have over-voltage protection function provided by the gate drive circuit, but the same function can be performed with MOV. The voltage snubber is needed for the energy buffer as well as the dv/dt protection. The current snubber function may be obtained by the line inductance.

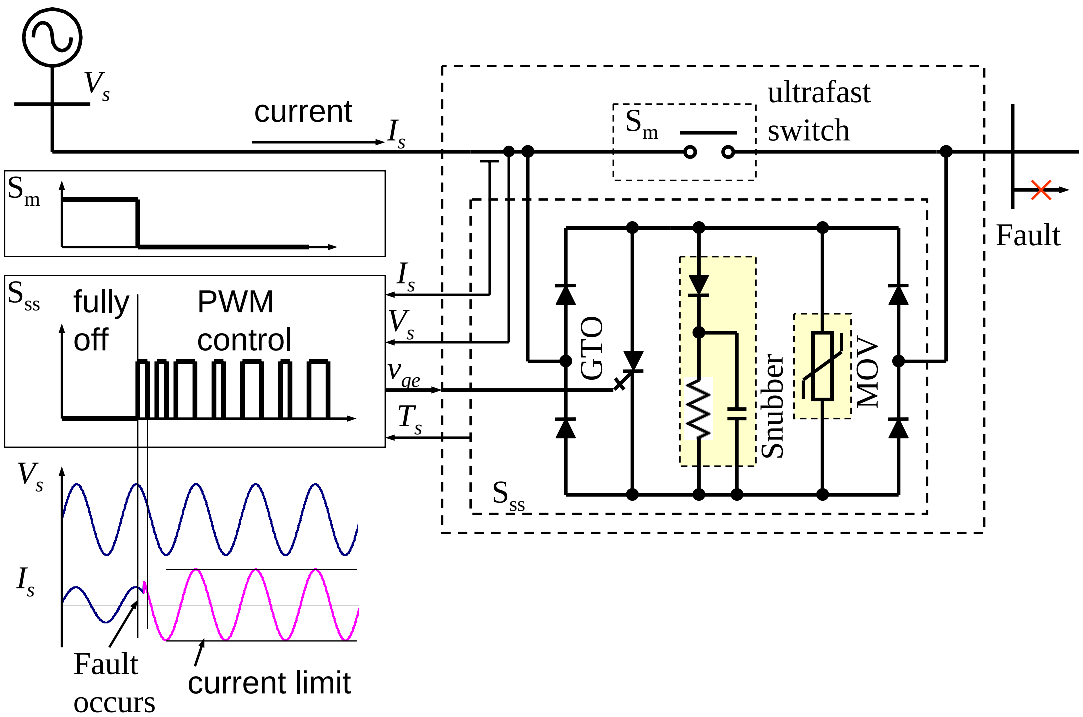

Figure A-4:
Prospective Hybrid Switch: Adopting GTO or GTO-Derived Device as the Switching Device for PWM Operation

Justification

This design is useful in a family of low-cost solid-state distribution switchgear that can expand the capabilities of existing distribution switchgears to a modular "integrated electrical interface" and create new service opportunities to meet the customers' requirement. The disclosed approach is a multi-functional, modular, hybrid design of power electronics based switchgear which will offer important advantages during design, testing, manufacturing and service stages namely:

- Design is simplified because within the module one is dealing with comparatively low voltages
- Testing is also simplified because of the reduced voltage level.
- The same modules can be applied to many different voltage ratings and applications
- One can use the same modules for different voltage breakers by stacking the appropriate number of modules depending on the voltage level of the breaker. This way we reap the benefits of mass production even further by:
- Having the same building block for different voltage breakers, thus simplifying manufacturing, testing and repair costs.

The prospective design has many features that are significantly different from conventional electromechanical circuit breakers, and will have a profound impact on present practices in distribution systems. A non-limiting list of enhancements over a conventional mechanical breaker includes: (1) current limiting of high magnitude fault currents, (2) faster clearing, (3) reduced maintenance, (4) reduced switching surges, and (5) high-speed load transfers. This design provides one or more improvements over the prior art.

Although the requirements for fault clearing, recloser, transfer switch, and current liming are different, the most difficult task is to turn the device off without going through zero crossing. Thus the first design criterion for a universally used switch is to be able to interrupt the current any time. In this case the gate controlled device is the best choice. For the cost and reliability concerns, the circuit must be as simple as possible to avoid excessive bulky passive components. In this case the pure silicon controlled rectifiers (SCR) based switch needs to be excluded. Even though SCR can be force-turned off by external commutation circuits for fault current limiting, the added components are simply not justifiable. Unfortunately all gate-controlled switches have high voltage drop that significantly degrades the efficiency. Thus the proposed switch is a hybrid version that utilizes fast mechanical switch for regular conducting and gate-controlled switch for fault clearing and current limiting.

Advantages of this design include:

- Sub-cycle operation
- Long Breaker cost life and Reduced Maintenance Costs
- SF6, is not required
- Lower Losses
- Less Expensive than "All solid-state" designs
- Cooling not required
- Reduced Switching Transients
- Current Limiting Capabilities

The next section provides the overall economic assessment for the prospective ***hybrid switchgear design***. Preliminary production cost and benefit analysis are based on existing and estimated component costs. Cost estimates are derived for two separate ratings 1) 15KV class 600A and 2) 35KV 1200A. Complete listing of all the parts and its individual costs are also provided.

Economic Assessment – An Overall Comparison

The prospective hybrid switch (PHS) can be implemented with any gate-controlled high-voltage devices. Since the efficiency relies on the mechanical switch, the selected device simply needs the ease of the controllability and high interrupting current capability. The IGBT is thus chosen for the first cut cost estimate. The cost difference with the use of other types of device should not be significant.

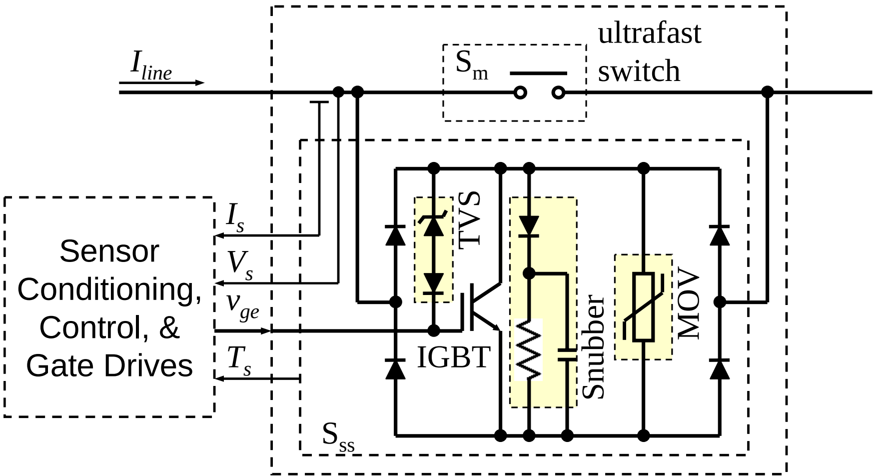

Figure A-5:
Circuit Configuration of the Prospective Hybrid Switch

To start with, a 15kV, 600A hybrid universal switch is used as the example for the estimation of system cost. In order to have 600A continuous and 12.5kA short-circuit current rating, we need two of 5SNA0600G650100, or other 6.5kV, 600A IGBTs. The BIL rating can be achieved with the selection of MOV or arrester. With 15kV line-to-line, the phase-to-neutral is 8.66kV or 12.2kV peak. By designing with twice voltage margin, we need four devices in series to give 26kV total voltage rating. Thus total number of devices per phase is 8. Figure A-6 shows the circuit configuration of the 15kV, 600A HV-IGBT based PHS that requires 4 solid-state switches in series, $S_{ss1} – S_{ss4}$.

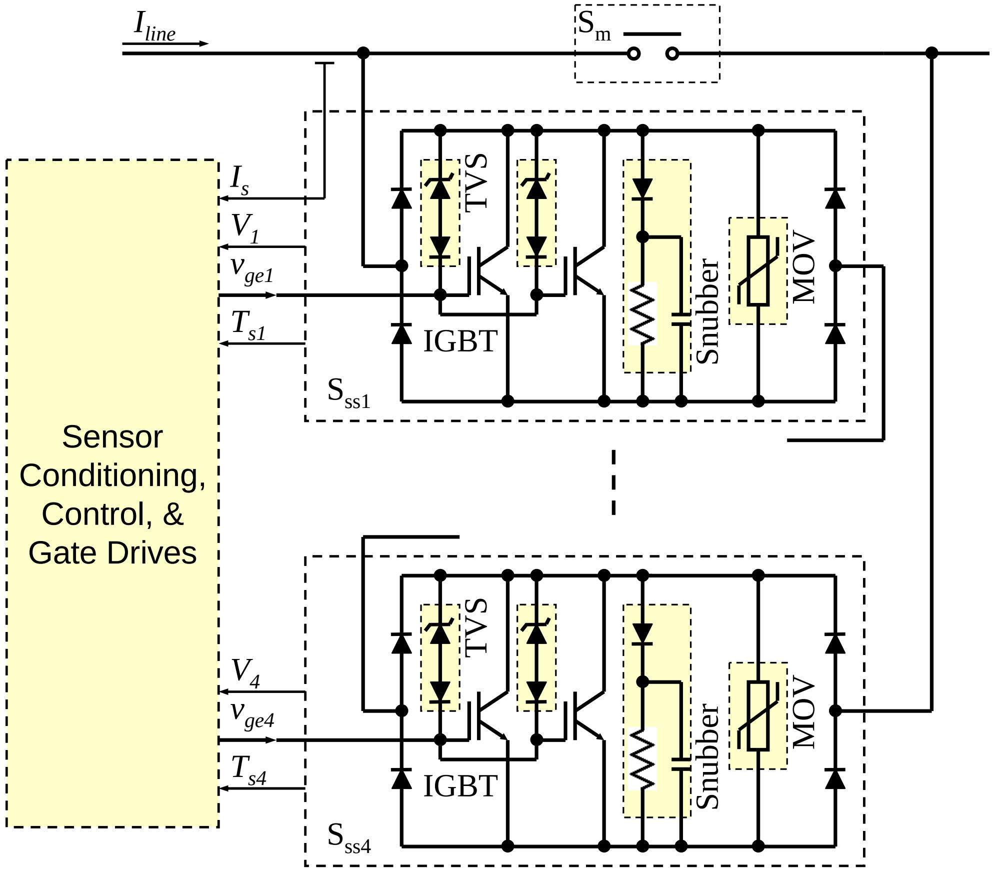

Figure A-6:
Circuit Configuration of the 15kV, 600A HV-IGBT Based Universal Hybrid Switch.

For 35kV, 1200A hybrid universal switch, the desired current rating needs 4 devices in parallel, and the desired voltage blocking needs 9 in series. Thus the total number of devices per phase is 36.

Based on a small quantity purchase, the production cost of the above two designs can be estimated as shown in Table A-1. The estimated cost of the 15KV, 600A design is approximately 7 times higher than a conventional recloser/circuit breaker of similar rating.

Table A-1
Estimates of Small-Quantity Production Cost for the Hybrid Universal Switch

	15kV, 600A PHS			35kV, 1200A PHS		
Component per Phase	qty	unit price	ext. price	qty	unit price	ext price
Solid-State Switch						
IGBTs	8	$ 1,500	$ 12,000	36	$ 1,250	$ 45,000
Rectifier Diodes	16	$ 200	$ 3,200	72	$ 200	$ 14,400
Transient Voltage Suppressor	4	$ 200	$ 800	9	$ 200	$ 1,800
Snubber Circuit	4	$ 250	$ 1,000	9	$ 250	$ 2,250
MOV	4	$ 200	$ 800	9	$ 200	$ 1,800
Heat Sink and Cooling	4	$ 350	$ 1,400	9	$ 350	$ 3,150
Voltage Sensors	4	$ 1,000	$ 4,000	9	$ 1,000	$ 9,000
Current Sensor	1	$ 400	$ 400	1	$ 400	$ 400
Gate Drives	8	$ 150	$ 1,200	36	$ 150	$ 5,400
Auxiliary Power Supplies	8	$ 100	$ 800	36	$ 100	$ 3,600
DSP Controller	1	$ 400	$ 400	1	$ 1,000	$ 1,000
Conditioning Circuit	1	$ 200	$ 200	1	$ 500	$ 500
I/O Interface	1	$ 200	$ 200	1	$ 500	$ 500
Mechanical and Assembly	1	$ 1,500	$ 1,500	1	$ 4,500	$ 4,500
Subtotal			$ 27,900			$ 93,300
Mechanical Switch						
Switch	1	$ 7,500	$ 7,500	1	$ 23,500	$ 23,500
Bushing	2	$ 400	$ 800	2	$ 1,400	$ 2,800
Bus and Wiring	1	$ 400	$ 400	1	$ 1,000	$ 1,000
Subtotal			$ 8,700			$ 27,300
Others						
Housing	1	$ 5,000	$ 5,000	1	$ 12,500	$ 12,500
Design Engineering	1	$ 5,000	$ 5,000	1	$ 12,000	$ 12,000
Installation and Testing	1	$ 5,000	$ 5,000	1	$ 15,000	$ 15,000
Subtotal			$ 15,000			$ 39,500
Total per Phase			$ 51,600			$ 160,100
Total per Three-Phase			$ 154,800			$ 480,300

The cost for the solid-state switch portion is more than 50% of the entire PHS. However, this percentage will come down in large quantity production. Also it can be seen that the cost of IGBT is about 25% of the entire PHS. Even if other lower cost gate-turn-off devices are used, the entire system cost may not see a noticeable difference. There are some other non-production related costs such as initial design and engineering, tooling, overhead, and inventory, etc.

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