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Advanced Power Electronics Controllers for Substations

Challenges and Solutions

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PRODUCT DESCRIPTION

Substations located at various points in the power delivery system serve several purposes. In a broad sense, power substations are installations capable of interrupting or establishing electric circuits and changing the voltage level, frequency, or other characteristic of the electric energy flow. Solid-state power electronic switching devices are continuing to evolve and multi-megawatt solid-state power control systems are becoming increasingly applied in industrial electrical installations. Both have a potential to play an enabling role in meeting the technical demands of future substations. Various demonstration projects under EPRI's FACTS and Custom Power programs have established the effectiveness of power electronics in improving the performance of transmission and distributions systems. The application of power electronics to improve the functionality of classical substation equipment is the focus of this project.

Results and Findings

The project explored the potential of several different power electronics devices for substation applications and identified the electronic clutch, a device to mitigate capacitor switching transient problems, as especially worthy of further development. The project conducted computer simulations and laboratory investigations to demonstrate the feasibility of the electronic clutch.

Challenges and Objectives

The project described in this technical report will be of interest to transmission and distribution system planners who are responsible for substation design and substation maintenance personnel in transmission and distribution businesses who are responsible for solving problems arising from capacitor switching transients.

Applications, Values, and Use

As demonstrated using computer simulations and experimental investigations, a power electronics device for mitigating problems arising from capacitor switching transients is ready for further commercial development and field testing. Solutions to substation problems based on power electronics will lead to reduced maintenance costs and deferred replacement costs for substation equipment.

EPRI Perspective

EPRI is well placed to develop advanced concepts in power electronics. For this project, EPRI brought together academic researchers, an advisory task force from the electric utilities, and electrical/electronic equipment vendors who will commercialize the technology as the results evolve to meet the demands of the marketplace.

Approach

The Technical Update published in December 2006 (EPRI report 1012367) reviewed challenges facing substation equipment and identified developments in power electronics devices with the potential to meet these challenges. The Technical Update published in December 2007 (EPRI report 1013923) presented the results from a functional mapping and validation study of two promising power electronic devices. This current update summarizes the work from the complete period and also describes detailed computer simulations and experimental validation of the electronic clutch as a solution for mitigating capacitor-switching transients in substations and distribution systems.

In the introductory chapter, the report reviews various challenges facing substation equipment while identifying various developments in power electronics devices. Chapter 2 reviews power circuit switching and describes the characteristics of mechanical-contact switching and solid state switching technologies, along with an outline of different ways of interconnecting in an ac system environment. Chapter 3 discusses the more significant problems facing substation equipment and presents solid state switching controller configurations for solving these problems. It also identifies selected solutions for the functional mapping and validation study, which include an Electronic Power Balancer to assist parallel operation of transformers in substations enabling capacity expansion and an Electronic Clutch to mitigate capacitor switching transients. Chapter 4 presents various options for realizing the Active Power Balancer for capacity addition of transformers as a consequence of load growth. Chapter 5 discusses the options for realizing the Electronic Clutch and presents computer simulations and experimental investigations. Chapter 6 and 7 provide a brief summary of the results along with recommendations for continuing work.

Keywords

Substations
Power electronics
Capacitor switching
Parallel operation of transformers
Capacity expansion

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1
INTRODUCTION

Continuing developments in solid-state power electronic switching devices are enabling enormous efficiency improvements in the electrical energy utilization sector. Multi-megawatt solid-state power control systems are becoming increasing applied in critical industrial electrical installations. Industrial demands for improved performance and energy productivity, coupled with customized high volume production, favorable scales of economy and increasing technical maturity of power converters are resulting in reduced costs approaching a few cents per watt in selected applications. Furthermore, the emergence of Silicon Carbide as a viable switching power semiconductor material, and advances in Diamond are promising higher voltage and higher temperature solid switches to push the technology envelope further towards higher power applications.

In the electric utility sector, pilot field demonstration projects under the rubric of Flexible AC Transmission Systems (FACTS) and Custom Power have established their effectiveness in improving the power delivery infrastructure, although their deployment have been modest. While FACTS devices are devoted to the improvement of the transmission system, Custom Power devices focus on the distribution system. In this project, power electronics opportunities for the improvement of functionality within power substations are investigated, with a particular focus on future challenges and solutions.

Power substations are situated at various locations within the power delivery system and are used for several purposes. In a broad sense, power substations are all installations capable of interrupting or establishing electric circuits and changing the voltage level, frequency, or other characteristic of the electric energy flow.

Substation Functions

Substations are designed to accomplish the following functions, although not all substations may operate to realize all these functions:

- Switch transmission and distribution lines into and out of the power network
- Connect electric generation plants into and out of the power network
- Transform the voltage from one level to another
- Regulate voltage to compensate for load variations and system voltage changes
- Reactive power compensation
- Frequency change: ac↔dc and ac↔ac

- Protect the system against overvoltages arising from lightning and other electrical surges
- Measure electric power quantities: Voltage, current, phase angle, power, frequency
- Perform relaying functions to protect equipment and prevent local faults from propagating throughout the system

Substation Equipment

The most common types of equipments found in substations are:

- Busbars
- Circuit Breakers/ Relays
- Disconnectors
- Fuses
- Power Transformers
- Regulating Transformers: Phase Shifters, Tap Changers
- Reactors
- Capacitors
- Advance compensation equipment
- Rectifiers/Inverters
- Lighting Arresters
- Potential Transformers
- Current Transformers
- Protective relaying systems
- Substation automation and communication equipment
- Grounding systems

Type of Substations

Substations have traditionally been classified according to different criteria. The most common practice is to identify generation substations, transmission substations and distribution substations. Alternatively, they may also be classified as set-up and step-down substations, depending on the voltage levels and the direction of the power flow. In addition, some are referred as compensation substations if the only purpose is to interconnect capacitors, reactors or advanced compensators into the power grid. Although it is still possible to find substations that may fit a specific type, these groupings are increasingly becoming obsolete as substations are now serving multiple purposes simultaneously. Figure 1-1 shows what may be called a generic substation containing all functions described above. A real substation would most likely contain a subset of these functions. As can be seen in the figure, a substation with a double-breaker double-bus scheme has been selected as an example. This corresponds to one of the standard bus schemes used in the industry. The block termed “Transmission Lines” corresponds to the most basic function a substation can provide, which is the switching of transmission lines into and out of the power network. The block termed “Transformers” accounts for the substations that transform the voltage level from transmission lines coming in and out of the substation. Also, large loads may be connected to the low voltage side of the transformers. The block named “Generation” accounts for the necessary interface in order to connect large power plants as well as small scale generators into the grid. The block termed “Standard Compensation” represents the traditional approach for providing reactive compensation to power networks by means of shunt/series capacitors and reactors. Finally, the block named “Advanced Functions” accounts for all modern solutions used to improve the operation and flexibility of the power delivery systems. Here is where the power electronics community has put most of the effort and extensive family of solid state devices has been developed, although a small number of them have actually been implemented as a commercial product. While most of these devices focus on the improvement of the transmission and distribution systems, they do account for improvements of the substation operation itself. The intent of this report is then to fill this gap by identifying the challenges and power electronics based solutions for the blocks termed “Transmission Lines”, “Transformers”, “Generation” and “Standard Compensation”, which leads to improvements at the substation.

Substation Challenges

After a pertinent literature review, the major challenges concerning substations that have been identified are as follows:

Life extension of existing facilities: Transformers and circuit breaker are critical equipment sensitive to demand growth. The consequences of demand growth are two fold (i) as the load increases, so does the steady state power (current) flow through circuit breakers and transformers and (ii) as a result of a bigger demand, new generating facilities are added into the network which almost unequivocally increases the level of short circuit current, with obvious consequences for circuit breakers and transformers. Life extension of these apparatus with the aid of power electronics devices is largely discussed throughout this report. Arc quenching in tap changers is another major issue in regard with the life extension of substations assets. EPRI has initiated a separated effort on this matter under the title “Transformer Life Extension” (P37.002) that focuses on this topic.

Mitigation of voltage fluctuation produced by nonlinear loads and varying generation sources: Nonlinear loads such as arc furnaces and electric welders and varying generation sources such as engine-driven generators and wind turbines produce voltage fluctuation at the nearby substation busbar which translates into power quality problems for other loads connected to the same substation. One of the most negative effects is the resulting light flicker. Current power electronics solutions that have successfully been used to address flicker problems along the latest research on this topic are evaluated in this report.

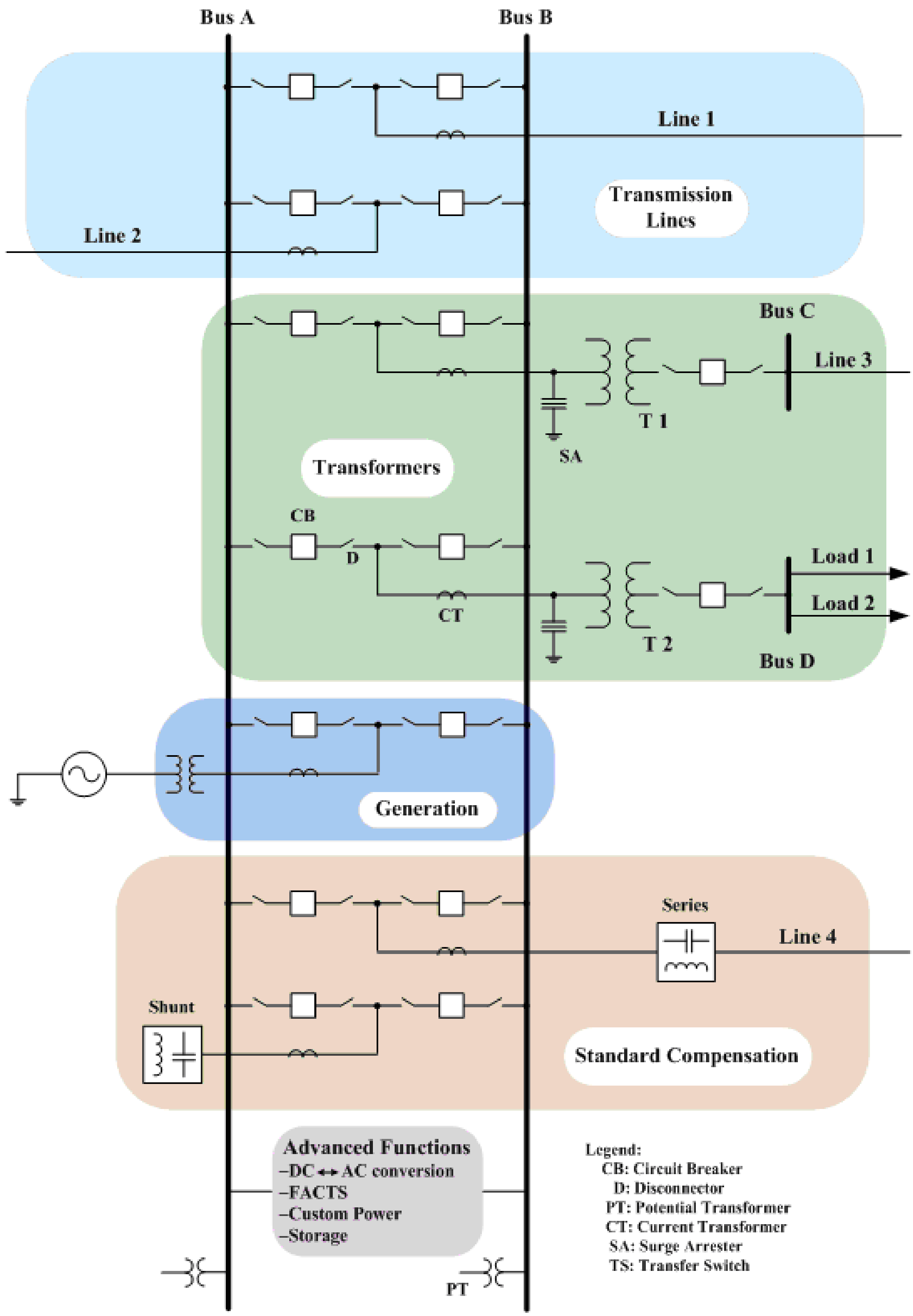


Figure 1-1
Schematic of a Double-Breaker Double-Bus Generic Substation

Improve Distributed Generation (DG) interface: As DG penetration continues to increase, better interface with the existing power network is highly desirable. Although this may be considered a problem concerning the generation sector rather than substations, it will be shown that power electronic devices located at the substation may be effective in reducing the impact of DG additions. The key idea here is that the existing power network and the protection system was conceived to operate with a relatively small number of large size synchronous generators. DG penetration is rapidly changing this scenario, calling for extensive research and solutions development in order to evaluate the consequences of DG additions.

Electronic clutch for capacitor switching: Capacitor banks connected in shunt at substation busbars are switched on and off routinely, depending on the level of voltage support needed at a particular time. The energizing transient that takes place at the switch-in event can produce high phase-to-phase overvoltages on a terminating transformer, excite resonances resulting in transient voltage magnification in secondary voltage networks, or cause problems on customer facilities. An electronic device termed "electronic clutch for capacitor switching" that has the potential of eliminating the switching transient is discussed in this report.

Fault current handling: It is well know that the addition of generating facilities, active loads, and parallel transmission lines into meshed networks have a negative effect as they increase the short circuit currents. Generators and active loads directly contribute to the fault current while parallel transmission lines decrease the effective impedance seen by the short circuit which translates into an increase of the fault current as well. Circuit breakers are especially sensitive to this as they have to interrupt the current under those faulty conditions. EPRI has an ongoing separate effort under the title "Solid-State Fault Current Limiter/Circuit Breaker Development" to address this particular issue.

As will be seen throughout the report, there is some degree of cross-coupling among these issues which opens opportunities for power electronics based devices to provide solution addressing multiple challenges.

2
POWER ELECTRONICS FOR SWITCHING AND CONTROL

Power electronics controllers are used in a wide variety of applications ranging from cellular phones and hybrid cars through industrial motor control systems. The basis for operation of any power electronic control device is the capability to turn-on and turn-off current flow through an electrical connection using solid state devices such as thyristors, transistors and diodes. These devices are functionally equivalent to throws of a switch realized using mechanical contacts found in circuit breakers and contactors.

Switchgear realized using mechanical contacts in circuit breakers may have a voltage blocking capacity of up to several 100s of kV, and current carrying capacity of up to several kA. Furthermore, they may have a current interrupting capability of up to 10s of kA and impulse voltage withstanding capacity of up to 1000s of kV. On the other hand, solid state switching devices feature a current carrying and interrupting capacity of only a few kA at the most and a voltage blocking capacity and impulse withstanding capacity of only a few kV at the most. However, they are capable of switching between their on and off states within periods as short as microseconds, compared to mechanical contacts that are much slower. The feature of high speed switching without any moving contacts makes them potentially attractive for performing power switching and control. Much of the application of power electronic controllers under the rubric of FACTS has been focused on developing solutions to improve the operation and controllability of entire transmission systems. Nevertheless, they may also be used for improving the operability of the substation components themselves.

In developing applications of power electronics controllers that can be applied in substations, it is rather critical to appreciate and understand the fundamental similarities and differences between mechanical switching devices such as oil-filled circuit breakers, SF_6 circuit breakers and vacuum circuit breakers, and solid state switching devices such as thyristors, diodes and transistors. These differences and similarities have an impact on how they can be applied in the substations. Characteristic features of different power circuit switching scenarios are reviewed further in order to highlight these features.

Characteristics of Power Circuit Switching

Power circuit switching characteristics refer to the typical behavior of voltage and current waveforms at switch terminals during turn-off and turn-on commutation events. In most scenarios, the switch invariably has an inductance in series with the path of current being commutated. As a result, upon turn-on, the switch current reaches a steady state value from zero with a controlled di/dt, as illustrated in Figure 2-1. On the other hand, the extinction of current through the switch subsequent to the initiation of a turn-off event may occur either in (a) cycle-completing mode or in (b) immediate-switching mode. The switch current waveforms in these two modes are illustrated in Figures 2-2 and 2-3.

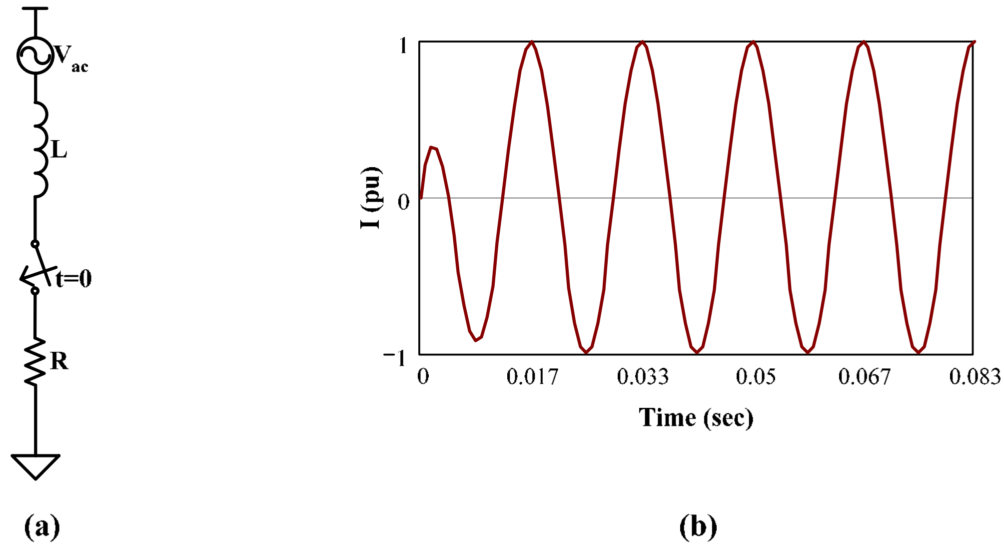


Figure 2-1
(a) Schematic of an Inductive Circuit Illustrating a Turn-On Switching Transient (b) Typical Waveform of Circuit Current Build-Up in the Following Turn-On of the Inductive Circuit

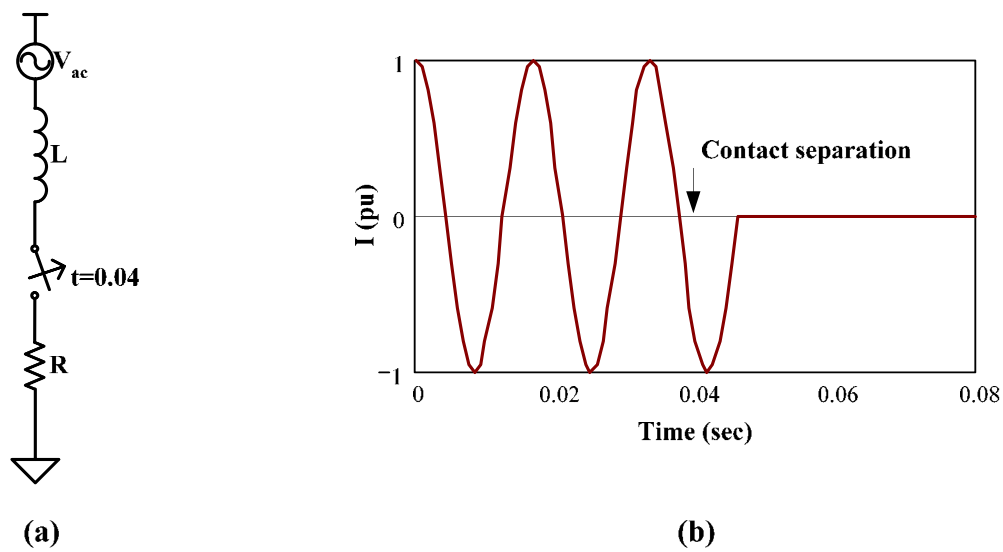


Figure 2-2
(a) Schematic of an Inductive Circuit Illustrating the Turn-Off Switching Transient in the Cycle-Completing Mode (b) Typical Waveform of Circuit Current during a Cycle-Completing Switching Mode

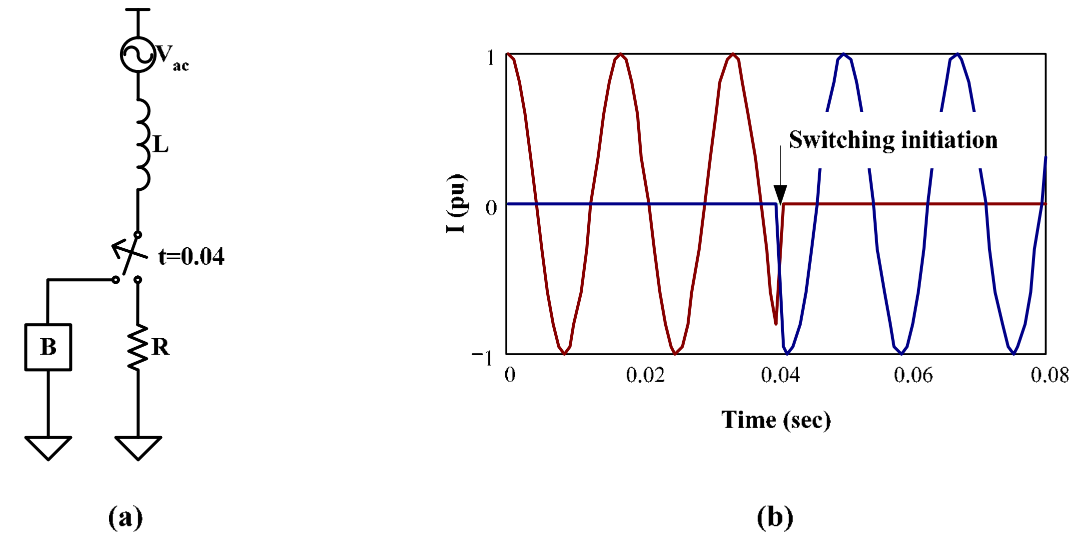


Figure 2-3
(a) Schematic of an Inductive Circuit Illustrating the Turn-Off Switching Transient in the Immediate-Switching Mode (b) Typical Waveform of Circuit Current during a Immediate-Switching Mode Illustrating the Complementary Current Flowing through the Bypass Path (B) following the Switching Event

In the cycle-completing mode, upon initiation of a turn off event, the switch continues to carry current until the next zero crossing of the current waveform before it enters a voltage blocking state. All mechanical switching contacts such as used in circuit breakers generally operate in the cycle-completing mode. On the other hand, in the immediate-switching mode, the current falls towards zero with an imperceptible delay. Certain solid state switching devices are capable of operating in the immediate-switching mode, thereby constraining circuit configurations that can safely accommodate the energy stored in the inductance of the current path during commutation. Figure 2-3 explicitly illustrates this distinction and the necessary requirement of providing a bypass path (B) to accommodate the current flow during immediate-switching as single pole double or triple throw switch. As may be observed from the figure, the pole of the switch carrying current is always terminated at one of the throws of the switch that provides a path for the current, i.e. the pole is never left in a floating position.

It is important to realize that all power electronic controllers essentially consist of solid state realizations of either cycle-completing devices or immediate-switching devices configured with external elements such as inductors, capacitors and transformers to realize particular functional requirements. The realization of the throws of the cycle-completing devices and immediate switching devices using solid state power semiconductors depend on the electrical properties of particular devices such as diodes, thyristors and transistors, as described in the following section.

Review of Semiconductor Switching Device Properties

Power semiconductor switches lie at the heart of any power electronics application. Together with reactive elements, they constitute the building blocks of various power controllers. Although they may be classified by different criteria, from a control point of view three different categories can be identified: uncontrolled, semicontrolled and fully-controlled switches. There have been a variety of power semiconductor switching devices introduced throughout the years, particularly in the fully-controllable category, but the focus here is limited to devices that have found their way into practical high-power applications.

Uncontrolled Switches

The power diode is the 'only' representative of uncontrolled switches. It is uncontrollable in the sense that it is on or off depending on the voltages and currents in the network it is connected to, not by any external action that can be taken. A photograph of high power Si Power Diode is illustrated in Figure 2-4. The circuit symbol as well as the ideal operating characteristic for a power diode is presented in Figure 2-5.

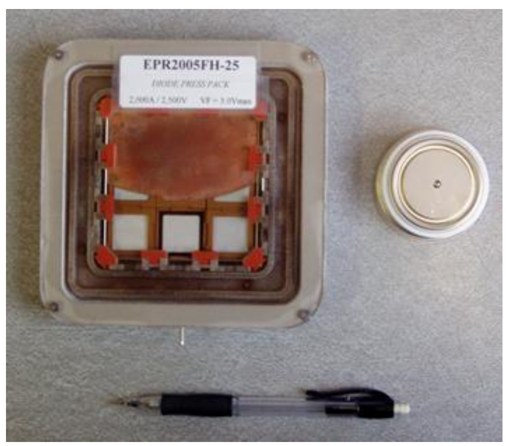


Figure 2-4
Photograph of Power Diodes

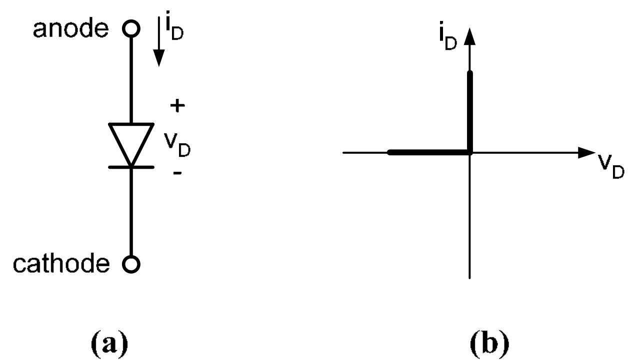


Figure 2-5
Symbol and Operating Region for a Power Diode

When on, the anode current, i_D, is positive and the anode-to-cathode voltage, v_D, is ideally zero so the diode behaves as a short circuit. Conversely, the anode current is ideally zero when off and the anode-to-cathode voltage is negative so the diode behaves as an open circuit. If it is off and the network conditions force v_D become positive, the diode turns on. If it is on and the circuit conditions force i_D to become negative, the diode turns off. Figure 2-6 illustrates typical waveforms associated with the diode operating in a switching circuit. As may be seen, operating by itself the diode turn off occurs in a cycle-completing mode. Power diodes can switch at frequencies of several kHz and are available with ratings of up to 9(kA) / 2.2(kA) and 2(kV) / 7.3(kA). As will be explained later, in utility applications power diodes are mostly used in conjunction with fully-controllable switches.

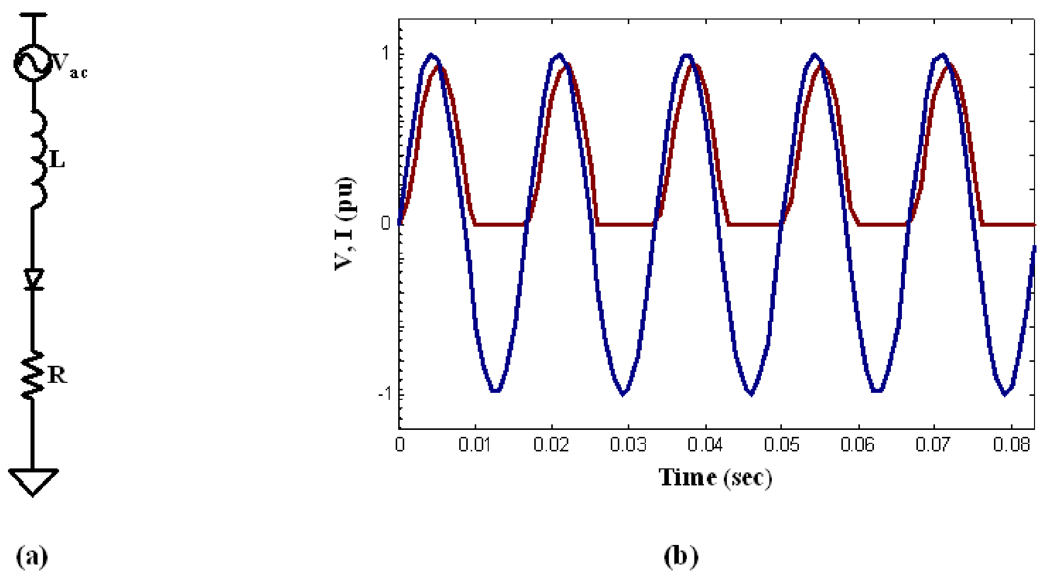


Figure 2-6
(a) Schematic of an Inductive Circuit with a Diode as Uncontrolled Switch (b) Typical Waveform of Circuit Voltage (V in Blue) Current (I in Red) Illustrating the Operation of a Diode

Semicontrolled Switches

Thyristors comprise the family of semicontrolled switches. Silicon Controlled Rectifiers (SCRs) are by far the most popular type of thyristor, which has led to the synonymous use of the terms thyristor and SCR. Thyristors are semicontrolable switches in the sense that under certain conditions they can be turned on at will through external control but the turn-off process is, as in the case of the power diode, determined by the power circuit. Because of this, they are also called turn-on devices. A photograph of high power thyristor is illustrated in Figure 2-7. Figure 2-8 shows the circuit symbol for a thyristor along with its idealized operating characteristics. As can be seen, in contrast with the diode, the thyristor has a third terminal usually referred to as the gate. If the device is off and no signal is applied to the gate, the device remains off irrespective of the polarity of anode-to-cathode voltage, v_{aK}. When v_{ak} is positive and a pulse of current is applied to the gate, the thyristor turns on, conducts positive current and will continue conducting until the network conditions change to force the current become negative. Thus, a thyristor behaves as a diode whose turn-on can be inhibited by holding off a gate pulse. Of course, the controllability that the thyristor device can provide is achieved by manipulating (delaying) the turn on so the power converter can perform its task in the power network.

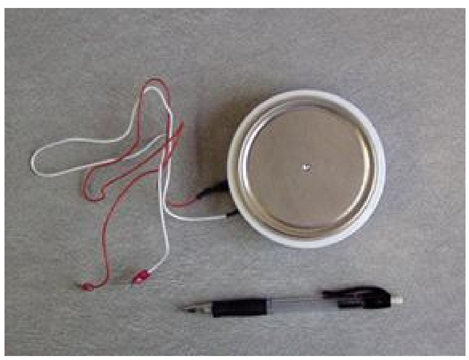


Figure 2-7
Photograph of a Thyristor

Figure 2-9 illustrates the typical waveforms associated with an SCR operating in a switching circuit. As may be seen, the SCR operates in the cycle-completing mode during turn-off. In some instances, it is possible to operate SCRs in immediate switching mode through the application of special ‘commutating circuits’. Thyristors were invented at the General Electric laboratories and are found with ratings of up 12 (kV) / 1.5 (kA) and 1.8 (kV) / 6.1 (kA). In power systems, thyristors are most often used in HVDC applications as well as in the realization of ac switches.

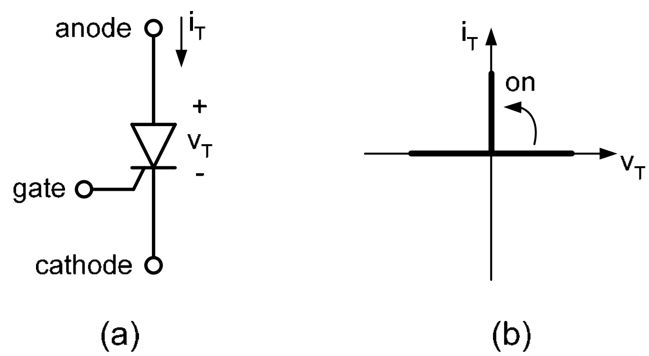


Figure 2-8
Symbol and Operating Region for a Thyristor

Fully-controlled Switches

The family of fully-controllable switches (FCS) is comprised of devices with the capability of turning-on as well as turning-off by external manipulation. Figure 2-10 shows the generic symbol for a fully-controllable device along with its idealized operating characteristics. In order to emphasize their functional interchangeability, the generic symbol illustrated in Figure 2-10 will be used in the subsequent chapters in place of symbols of particular devices. Although not explicitly shown in the figure, fully-controllable switches also posses a third terminal which allows for control of the state of the switch.

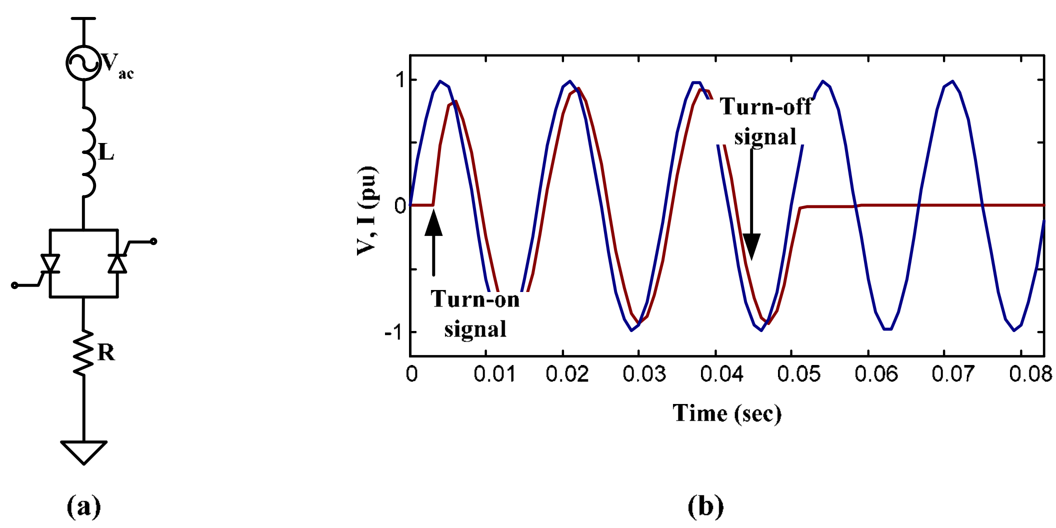


Figure 2-9
(a) Schematic of an Inductive Circuit with Back-Back Connected SCRs (b) Typical Waveform of Circuit Current (I in Red) and Voltage (V in Blue) Illustrating the Switching of the SCRs in the Cycle-Completing Mode

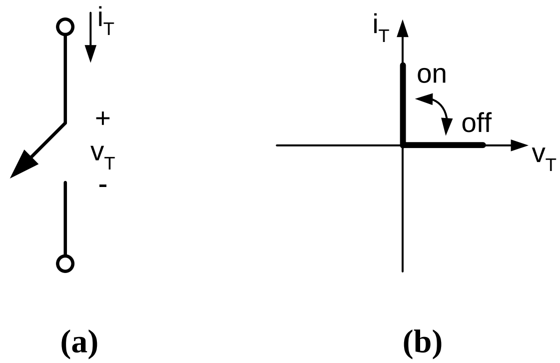


Figure 2-10
Symbol and Operating Region for a Generic Fully-Controlled Switch

When v_T is positive and a control signal is applied to the gate, the switch turns on and conducts positive current, thus behaving as a short circuit. The switch can be turned off at will by applying another control signal to the gate. When off, the switch can block a positive voltage (and in some cases a negative voltage as well) so it behaves as an open circuit. Depending on the specific type of switch, the control signal can be a continuous or a pulse of voltage or current. These devices operate in the immediate-switching mode during turn-off (and turn on). Therefore it is imperative that they be used in circuits in a manner that provide a bypass path for accommodating energy stored in inductive current paths during turn-off. In order to utilize typical fully controlled switches in an ac circuit, two of them need to be interconnected along with anti-parallel diodes, together configured in series opposition as illustrated in Figure 2-11.

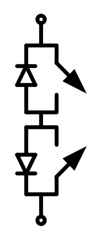


Figure 2-11
Generic Fully Controlled Switches Configured with Diodes Appropriately Connected to Enable Positive and Negative Current Conduction and Voltage Blocking Capability

Several types of fully-controllable switches, whose symbols are shown in Figure 2-12, are listed in Table 2-1. All of them are based on either thyristor or transistor structure. In general, thyristor based devices have the advantage of being able to conduct high currents with relatively low losses, but they need an additional protective network for the switching process. On the other hand, devices based on transistor structure feature relatively high conduction losses but can switch without any external assistance. As can be seen from the Table 2-1, only a few of these switches are commercially available for utility applications. Following the chronological order of appearance in the market, GTOs, IGBTs and IGCT/GCT are briefly described below.

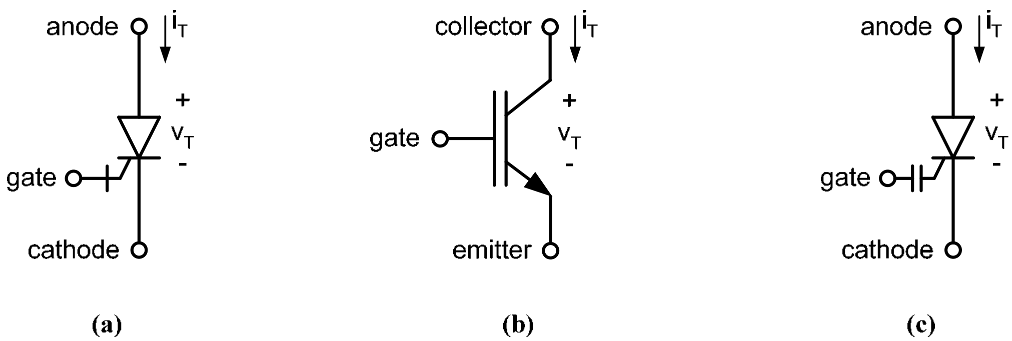


Figure 2-12
Symbol for Fully-Controllable Switches (a) GTO (b) IGBT (c) IGCT

Gate Turn-off Thyristor (GTO)

Figure 2-12(a) shows the circuit symbol for a GTO and a photograph of high power GTO is illustrated in Figure 2-13. As with the thyristor, when v_T is positive the GTO is turned applying a current pulse of short duration into the gate terminal which latches the device on its on-state. Once on, the GTO does not need any further gate action to keep conducting. In order to turn it off, a pulse of negative current of short duration but high magnitude has to be applied into the gate. GTOs require a protective circuit termed “snubber” to help both the turn-on as well as the turn-off process. During the turn-on process, inductive snubbers are use to slow down the rate of current rise. Conversely, capacitive snubbers are used to slow down the rate of voltage rise that occurs during the turn off. Also invented at the GE laboratories, GTOs are used in the range of 50 to 500 (Hz) and are available with ratings as high as 6(kV) / 6(kA). ABB and Mitsubishi are the major vendors of GTOs, and they are primarily used for the realization of multi-pulse voltage source inverters.

Table 2-1
Commercially Available Fully-Controllable Switches for High Power Applications

Thyristor Structure	Transistor Structure
Commercially Available for High-Power Applications	**Commercially Available for High-Power Applications**
GTO (Gate Turn-Off Thyristor)	IGBT (Insulated Gate Bipolar Transistor)
IGCT (Integrated Gate-Commutated Thyristor)	
GCT (Gate-Commutated Thyristor)	
Other Devices	**Other Devices**
ETO (Emitter Turn-Off Thyristor)	IEGT (Injection-Enhanced Gate Transistor)
MTO (MOS Turn-Off Thyristor)	BJT (Bipolar Junction Transistor)
MCT (MOS-Controlled Thyristor)	Darlington Transistor
FCT (Field-Controlled Thyristor)	Power MOSFET
EST (Emitter-Switched Thyristor)	JFET (Power Junction Field Effect Transistor)
IGTT (Insulated Gate Turn-off Thyristor)	
IGT (Insulated Gate Thyristor)	
S-GTO (Super GTO)	

Figure 2-13
Photograph of a GTO

Insulate Gate Bipolar Transistor (IGBT)

Figure 2-12(b) shows the circuit symbol for an IGBT and a photograph of high power IGBT is illustrated in Figure 2-14. In contrast with the GTO, the IGBT turns on when v_T is positive and a voltage signal is applied to the gate. It remains on as long as such a signal is present. Once removed, the IGBT turns off. Although IGBTs are functionally equivalent to GTOs, they feature a transistor structure and therefore the switching process can be performed with great ease. They can turn on and off very quickly and without the need of snubbers. Because of these features, IGBTs have become the device of choice for many applications. The seminal work which led to the development of the IGBT was done at the RCA laboratories in the early 80s. High voltage IGBTs can be switched at frequencies as high as a few hundred Hz and are available with ratings as high as 1.7 (V) / 3.6 (kA) and 6.5 (kV) / 600(A). Eupec, ABB, Fuji and Dynex are among the vendors of high power IGBTs. S&C Electric has MW scale high power outdoor UPS systems using IGBTs.

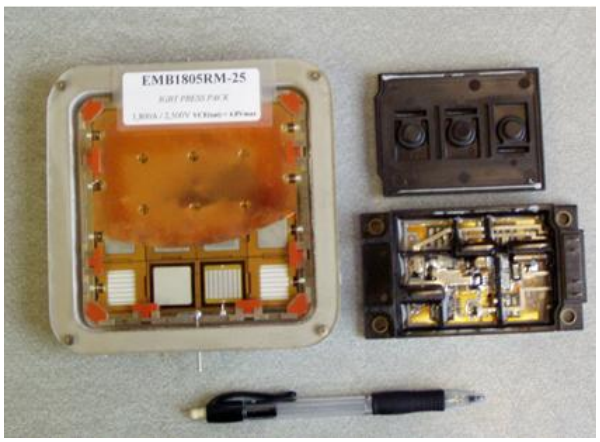


Figure 2-14
Photograph of an IGBT

(Integrated) Gate-Commutated Thyristor (IGCT / GCT)

IGCT and GCT are the ABB and Mitsubishi version of the same device. They are primarily based on the GTO structure and are functionally equivalent. Indeed, some applications using GTOs are replacing the switches by IGCTs/GCTs. The main difference is that in the case of IGCTs/GCTs the gate terminal features a very low inductance so the device can be turned off almost as fast as an IGBT and without the need of a protective snubber. Thus, the IGCT/GCT behaves as a GTO during its on state and as an IGBT during turn off. Only at turn on is an inductive snubber network needed. The circuit symbol used for IGCTs/GCTs is shown in Figure 2-12(c) and a photograph of high power IGCT is illustrated in Figure 2-15.

They have the same operating characteristics as the generic fully-controllable switch. The typical switching frequency is, as in the case of the GTO, in the range of 50 - 500 (Hz). However, in contrast to the GTO, the upper switching frequency is only limited by the ability of the system to remove the heat generated in the switching process. As a result of this, it is not impossible to have in the near future IGCTs/GCTs capable of switching at frequencies as high as 40 (kHz). IGCTs are commercially available from ABB with ratings of up to 3.6 (kV) / 1.3 (kA). Mitsubishi offers GCTs with the same voltage rating but with a current rating only up to 500 (A). IGCTs have successfully been used in China and Japan for realization of converters of up to 50 (MVA).

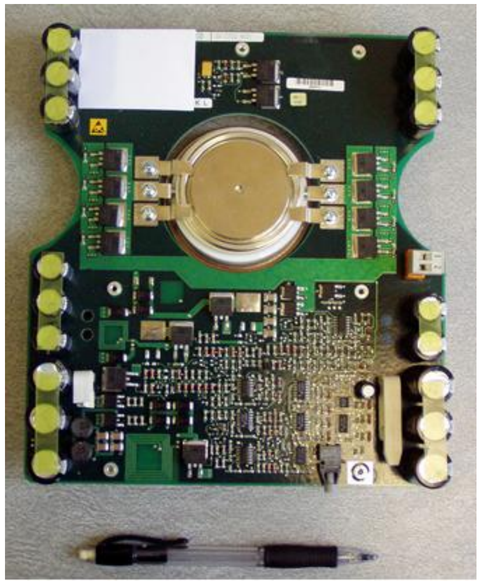


Figure 2-15
Photograph of an IGCT

State-of-the-Art Power Semiconductors

The current commercial availability of high power semiconductors is summarized in Figure 2-16. Appendix A includes the particulars of the devices used in the graph. As can be seen on the horizontal axis of the graph, the maximum *average* current has been used as a common metric to express the current capability of the various switches. This is clarified because some fabricants use the maximum *interruptible* current to specify the current capability of a device, which can lead to confusion when selecting switches for a specific application.

Table 2-2 presents the nominal current carrying capacity and voltage blocking capability of various switching technologies including mechanical contact and solid state switching devices. It may be noticed that due to the significantly lower voltage ratings of solid state devices, it is common to find arrangements where individual devices are stacked in series in order to achieve higher voltage rating as well as to provide redundancy in case of the failure of a device. In these cases, the stack of series connected devices is referred to be a ‘valve’.

Ongoing Developments in Power Semiconductors

It has long been recognized that power electronics will play a major role in power systems in the near future, prompting extensive research on high power semiconductor technology to be performed. Some researchers have focused on the development of new devices using silicon as the semiconductor material. A second research line has been the investigation of new wide-bandgap semiconductor materials. All high power switching devices commercialized today use silicon (Si) as the semiconductor material. However, it is well known that materials such as silicon carbide (SiC) and diamond (C) feature some properties that make them more suitable than Si for the fabrication of power switching devices. In the following paragraphs, the newest silicon-based power devices that may become suitable for utility applications are briefly described. Next, the materials that may offer an improved performance with respect to silicon are also discussed.

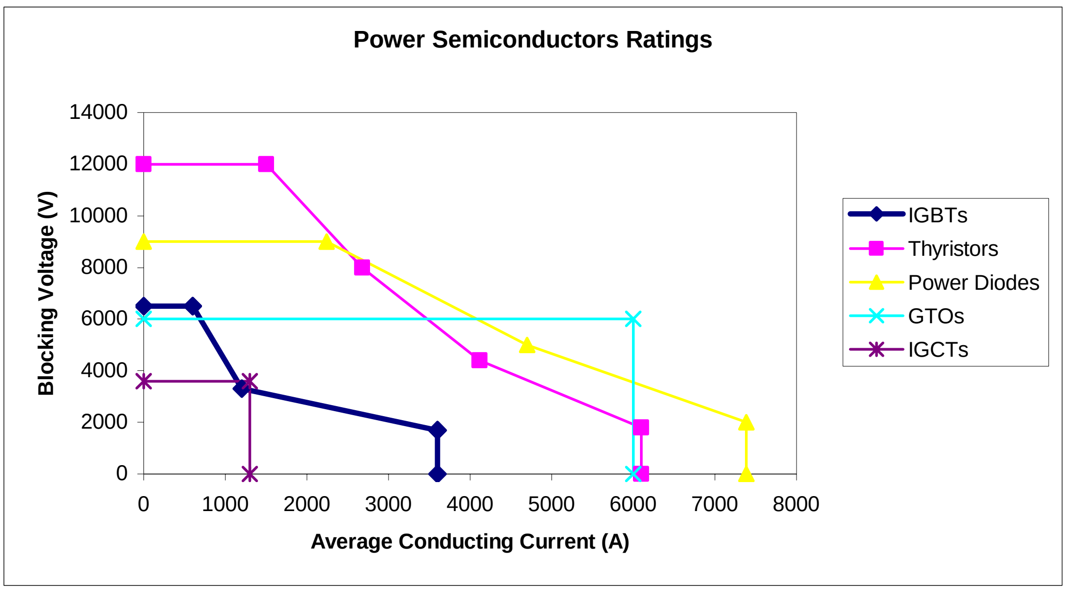


Figure 2-16
Power Semiconductors State-of-Art

Table 2-2
Typical Current Carrying Capacity and Voltage Blocking Capacity of Various Switching Technologies

Switching technology		Nominal current (kA)	Nominal blocking voltage (kV)
Mechanical	Vacuum	3-4	36
	Air	4	420
	Gas	5	800
	SF6	4	800
Solid state	Diodes	7-8	9
	SCRs	5	12
	IGBTs	3-4	6.5
	GTOs	6	6
	IGCTs	1.3	3.6

Devices

Emitter Turn-Off Thyristor (ETO)

As in the case of the IGCT, the ETO is an advanced form of GTO. The ETO is built with a conventional GTO in conjunction with power MOSFETs used as auxiliary switches whose function is to divert the cathode current through the gate terminal during the turn-off process [23]. This technique, known as “hard-driven” turn-off, allows the elimination of the need for turn-off snubbers as well as an increase of the switching frequency. Preliminary studies suggest that in the near future the ETO may become a serious competitor of the IGCT as an ETO has the potential for lower cost than an IGCT of similar specifications.

MOS Turn-Off Thyristor (MTO)

Developed by Silicon Power Corporation, the MTO also uses a conventional GTO along with an arrangement of power MOSFETs for assisting the turn off process. MTOs have been fabricated with ratings up to 4500V, 400A.

Super Gate Turn-Off Thyristor (S-GTO)

Among the newest developments reported in the GTO technology from Silicon Power Corporation are the Super GTO devices, demonstrated in pulsed power applications at up to 10kV, 400 kA ratings. A photograph of a demonstration prototype is illustrated in Figure 2.17. This SGTO device is being used by EPRI in the development of its 69 kV and 15 kV SSCL units and in the Intelligent Universal Transformer to be tested in 2009.

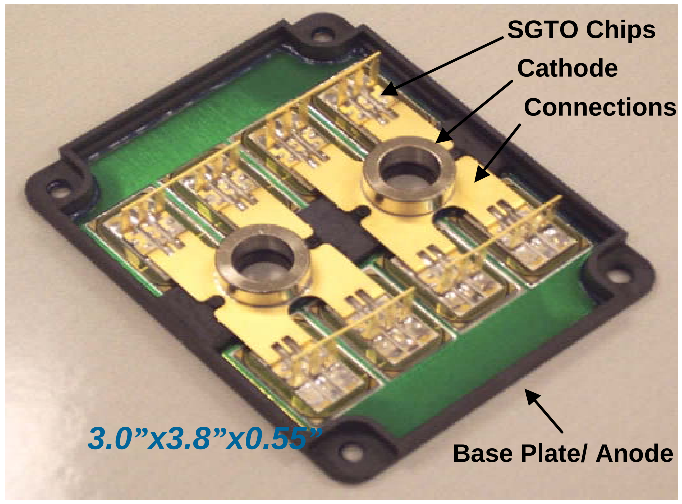


Figure 2-17
Photograph of an 800A, 5kV ThinPak Super GTO Module

Injection-Enhanced Gate Transistor (IEGT)

IEGT can be described as an advanced version of the IGBT. Developed by Toshiba in Japan, they incorporate a mechanism called electron injection enhancement which results in a lower on-state voltage with respect to the IGBT while keeping intact the advantages of conventional IGBTs, such as easy gate controllability and superior switching speed. The result is a device very similar to the IGBT but with reduced conduction losses. IEGTs have successfully been used in motor drive applications with ratings up to 8(MVA) and have been proposed for utility applications.

Materials

Advanced materials such as silicon carbide and diamond have some properties that make them superior to silicon for the fabrication of power semiconductors. The two most important metrics used as figure-of-merit when discussing different semiconductor materials for possible use in producing power devices are the breakdown electric field and the thermal conductivity. A high breakdown electric field translates into a small on-state resistance and therefore an improvement of the device efficiency. Also, superior on-state performance leads to lower switching loss that in turn can be traded off to enable higher switching frequencies. A high thermal conductivity translates into enhanced heat dissipation and power-efficient high temperature operation. Or, in other words, for a given operating temperature, much more power can be applied to the device. Table 2-3 shows these metrics for silicon carbide and diamond in comparison to silicon.

Table 2-3
Merit Metrics of Semiconductor Materials (@ 300°K)

Material	Breakdown Electric Field (V/cm)	Thermal Conductivity (W/m·K)
Silicon (Si)	300,000	130
Silicon Carbide (SiC)	1,300,000 – 3,200,000	700
Diamond (C)	5,700,000 – 7,000,000	600 – 2000

As can be seen from the table, silicon carbide has up to ten times higher critical electric field and six times higher thermal conductivity than silicon. Even though these advantages have been known for a long time, SiC-based power devices had not been developed until recently. Difficulty with material processing, presence of crystal defects such as micropipes and dislocations, and lack of abundant wafer suppliers have all contributed to a lack of rapid progress in making SiC power devices commercially available. However, these difficulties are being overcome rapidly and the power electronics community foresees SiC as the semiconductor material of the 21st century. Devices with ratings of up to 10 kV, currents up to 20A have been successfully fabricated and demonstrated (illustrated in Figure 2-18 through Figure 2-20). On the other hand, although diamond material features even better metrics than the SiC, the material fabrication technology is much less mature and developed than for SiC. Therefore, at least in the short term, diamond-based power semiconductor technology is not seen as a real opportunity.

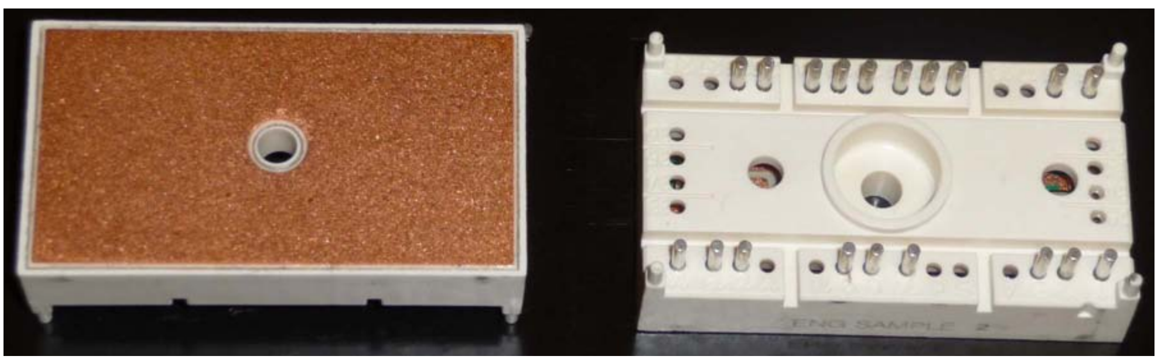


Figure 2-18
Package Details from a Switch Module Using SiC MOSFETS (Courtesy, NIST)

Figure 2-19
Package Details from a Switch Module Using SiC MOSFETS (Courtesy, NIST)

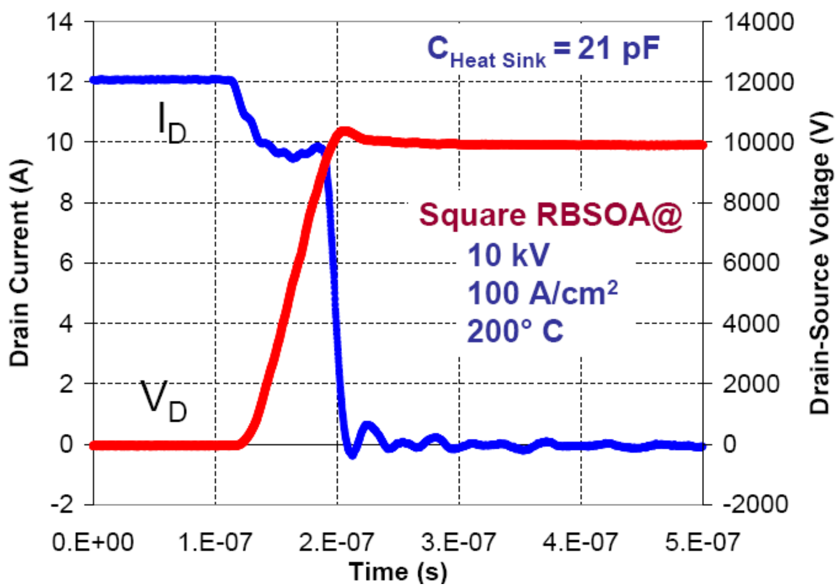


Figure 2-20
Switching Waveforms from a 12kV 20A SiC MOSFET (Courtesy NIST)

Power Switching Controller Realizations

Cycle completing control devices and immediate switching control devices are used to realize switching controller in different manners due to their differences in characteristics of turn-off behavior.

Cycle-Completing Control Devices

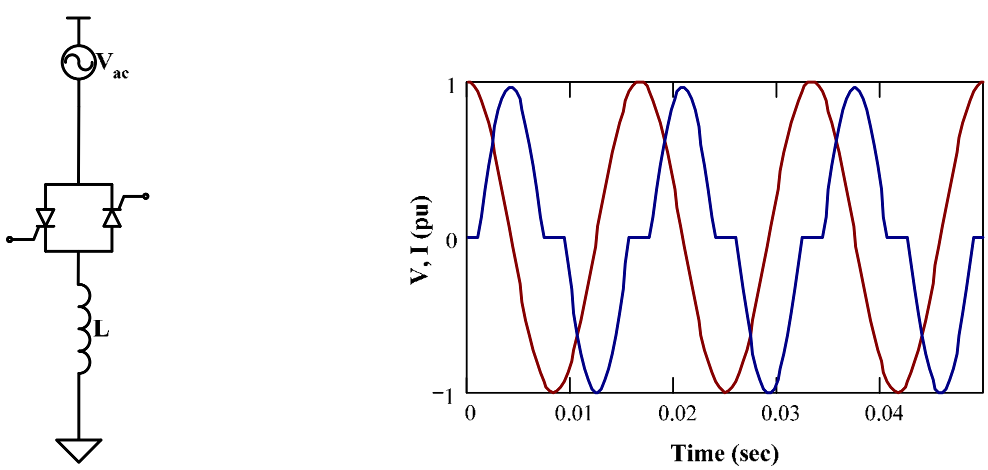
Cycle completing control devices may be applied either in integral-cycle switching mode or in sub-cycle switching as described further.

Integral-Cycle Switching

An examination of the turn-off switching behavior of mechanical contacts in circuit breakers shown in Figure 2-2(b) and SCRs in Figure 2-9(b) illustrates that, two SCRs connected anti-parallel can be used as a direct drop-in replacement for circuit breakers. However, since the voltage blocking capability, current carrying capability and operating losses of SCRs in relation to mechanical contacts are much poorer, their application at substation voltage levels requires them to be derated heavily through series and parallel connections along with appropriate monitoring, protection and cooling systems.

Sub-Cycle Switching

Since the response time of SCRs are in the order of a few tens of microseconds, as opposed to several milliseconds in the case of mechanical switching contacts, they offer the possibility of controlling the current through a path every half cycle of the power excitation. Schematic of their application and their operating waveforms in this mode of operation realizing a variable reactor is illustrated in Figure 2-21.



(a) (b)

Figure 2-21
Schematic of an Inductive Circuit with Back-Back Connected SCRs Controlled in a Sub-Cycle Switching Mode (b) Typical Waveform of Circuit Voltage and Current Illustrating the Switching of the SCRs Under Sub-Cycle Control

Immediate Switching Control Devices

Immediate switching control devices may be configured using a lossy bypass switching mode or the capacitive bypass switching mode as described further.

Lossy Bypass Immediate-switching

As illustrated in Figure 2-3, immediate switching control devices always require a bypass path in order to accommodate the energy stored in the current path of the switching circuit. In its simplest form, the bypass path is provided by a dissipative device such as a zinc oxide (ZnO) arrestor, that has nonlinear V-I characteristics and absorb the transient energy immediately following the switching operation, while limiting the steady state current flow to leakage levels. A schematic of realization of such a switching circuit along with associated voltage and current waveforms are illustrated in Figure 2-22.

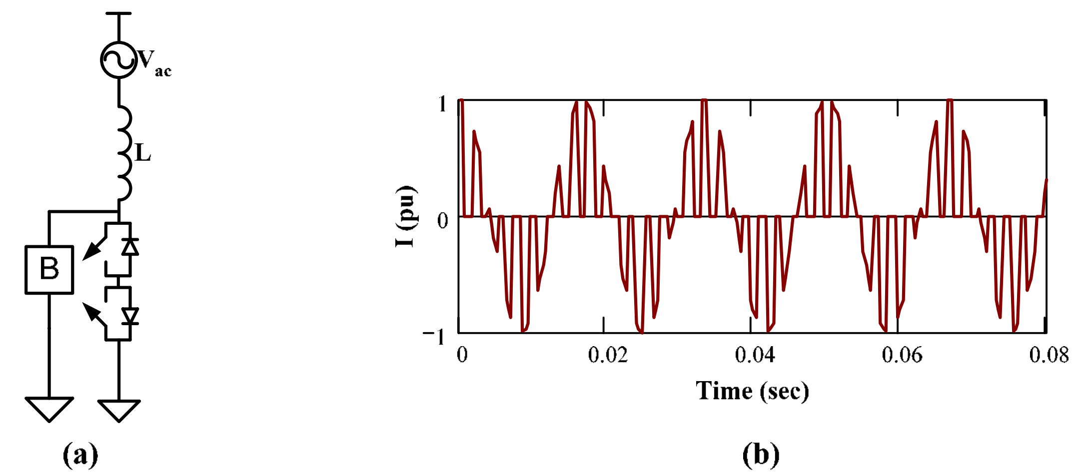


Figure 2-22
(a) Schematic of an Inductive Circuit with Solid State Switching Devices with a Lossy Bypass Device B (b) Typical Waveform of Switch Current

Capacitive Bypass Immediate-switching

The approach of realizing alternative bypass paths in the immediate switching control circuits arranged as multiple throw switches, in a manner such that each of the throws terminates in a capacitive load is more common in advanced power controllers. Furthermore, it is also possible to cascade such multiple throw switches in the power flow path in 'bridge' configurations to provide additional design and operating advantages, without violating the characteristic properties of the switches, as illustrated in Figure 2-23.

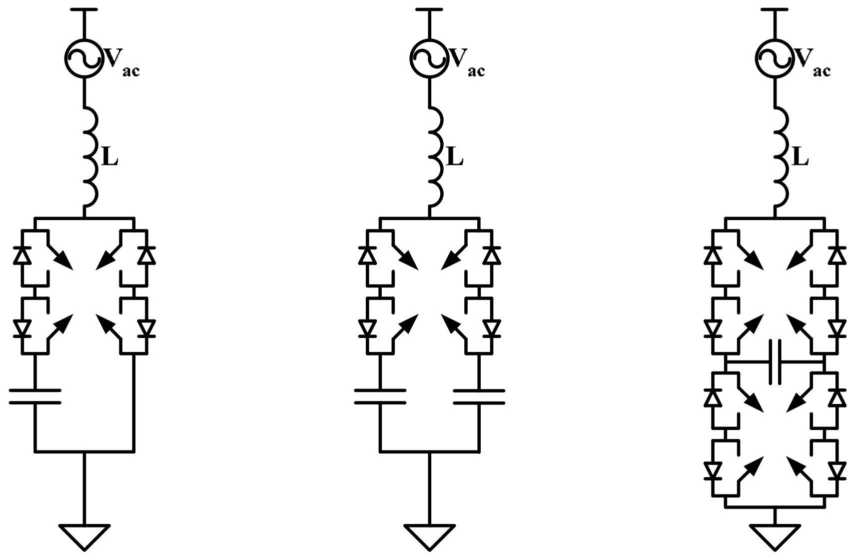


Figure 2-23
Schematic Diagram of Inductive Circuits with Solid State Switching Devices with Capacitive Bypass Immediate Switching in Single Ended, Half Bridge and Full Bridge Configurations

In all of these cases, it is possible to maintain the voltage across the capacitor to be purely dc, through appropriate switching strategies. Under such instances, the switching circuit can be realized using reduced number of fully controlled switches connected in parallel with diodes, as illustrated in Figure 2-24, for economical reasons.

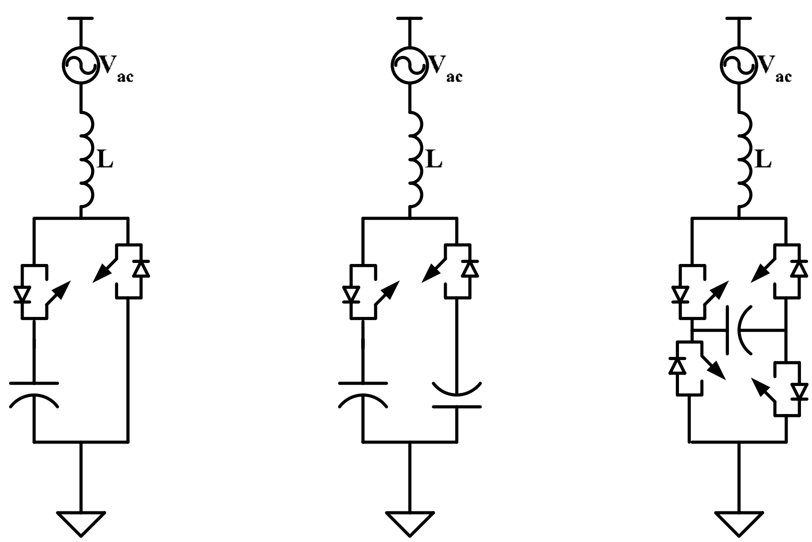


Figure 2-24
Schematic Diagram of Inductive Circuits with Solid State Switching Devices with Capacitive Bypass Immediate Switching, with Capacitors Maintained At DC Bias

The number of throws per switch can further be increased to three, where each of the throws is terminated in a capacitive node. The realization of the multiple throw switch while the capacitor voltages regulated to be dc is illustrated in Figure 2-25.

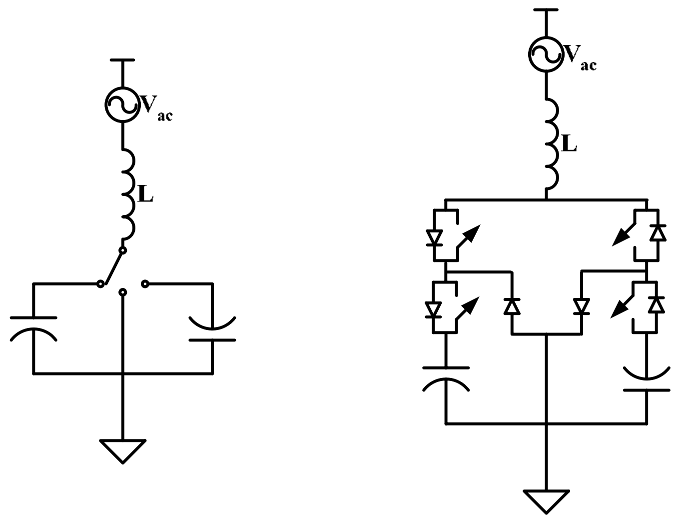


Figure 2-25
Schematic Diagram of Inductive Circuit with a Three Throw Switch and Semiconductor Switch Realization, with Capacitors Maintained at DC Bias

Voltage Matching of Switching Controllers

It must be recognized that the limited voltage blocking capability, current carrying capability and operating losses of solid state switching devices are much poorer in comparison to the mechanical contact counterparts. Therefore all the applications and realizations of controllers at substation voltage levels require appropriate accommodations to provide voltage matching.

Among these, the simplest mechanism is the use of step-down or step-up transformers, as illustrated in Figure 2-26(a). On the other hand, several Solid State Controllers (SSC) may be connected in series as illustrated in Figure 2-26(b), which allows the net voltage to be shared among the constituent devices. Alternatively, each switch itself may be realized using a series connection of several individual solid state switching devices, as illustrated in Figure 2-22(c). Furthermore, a particular controller system realization may utilize a combination of these techniques to realize voltage matching i.e. series connection of switching devices, transformer interface, and series connection of switching controllers.

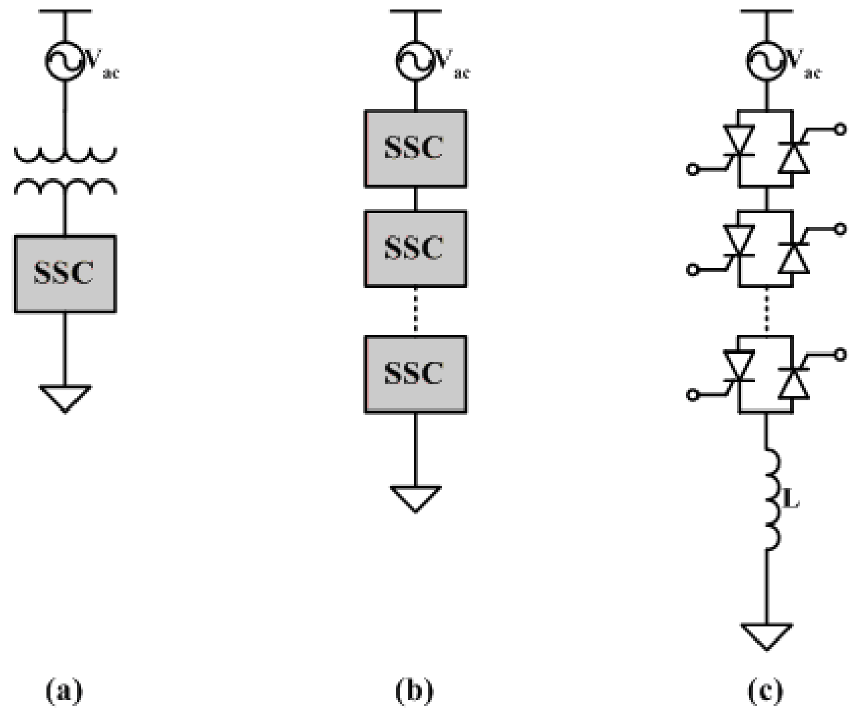


Figure 2-26
Schematic Diagram of Voltage Matching of Switching Devices with Utility System Voltage using (A) Step-Up/Step-Down Transformers (B) Series Operation of Switching Power Controllers (C) Series Operation of Switching Devices

Operating Modes of Switching Controllers

The application of integral-cycle switching of cycle-completing controllers and the lossy bypass immediate-switching controllers are generally used in a manner to realize periodic switching events that may happen a few times a day or relatively rare abnormal events accompanying faults. These devices realize their function through appropriate selection of passive components incorporated in the circuit. On the other hand, all solid state switching controllers that operate in immediate switching mode may be actively controlled through appropriate switching to emulate various functions through duty ratio control. Although these devices have certain natural operating features, they may be modified through appropriate closed loop regulation. For instance, the device illustrated in Figure 2-24 realizes a variable voltage source at the ac terminals. However, it may be used to realize a variable current source or a variable reactance within their particular design and control range, through feedback control as illustrated in Figure 2-27.

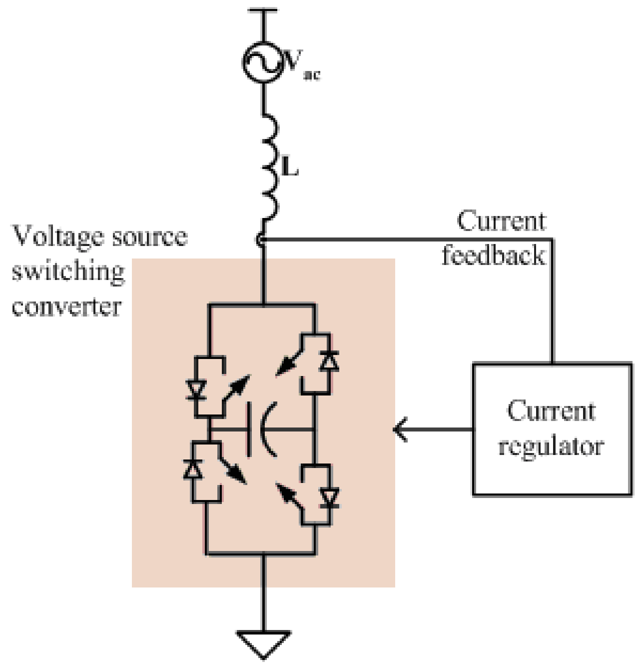


Figure 2-27
Schematic Diagram Illustrating the use of a Voltage Source Switching Converter Operating as a Current Source Realized using Feedback Control

3

SUBSTATIONS CHALLENGES AND SOLUTIONS

This chapter describes the major challenges faced by substation in the near future along with the role of power electronics in proving solutions.

Incremental Capacity Addition in Substations

The standard methods for studying capacity expansion of substation include load growth forecast, power flow programs, short-circuit and fault-current calculation programs, voltage drop calculation programs, and total system impedance calculation programs. These, combined with other tools such as voltage regulation, capacitor planning, and reliability, give insights of the type and timing for expansion needs. The result of these studies may indicate the need of constructing an entirely new substation or the replacement or upgrade of a specific piece of equipment at existing substations. One of the major components at substations is the power transformers used to accommodate the voltage levels of the input side with the output side. When the study indicates a need for an increase in the transformation capacity, the possible solutions are either the replacement of the existing transformer for a new one of bigger capacity, or the addition of a second unit in parallel with the exiting one. The latter is the most attractive option, economically and from the reliability point of view. However, satisfactory operation of transformers in parallel is subject to a series of requirements as review in the following section.

Nominal Operation of Parallel Transformers

The main requirement for optimal operation of transformers in parallel is that the load current through them ought to distribute proportionally to their rated power so that the total capacity of the transformers set corresponds to the sum of the individual transformer capacity. In order to quantify this requirement, consider the operation of two transformers in parallel as depicted in Figure 3-1.

As can be seen, the transformers are being modeled by their series branch along with an ideal transformer. As it is usual for system studies, the magnetizing branch has been neglected. The load currents through each transformer can expressed as

$$I_1 = \left(\frac{1}{n_1} - \frac{1}{n_2}\right)\frac{V_m}{Z_1 + Z_2} + \frac{Z_2}{Z_1 + Z_2} I_L \qquad \textbf{Eq. 3-1}$$

$$I_2 = \left(\frac{1}{n_2} - \frac{1}{n_1}\right)\frac{V_m}{Z_1 + Z_2} + \frac{Z_1}{Z_1 + Z_2} I_L \qquad \textbf{Eq. 3-2}$$

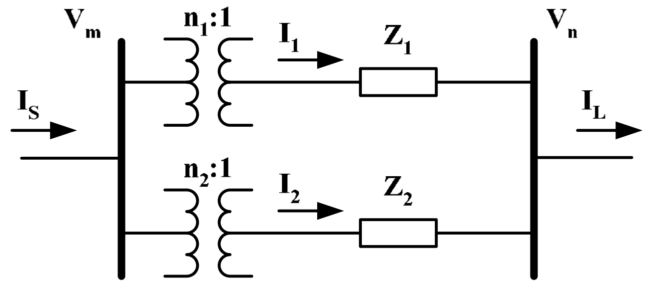


Figure 3-1
Schematic of Two Transformers in Parallel

Equations (3-1) and (3-2) show that under no load i.e., I_L=0, there still is an undesirable circulating current whose origin lies on the different transformation ratio of each transformer. Thus, if equal transformation ratio (n_1=n_2) is imposed as an operating restriction, such a circulating current is readily eliminated. Under that condition, dividing Equation (3-1) by (3-2) yields to

$$\frac{I_1}{I_2} = \frac{Z_2}{Z_1} \quad \textbf{Eq. 3-3}$$

If the impedances are expressed in per unit with respect to each transformer's rated values, Equation (3-3) becomes

$$\frac{I_1}{I_2} = \frac{(Z_2) \cdot V^{rated} / I_2^{rated}}{(Z_1) \cdot V^{rated} / I_1^{rated}} \quad \textbf{Eq. 3-4}$$

where the notation (·) has been chosen to express per unitized values. Equation (3-4) can be rewritten as

$$\frac{I_1}{I_2} = \frac{(Z_2) \cdot S_1^{rated}}{(Z_1) \cdot S_2^{rated}} \quad \textbf{Eq. 3-5}$$

As can be seen, the transformers will share the load proportionally to their rated power only if (Z_1)=(Z_2). If that condition if not satisfied, one of the transformers will hit its rated capability limiting further power transfer in spite of having available loading capability on the other unit.

Short-circuit Operation of Parallel Transformers

In order to understand the system's consequences of adding a transformer in parallel with an existing unit, consider first the situation presented in Figure 3-2(a). It corresponds to a single transformer (T_1) feeding a passive load Z_L. The source side has been represented by the Thévenin equivalent seen from bus m upstream. Also, a circuit breaker (CB) has been located downstream bus n whose function is to provide the ability to connect/disconnect the load Z_L from the system as well as isolate short-circuits downstream bus n.

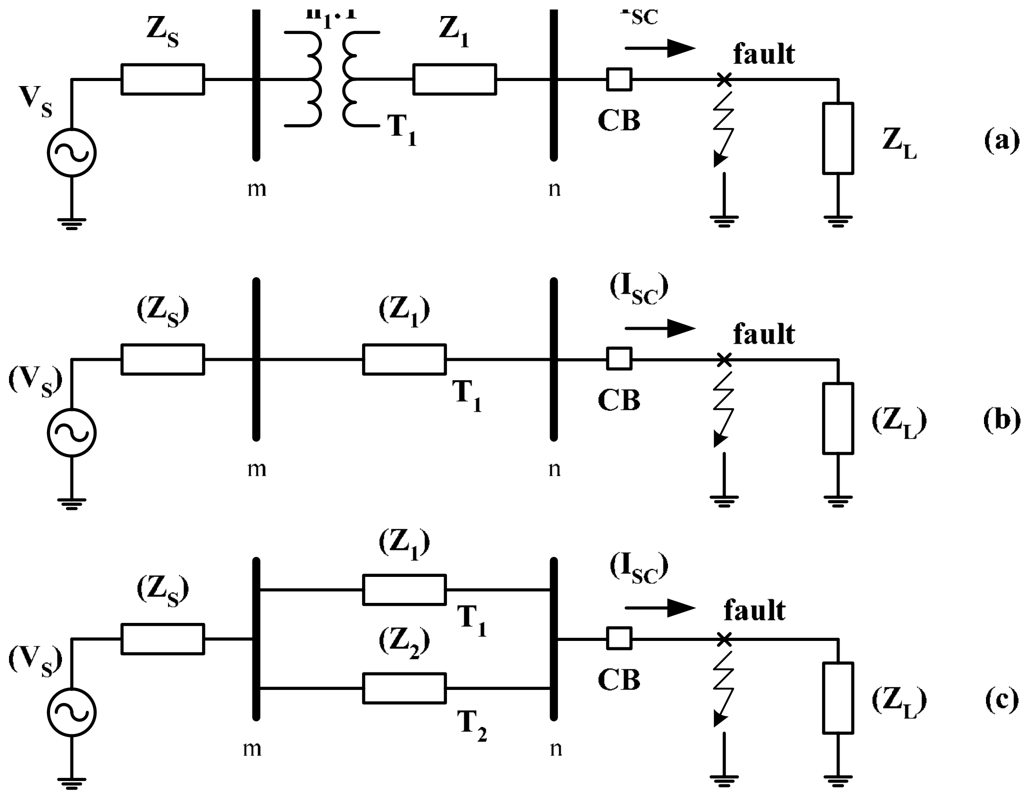


Figure 3-2
Schematic of Transformers in Parallel under Short-Circuit

Consider a three-phase short-circuit occurring just downstream the circuit breaker as shown in the figure. In order to simplify the analysis, let the circuit be per unitized as shown in Figure 3-2(b). Now, consider the addition of a second transformer T_2 in parallel with T_1 as shown in Figure 3-2(c). Assuming typical per unitized values for the voltage source as well as the various impedances, a sketch of the short-circuit current can be simulated considering both cases. Figure 3-3 shows such a situation. As can be seen, the short-circuit current increases significantly when T_1 is operated in parallel with T_2. The increase occurs at both the peak and steady-state values of the short-circuit current. This may not be tolerated by the circuit breaker specifications and the protection scheme. As a result, a new circuit breaker would need to be installed and the protection scheme would have to be redesigned.

In summary, the addition of a transformer in parallel with an existing unit would be satisfactory if (a) the new transformers have the same transformation ratio as the existing one so that there is no circulating current; (b) the per unitized series impedance of the new transformer matches the series impedance of the existing unit, and (c) the new transformer does not contribute to the short-circuit level

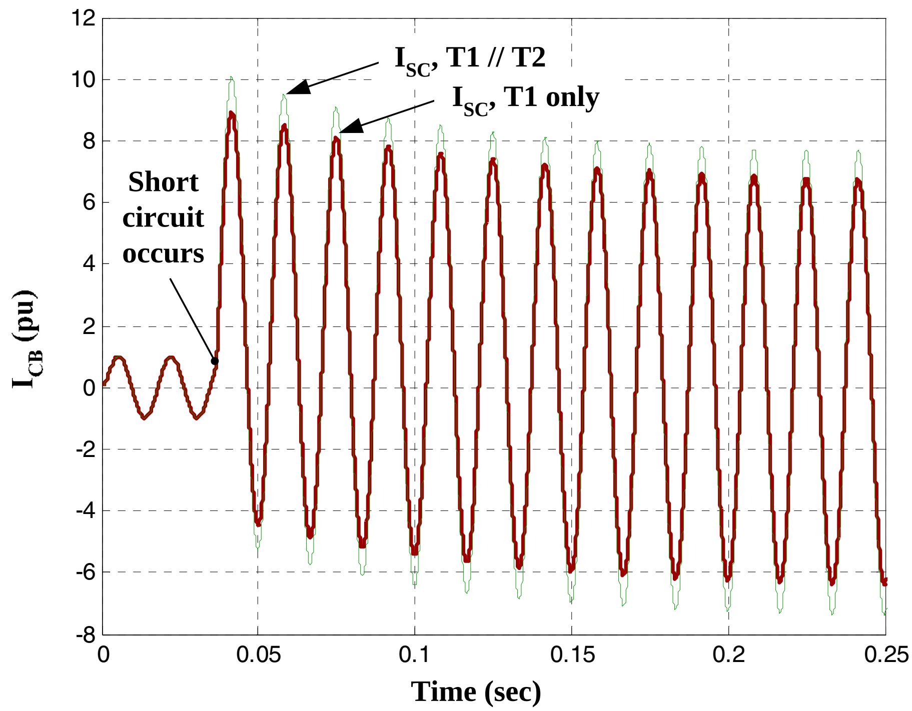


Figure 3-3
Short-Circuit Current Waveforms

It should be noted that these requirements are usually satisfied when a substation is conceived from the beginning as having more than one transformer operating in parallel. The usual approach is the construction of two identical transformers so (i) and (ii) are automatically satisfied. Also, circuit breakers and other equipments are designed to withstand the short-circuit of both transformer so (iii) does not represent a problem. Thus, restrictions (i) through (iii) become an issue only when adding an additional transformer onto an existing substation.

Obviously, restrictions (i) and (ii) may be satisfied by means of asking the fabricant to build the additional transformer with specific transformation ratio and leakage impedance. While the former is very likely to happen as in the transmission/distribution system the voltage levels have been standardized, the latter would lead to undesired premium payments. On the other hand, it is very likely that the existing transformer is equipped with on-load tap-changers (LTCs) which would result in having dynamic transformation ratio as well as series impedance. As a result, it may be concluded that a dynamic method for regulating the paralleling operation of transformers is highly desirable.

Figure 3-4 shows a magnetic solution that was proposed several decades ago. As can be seen from the figure, a small autotransformer (T_{AT}) connected between the transformers' secondary can force the load current I_L to divide between the two windings of the autotransformer so that the net magnetomotive force acting on its core is zero. Therefore the currents through T_1 and T_2 are inversely proportional to the number of turns in the two autotransformer's windings. Adjustment of these turns will split the load current properly. While this approach may solve restriction (ii), it does not offer a comprehensive solution for all restrictions. Also, due to its mechanical nature, it lacks speed of response.

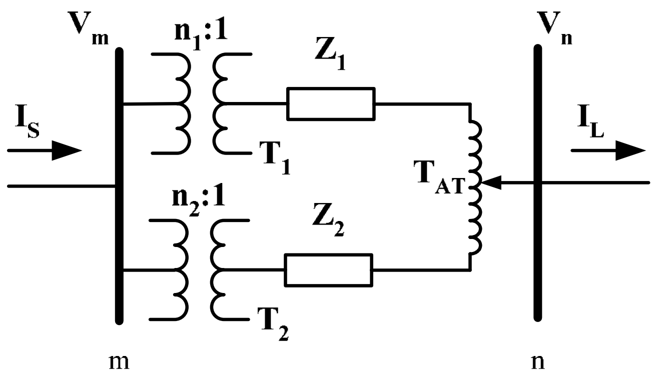


Figure 3-4
Parallel Transformers Operation using an Autotransformer for Proper Load Sharing

However, power electronics based solutions can provide satisfactory performance regarding all three operational restrictions. Consider the insertion of a Solid State Controller (SSC) connected in series with the additional transformer T_2, as depicted in Figure 3-5(a). As discussed in Chapter 2, a series controller can take the form of an adjustable impedance or an adjustable voltage source depending on the feedback controller configuration, leading to the equivalent circuits presented in Figures 3-6 (b).

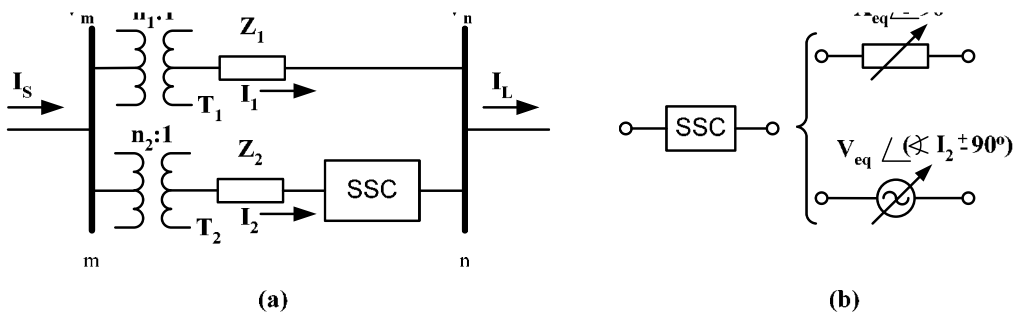


Figure 3-5
(a) Solid State Controller for Parallel Operation of Transformers (B) Possible Control Modes

The requirement (ii) can easily be met by any controller that can selectively behave as an inductor or a capacitor. Topologies presented in Figures 3-6 (a) and (b) would be adequate. They correspond to a Thyristor Controlled Series Capacitor (TCSC) structure and a Static Synchronous Series Compensator (SSSC) structure, respectively. Fundamental operating principles of these devices have extensively been treated in the literature.

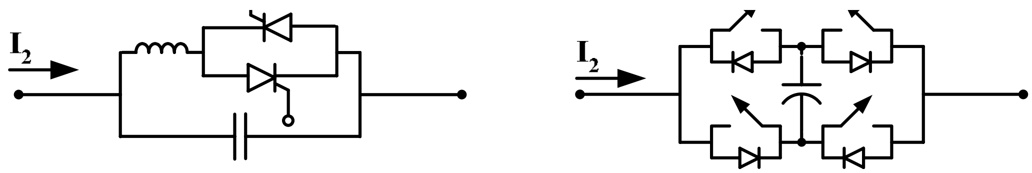


Figure 3-6
Realizations for a Series SSC Capable of Improving the Operation of Transformer in Parallel

With any of these devices operating as an adjustable impedance, Equations (3-1) and (3-2) become

$$I_1 = (\frac{1}{n_1} - \frac{1}{n_2}) \frac{V_m}{Z_1 + Z_2 + Z_{eq}} + \frac{Z_2 + Z_{eq}}{Z_1 + Z_2 + Z_{eq}} I_L$$ **Eq. 3-6**

$$I_2 = (\frac{1}{n_2} - \frac{1}{n_1}) \frac{V_m}{Z_1 + Z_2 + Z_{eq}} + \frac{Z_1}{Z_1 + Z_2 + Z_{eq}} I_L$$ **Eq. 3-7**

It can be seen that if n_1=n_2, the condition (Z_1) = (Z_2) + (Z_{eq}) can easily be met by properly adjusting Z_{eq}.

If the transformer T_1 is equipped with tap changers, then the restriction (i) becomes an issue because n_1 would dynamically change as the tap changers are adjusted. However, is the SSC is operated as an adjustable voltage source, the voltage at the secondary side of T_2 can be manipulated in order to eliminate the circulating current that would result if no action is taken. With the SSC operating as an adjustable voltage source, Equations (3-1) and (3-2) become,

$$I_1 = (\frac{1}{n_1} - \frac{1}{n_2}) \frac{V_m}{Z_1 + Z_2} + \frac{V_{eq}}{Z_1 + Z_2} + \frac{Z_2}{Z_1 + Z_2} I_L$$ **Eq. 3-8**

$$I_2 = (\frac{1}{n_2} - \frac{1}{n_1}) \frac{V_m}{Z_1 + Z_2} - \frac{V_{eq}}{Z_1 + Z_2} + \frac{Z_1}{Z_1 + Z_2} I_L$$ **Eq. 3-9**

It can be seen that by selecting $V_{eq} = (1/n_2 - 1/n_1) \cdot V_m$, the circulating current is readily eliminated. As the constraint (iii) requires to quickly isolate (open) the additional transformer upon the occurrence of a short circuit, the topologies presented in Figure 3-6 may not be adequate. If the controlled switches are turned off in either of the converters, there would still be a path for the current to continue to follow through the capacitor, and the dynamic interaction of the short circuit current with the capacitor if not clear at first glance. This may be evaluated through detailed computer simulations. An alternative approach would be to consider converters that do not include capacitors on their realizations. Possible approaches are presented in Figure 3-7 (a) and (b). They both realize an adjustable reactor but in (a) it is built utilizing SCRs operating in the cycle-completing mode, whereas in (b) FCSs controllable switches are used with diodes operating in the immediate switching mode. While in steady state both of them would operate in their on-state (bypass mode), their behavior become substantially different under a short circuit scenario.

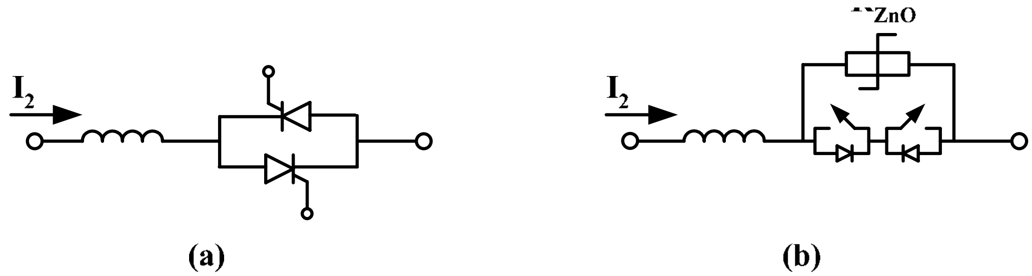


Figure 3-7
Schematic of Controlled Reactors Realized with (a) SCRs and (b) FCSs

Consider again a short circuit occurring at the location shown in Figure 3-2. The short circuit current splits through the two transformers connected in parallel. Figures 3-8(a) and (b) show, respectively, the ability of the SCR-based SSC and the FCS-based SSC to interrupt the short circuit current. As can be seen in the figure, the SCR-based SSC can interrupt the current only at the next zero crossing, so it would no be able to limit the peak short circuit current. However, the FCS-based SSC can interrupt the current as soon as a turn-off signal is sent to the corresponding switch. As shown in the figure, the energy trapped in the inductor is quickly dissipated in the zinc oxide arrester.

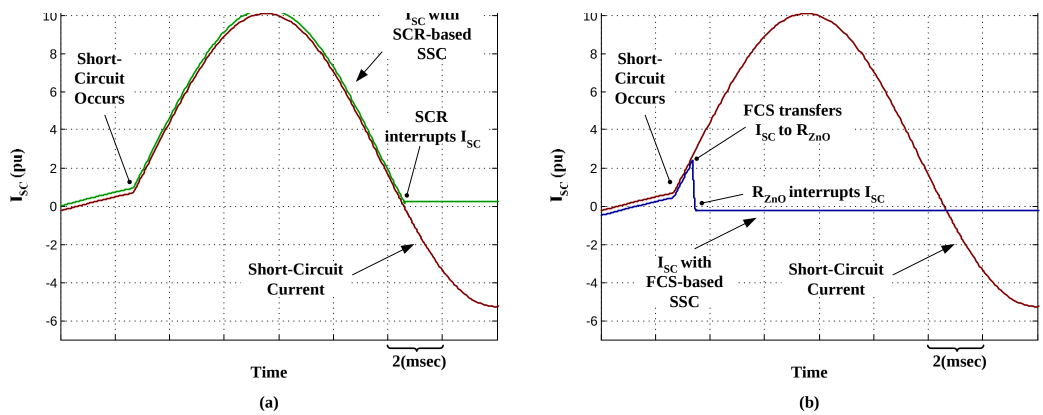


Figure 3-8
Short Circuit Current through Transformer T_2 (a) Interruption with a SCR-Based SSC (b) Interruption with a FCS-Based SSC

Although the different techniques illustrated above have the functional capability to manage power flow and short circuits among parallel connected transformers, their relative advantages and disadvantages are unclear. Thus, future investigations will focus on the unveiling the various tradeoffs among these approaches.

Mitigation of Voltage Flicker from Nonlinear Loads and Varying Generation Sources

Voltage fluctuation is a severe power quality problem as it leads to light flicker, fluctuating torque in machinery loads, and the malfunction of protection devices and process control devices. This problem has its origins in loads such as arc furnaces and electric welders, and varying power sources such as certain engine-driven generators and wind turbines. Figure 3-9(a) shows the scenario in which voltage fluctuations, or simply flicker is observed. The flicker source draws a current waveform that contains a 60 Hz fundamental component along with random sub-harmonic content in the range of a few Hz to approximately 30 Hz. Flicker source is typically modeled as a current source as shown in Figure 3-9(b). The sub-harmonic currents propagate into the network and cause voltage fluctuation at the point of common coupling (PCC) at the corresponding frequencies. The bus labeled V_{PCC} at the nearby substation feeds the flicker source as well as other ambient loads.

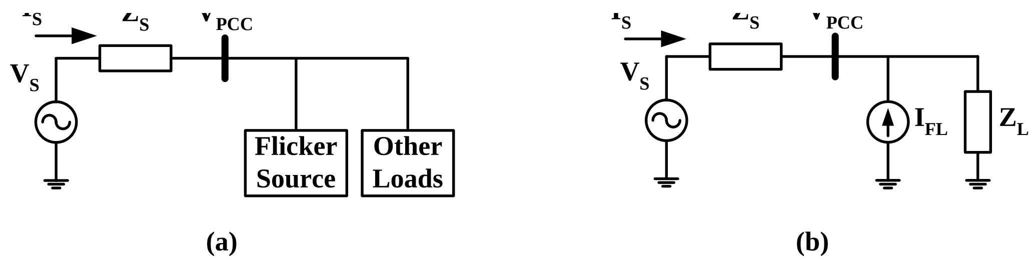


Figure 3-9
(a) Schematic of Flicker Source and (b) Its Equivalent Circuit

Figure 3-10(a) shows an example of the three-phase current drawn by a flicker source such as an arc furnace. In this case, the load draws amplitude modulated reactive current with a maximum amplitude of 70% and a modulation frequency of 20 (Hz). The corresponding voltage at PCC is shown in Figure 3-10(b). As can be seen, the voltage presents a dip of about 10% and with a variation frequency of the same 20 (Hz).

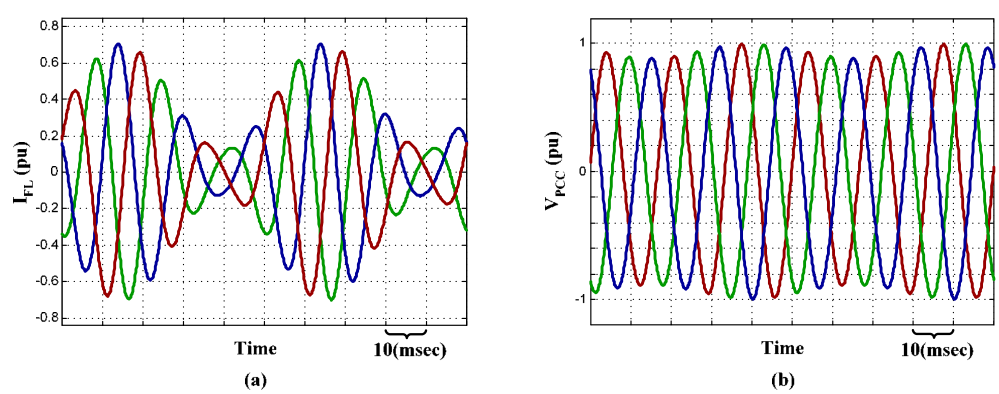


Figure 3-10
(a) Current Drawn by an Arc Furnace Load and (b) the Resulting Voltage Fluctuation at the Point of Common Coupling

As a result of the voltage fluctuations at PCC, other loads connected to the substation would experience the power quality problems described above. Among them, the light flicker is by far the most serious as it affects humans, producing eye irritations, headaches, and migraines. Ideally, it may be desired that the variations in the voltage at the point of common coupling at a load location (ΔV_{PCC}) to be as close to zero as possible to eliminate flicker.

Shunt Controllers

The classical approach to mitigate these voltage fluctuations have been to increase the size and number of generating units or to make the network more densely interconnected. However, this method has proven to be very expensive and insufficiently effective. More recently, techniques based on reactive power management have become more widespread. The concept of reactive power management is established by sizing the power system according to the maximum demand of real power, and to manage the reactive power by means of compensators and other equipment. This approach is more practical and economic. Within this framework, shunt reactive power compensators connected as shown in Figure 3-11(a) have successfully been used.

Figure 3-11(b) shows the possible operating modes for the Solid State Compensator (SSC). As discussed in Chapter 2, shunt controllers can take the form of adjustable impedance or adjustable current source depending on the type of feedback control system employed. Controlling the reactive power by means of introducing a reactive power source in parallel with the load may result in voltage regulation at the point of common coupling. An advantage of a shunt location is that the flicker-generating load can be counterbalanced locally.

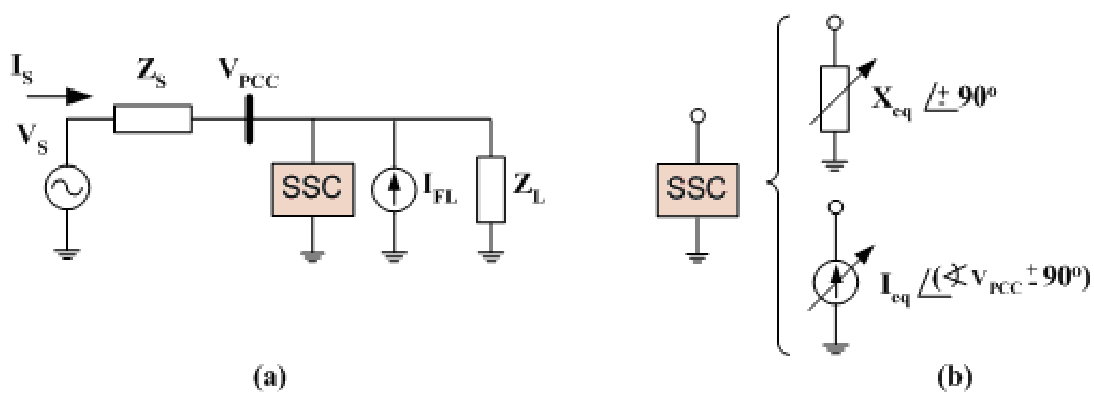


Figure 3-11
(a) Schematic of Voltage Fluctuations Mitigation at PCC using Shunt Controllers and (b) the Possible Approaches for Control

By appropriately injecting a controlled amount of reactive current at the point of common coupling, the effect of active and reactive components of the current in the line impedance can be controlled. In general, the compensation system's most important function is to maintain a substantially steady voltage profile therefore maintaining the relative voltage change (ΔV_{PCC}) within a predetermined margin. Figures 3-12 (a) through (c) show the most prominent topologies that have been investigated to realize the shunt flicker controller.

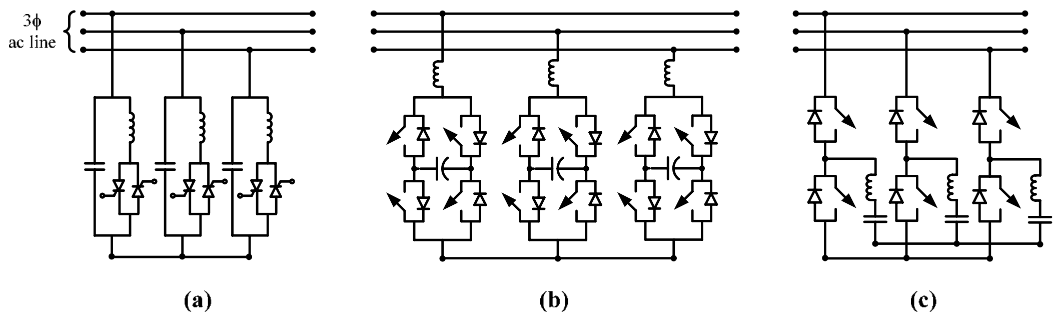


Figure 3-12
Topologies Suitable for the Realization of Shunt Flicker Controllers (a) Intellivar-Based, (b) D-Statcom-Based (c) SSFC-Based

The Intellivar shown in Figure 3-12(a) is topologically equivalent to the Static VAr Compensator (SVC). This device is one of the most commonly used reactive power compensator. It consists of a Thyristor Controlled Reactor (TCR) and a fixed capacitor connected in shunt at the point of compensation. The conduction period of the TCR can be varied by controlling the firing angle of the thyristor. Consequently, the TCR in conjunction with the capacitor bank may be considered to be a controllable susceptance, and can therefore be used as a reactive power compensator. The Intellivar has been implemented for flicker mitigation purposes with ratings up to 85 (MVA). However, due to its low speed of response, reduction for frequencies above 5 (Hz) has not been very successful, and a substantial amount of harmonics is introduced in the system.

The Distribution STATic COMpensator (D-Statcom) shown in Figure 3-12(b) has been amply investigated in the last two decades for the purpose of static reactive compensation. Similar to the Intellivar, the D-Statcom has the capability of injecting and drawing reactive power. However, it uses a DC link capacitor and a DC-AC inverter to realize the control function. It should be noticed that the topology shown in the figure in terms of H-bridges is just one of several options for the realization of the inverter system. By means of a phase-locked-loop (PLL), the output current of the inverters is synchronized with the bus voltage such that the phase angle between them is $\pm 90^{o}$ at steady state. By an appropriate feedback control strategy, the reactive current drawn by the flickers source can be compensated, and hence result in reduction of flicker. A field demonstration of this device has been reported in the literature.

The topology presented in Figure 3-12(c) has been termed Solid State Flicker Controller (SSFC). It uses Pulse Width Modulation (PWM) in order to inject a fast acting variable amount of capacitance in parallel with the flicker source. The details regarding principle of operation of this device have been reported in the technical literature. The SSFC constitutes a promising device as it features several advantages with respect to the Intellivar and the D-Statcom. The most critical feature of a reactive power compensator to be effective in flicker reduction is the speed response. Typically, if a compensator has a control time delay of 10 (ms), no matter what the voltage rating, it can reduce flicker but not in a significant amount. On the other hand, if the delay is greater than 20 (ms) flicker can be accentuated for several frequencies. The switching times of state of the art semiconductors used in PWM applications have increased dramatically, therefore decreasing the response time, and harmonics. These advances in technology have broadened the possibilities of devices such as the PWM converters in applications such as voltage regulation.

The SSFC offers high-speed control compared with phase angle based controller such as the Intellivar and simplicity compared with the inverter-based controllers such as the D-Statcom. Table 3-1 shows a comparison of the main features of each device. These qualities make the SSFC ideal for the realization of a fast acting, variable reactive power source. A laboratory scale prototype of the SSFC has been tested and the results have shown the viability of this device to become a serious competitor of shunt reactive compensators in the near future.

Table 3-1
Comparison among the Various Topologies

Device	Speed of Response (Hz)	Harmonic Content	Control Architecture	Technology Maturity
Intellivar	5	High	Complex	High
D-Statcom	10	Low	Complex	Medium
SSFC	>100	Low	Simple	Novel

Series Controllers

Recent research work has shown that voltage fluctuations problem can be approached by series compensation as well. Figure 3-13(a) shows the basic schematic for the approach. Instead of directly compensating for the fluctuations in the current drawn by the flicker source, one could compensate for the voltage drop in Z_s due to those oscillations in order to eliminate the voltage oscillations at PCC. As shown in Figure 3-13(b), the solid state controller in this case has to be operated in a control mode of either adjustable impedance or adjustable voltage source.

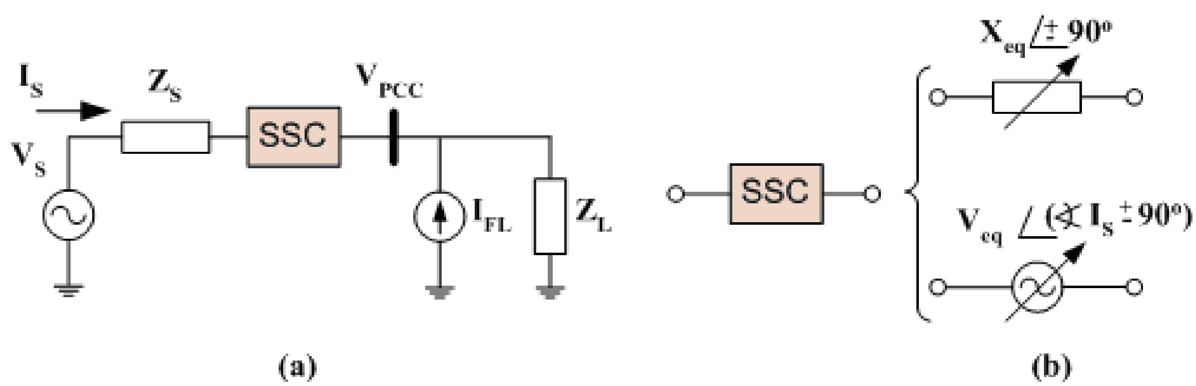


Figure 3-13
(a) Schematic of Voltage Fluctuations Mitigation at PCC using Series Controllers (b) Possible Approaches for Control

Potential topologies that could be effective for the implementation of series flicker controllers are presented in Figures 3-14(a) through (c).

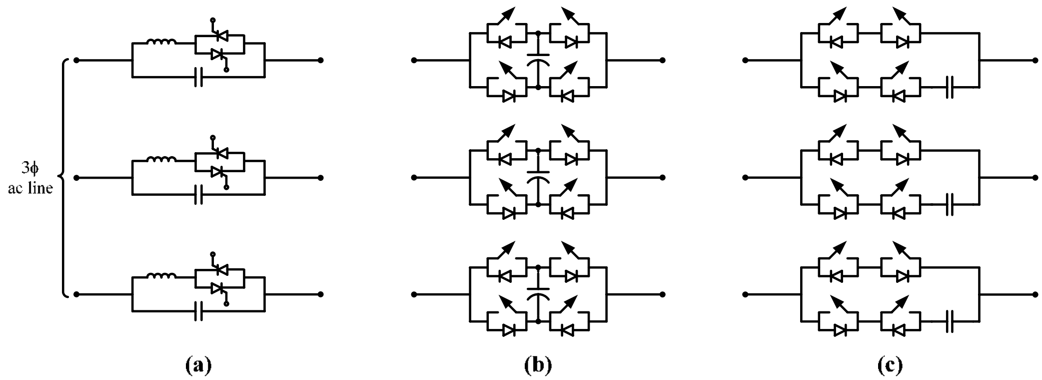


Figure 3-14
Topologies Suitable for the Realization of Series Controllers (a) Intellivar-Derivative (b) DVR-Derivative and (c) PWM Capacitor-Derivative

As can be seen, the Intellivar-derivative and the dynamic voltage restorer- derivative devices have exactly the same topologies as their shunt counterparts. The difference lies on the control loop that make them compensate for voltage rather than current fluctuations. On the other hand, the series SSFC has been modified in order to comply with stiffness requirements of poles and throws. Operating details of these three devices have been reported in the technical literature, although for different applications. While the attributes presented in Table 3-1 still hold for the series case, it is unclear at first glance how these devices would compare with their shunt counterparts. Thus, future investigations will focus on the unveiling the various tradeoffs among these approaches.

Solid-State Distributed Generation Interfaces

Distributed generation systems are emerging as an alternative to conventional central station based electrical power systems in congested locations to meet demand growth particularly in transmission constrained situations. Several recent standards including the IEEE 1547 address the interconnection requirements in a systematic manner to ameliorate anticipated technical issues. In particularly demanding situations such as heavily loaded network systems in urban regions where DG can have the greatest impact, the connection of new DG increases the fault current level and disturbs the coordination of the existing over current protection system. These problems may be solved by upgrading the circuit breakers capabilities and redesigning the protection system. However, this solution is not practical as it demands an immense capital cost. Therefore, several techniques based on operating procedure such as network splitting and sequential network tripping schemes and others based on hardware such as current limiting reactors and fault current limiters have been considered to address these issues. Within them, the fault current limiters (FCL) are the most promising devices as they offer the greatest flexibility. Advanced power electronics approaches that go beyond limiting fault current contributions are considered further.

Series Controllers

A solid state converter may be used to interconnect between the DG and the grid to provide a controlled interface, as illustrated in Figure 3-15(a). The SSC device introduced in series at the interconnection may be operated as a lossy resistive device or as a controlled voltage source capable of absorbing energy as shown in Figure 3-15(b). Figure 3-16 shows the realization of each of these devices using SCR and FCS type of semiconductor switches. An appropriately designed device would be capable of providing the following functions:

- Limit short-circuit current
- Provide means for synchronization
- Reducing flicker
- Providing tie line power flow control
- Enhance generator transient stability
- Suppress shaft torque oscillation
- Anti-islanding

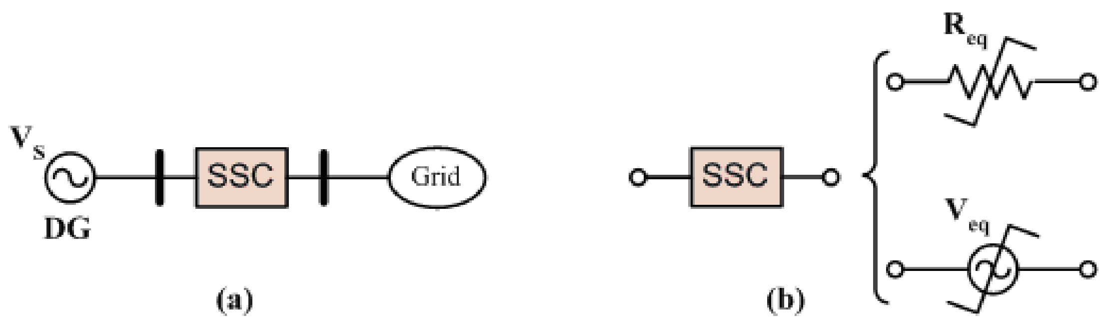


Figure 3-15
(a) Schematic of a Series SSC Acting as an Interface Device and (b) Its Possible Realizations

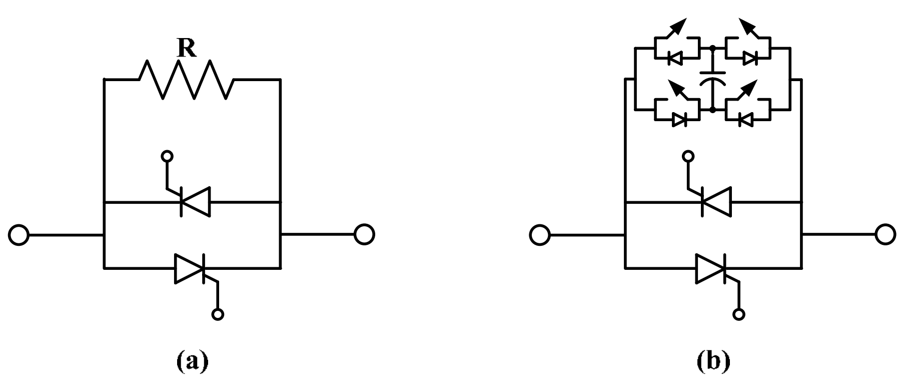


Figure 3-16
(a) Realizations of a Bypass Resistor and (b) a Bypass Voltage Source Series Inverter

Shunt Controllers

- A solid state converter may be applied in shunt at the point of connection of DG to the grid, as illustrated in Figure 3-17. The SSC device introduced in shunt at the interconnection may be operated as a lossy resistive device or as a controlled current source capable of absorbing energy as shown in Figure 3-17(b).

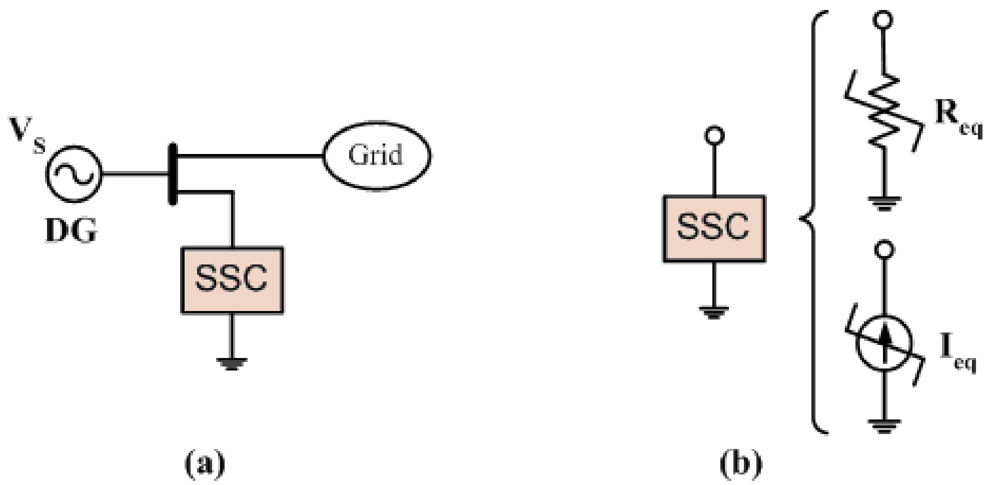


Figure 3-17
(a) Schematic of a Shunt SSC Acting as Damper Device and (b) Its Possible Realizations

Figure 3-18 shows the realization of each of these devices using SCR and FCS type of semiconductor switches.

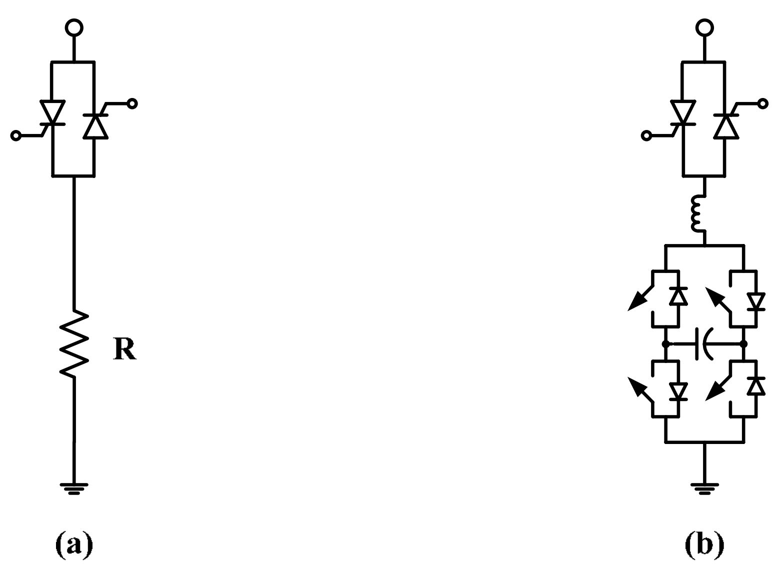


Figure 3-18
(a) Realizations of a Breaking Resistor and (b) a Breaking Voltage Source Shunt Inverter

An appropriately designed device would be capable of providing the following functions:

- Enhance generator transient stability
- Damp SSR
- Damp subsynchronous shaft torques
- Facilitate the synchronization of the prime-mover with the generator

The shunt and series connected devices illustrated above are capable are performing some of the interface functions identified for interconnection of DG systems in congested network locations, depending upon their configuration. Continuing investigations will focus on evaluating these devices in fulfilling their functionalities in the most economical manner.

Electronic Clutch for Capacitor Switching

There are a several important transient-related concerns in the application and operation of transmission voltage level capacitor banks. The capacitor bank energizing transient shown in Figure 3-19 is among the most frequent utility system switching operations. It can produce high phase-to-phase overvoltages on a terminating transformer, excite resonances resulting in transient voltage magnification in secondary voltage networks, or cause problems on customer facilities. Their application concerns at substations include insulation withstand level, switchgear capabilities, energy duties of protective devices, and system harmonic considerations. They may also have negative impacts on power quality, especially for customer power systems. Typical power quality problems related to utility capacitor bank switching include: customer equipment damage or failure due to excessive overvoltage, nuisance tripping of variable-speed drives or other process equipment shutdown, failure of transient voltage surge suppressors (TVSS) failure and interruptions of sensitive data process locations.

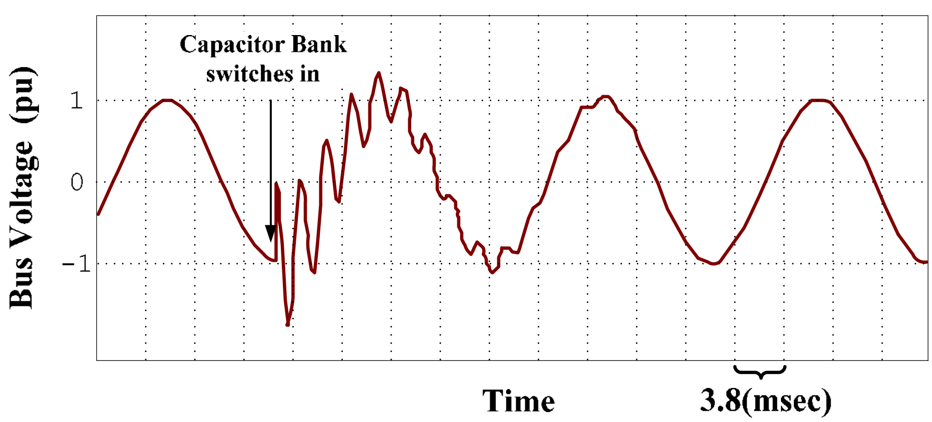


Figure 3-19
Example of a Voltage Transient Resulting from Interconnecting a Capacitor Bank

A suitably designed SSC device applied in conjunction with an existing or classical capacitor bank can prevent all the problems associated with capacitor switching transients by acting as a 'clutch' to modulate the energy flow during switching. A schematic of a realization of an electronic clutch is illustrated in Figure 3-20.

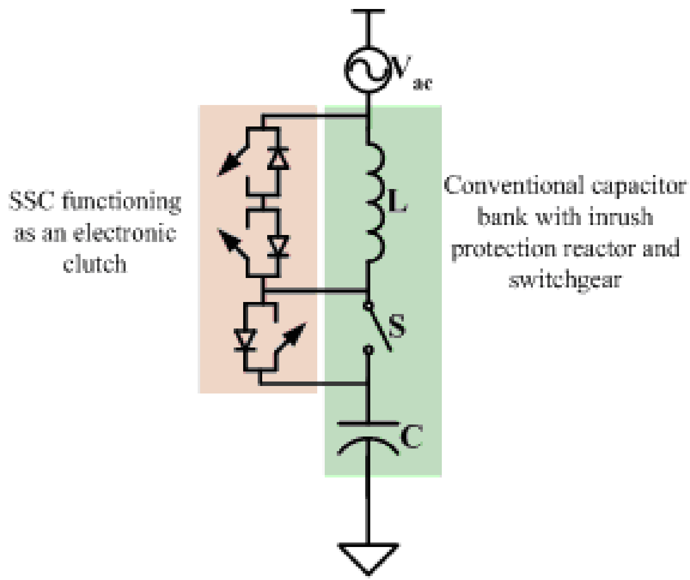


Figure 3-20
Schematic of the Realization of an Electronic Clutch for Capacitor Switching

A suitably designed and operated electronic clutch can prevent the following problem associated with capacitor switching.

- Prevention of transient overcurrent and overvoltage magnitudes for normal capacitor bank energizing operations
- Smooth transients during switching events
- Inrush current limiting
- Outrush current limiting for nearby fault conditions
- Prevention of restrike events
- Phase-to-phase transients at transformer terminations
- Prevention of voltage magnification due to system resonance
- Prevention of ferroresonance problems with nearby transformers

Summary

This chapter has presented a preliminary review of selected applications of power electronics devices that may be used in substations. In the following two chapters solutions for transformer capacity addition and capacitor switching are discussed in more detail.

4
TRANSFORMER CAPACITY ADDITION IN SUBSTATIONS

Standard methods for studying capacity expansion of substation include load growth forecast, power flow programs, short-circuit and fault-current calculation programs, voltage drop calculation programs, and total system impedance calculation programs. These, combined with other tools such as voltage regulation, capacitor planning, and reliability, give insights of the type and timing for expansion needs. The result of these studies may indicate the need of constructing an entirely new substation or the replacement or upgrade of a specific piece of equipment at existing substations. One of the major components at substations is the power transformers used to accommodate the voltage levels of the input side with the output side. When the study indicates a need for an increase in the transformation capacity, the possible solutions are either the replacement of the existing transformer for a new one of bigger capacity, or the addition of a second unit in parallel with the exiting one. The latter is the most attractive option, economically and from the reliability point of view.

Nominal Operation of Parallel Transformers

The main requirement for optimal operation of transformers in parallel is that the load current through them ought to distribute proportionally to their rated power so that the total capacity of the transformers set corresponds to the sum of the individual transformer capacity. In order to quantify this requirement, consider the operation of two transformers in parallel as depicted in Figure 4-1.

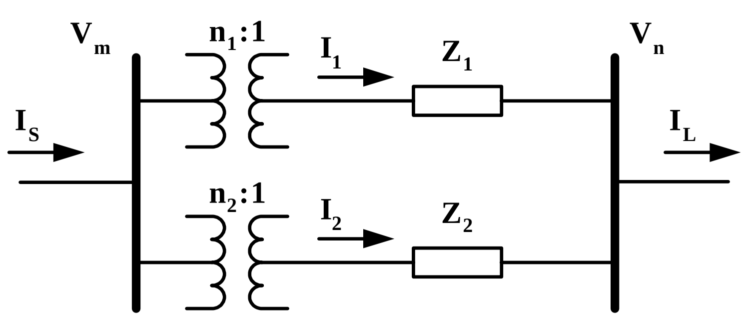


Figure 4-1
Schematic of Two Transformers Connected in Parallel

Series Balancing Transformer

A completely passive solution for ensuring adequate load sharing between the two transformers is illustrated in Figure 4-2. A balancing transformer is connected in series with the existing parallel transformers. The design procedure for the series balancing transformer is shown in equations (4-1) to (4-3). The turn ratio of the series common transformer is designed to be $1/S_1^{rated}:1/S_2^{rated}$, so that as balanced current flows through the transformer, the flux induced in the transformer will cancel each other. In case of unbalanced current, the flux is not equal to zero, thus produces an inductance in the common series transformer, as a result, the unbalanced current will be minimized. Consequently, the impedance of each path in Figure 4-2, is $Z_1 + Z_{eq1}$, $Z_2 + Z_{eq2}$. When the unbalanced current flows, $(Z_{eq1}) > (Z_1)$, $(Z_{eq2}) > (Z_2)$, and $(Z_{eq1}) = -(Z_{eq2})$ will be satisfied, with this, the currents in each part will automatically be balanced because $Z_1 + Z_{eq1}=Z_2 + Z_{eq2}$. Typically, the MVA rating of the common series transformer is less than 5%.

$$V_p = \frac{S_2 \cdot (V_{n(L\text{-}N)})(\%L_2 - \%L_1)}{S_2 + S_1} \qquad \textbf{Eq. 4-1}$$

$$V_s = \frac{S_1 \cdot (V_{n(L\text{-}N)})(\%L_2 - \%L_1)}{S_2 + S_1} \qquad \textbf{Eq. 4-2}$$

$$S_{series} = \frac{S_1 \cdot S_2(\%L_2 - \%L_1)}{S_2 + S_1} \qquad \textbf{Eq. 4-3}$$

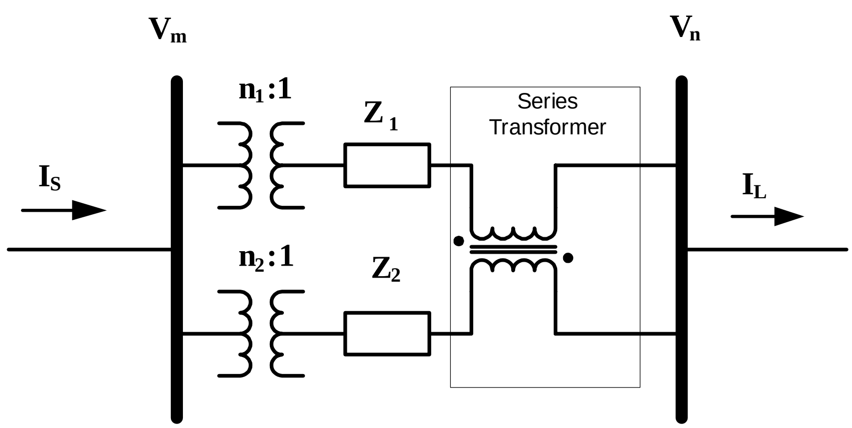


Figure 4-2
A Passive Solution for Balancing Power among Parallel Connected Transformers

A case study to demonstrate the operation of this approach is illustrated in Figure 4-3. The circuit configuration consists of 345kV utility power, parallel transformers and a 200MW, 60MVAr inductive load. Generally, the impedance of the transformers ranges from 5 to 10%. Considering the worst case for power-flow imbalance, Transformer 1 is assumed to have an impedance of Z_1=10% and Transformer 2 is assumed to have an impedance of Z_2= 5%. It is also assumed that $n_1=n_2$, thus we have that S_1^{rated}=200MVA, and S_2^{rated}=50MVA.

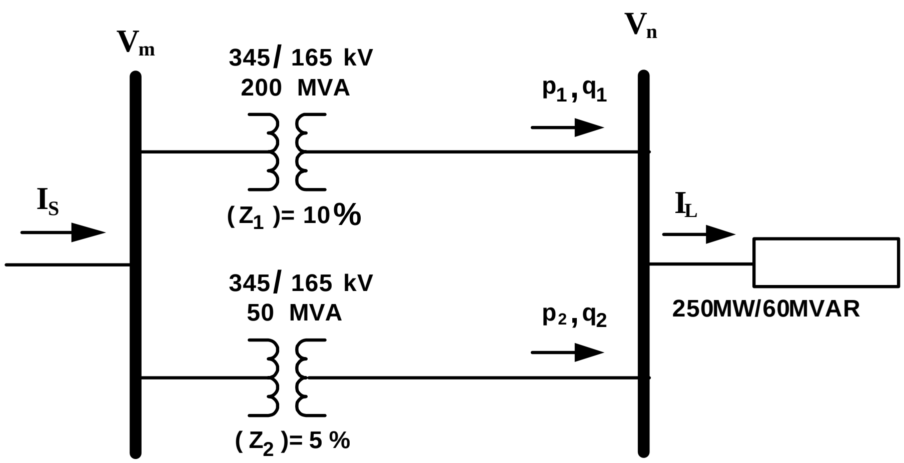


Figure 4-3
Schematic of 345kV Utility Parallel Connected Transformer

Figure 4-4 shows the simulation results without any solutions for load balancing among the parallel connected transformers. It may be noted that active power of each transformer depends on the difference between their impedances. Thus, the power flow is unbalanced as shown in the graph. In particular, the active power of the second transformer, p_2 exceeded its MVA rating of S_2^{rated}=50MVA.

Figure 4-5 shows the simulation results with a solution for the load balancing among the parallel connected transformers using a series transformer. The MVA rating of each parallel transformer is 200MVA and 50MVA, respectively. Thus the ratio of power flow through the transformers should be 4:1. In Figure 4-5 it may be noticed that the power flow through the two parallel transformers are well balanced, and match their ratings.

While the passive approach illustrated above is capable of providing an effective solution in term of size and cost, it requires a custom design of the series transformer, and a reconnection of the existing transformer circuit. Power electronics based solutions that may operate in a plug-and-power manner are explored further.

In the previous technical update, it was concluded that power electronics based solutions can provide satisfactory performance regarding all operational restrictions of parallel connected transformers. Consider the insertion of a Solid State Controller (SSC) connected in series with the additional transformer T_2, as depicted in Figure 4-6(a). The realization of the SSC using a Back-to-Back configuration and a Shunt/Series Bypass configuration are discussed further.

Back-to-Back Configuration

Figure 4-7 illustrates a solution using a Back-to-Back (BTB) configuration. The BTB system consists of two series ac/dc converters connected back-to-back, a common dc link capacitor, and two shunt transformers. Both converters together can control the current, I_2 shown in Figure 4-7, independent of the impedances, Z_1 and Z_2 and thus balance the power flow among the paralleled connected transformers.

However, this solution has a disadvantage in terms of the physical size and cost. The BTB system would require 100% MVA rating that is the same as the rating of the additional transformer because of the current I_2 flowing through the BTB system and the additional parallel transformer.

Shunt/Series Bypass Configuration

As an alternative solution for balancing the power flow among parallel connected transformers, a Shunt/Series Bypass (SSB) configuration is proposed. In principle, the configuration of the SSBS could be either a AC/DC/AC or AC/AC/AC. The AC/DC/AC configuration is illustrated in Figure 4-8. The SSBS consists of series and shunt converters connected back-to-back, a common dc capacitor, and two step-down series/shunt transformers.

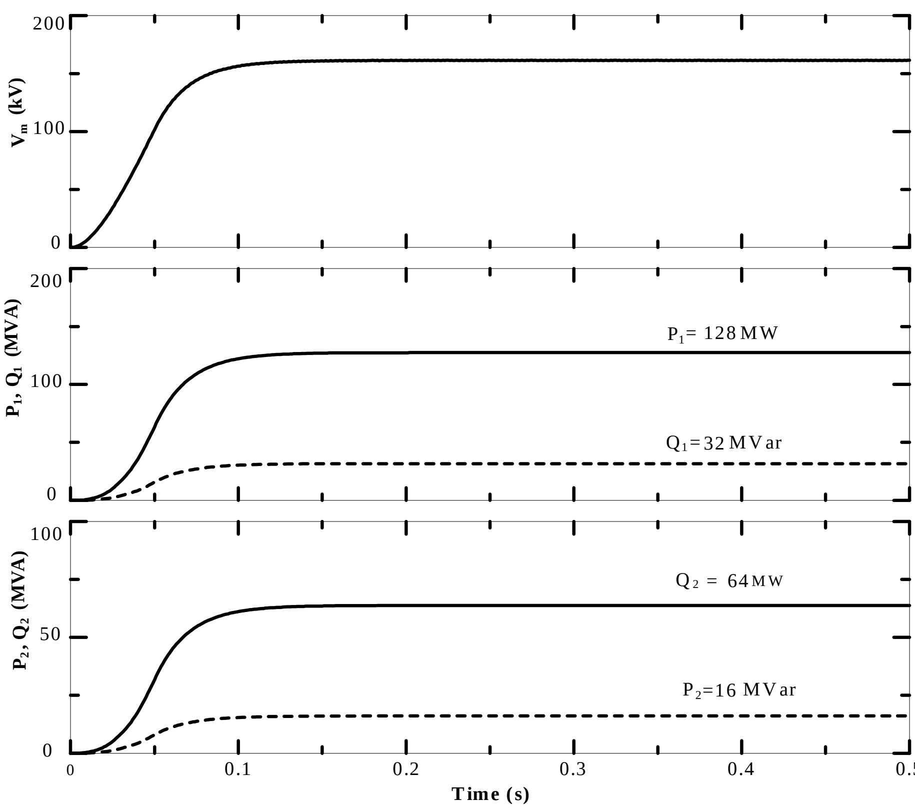


Figure 4-4
Simulation Result Showing Real Power and Reactive Power for Parallel Connected Transformers.

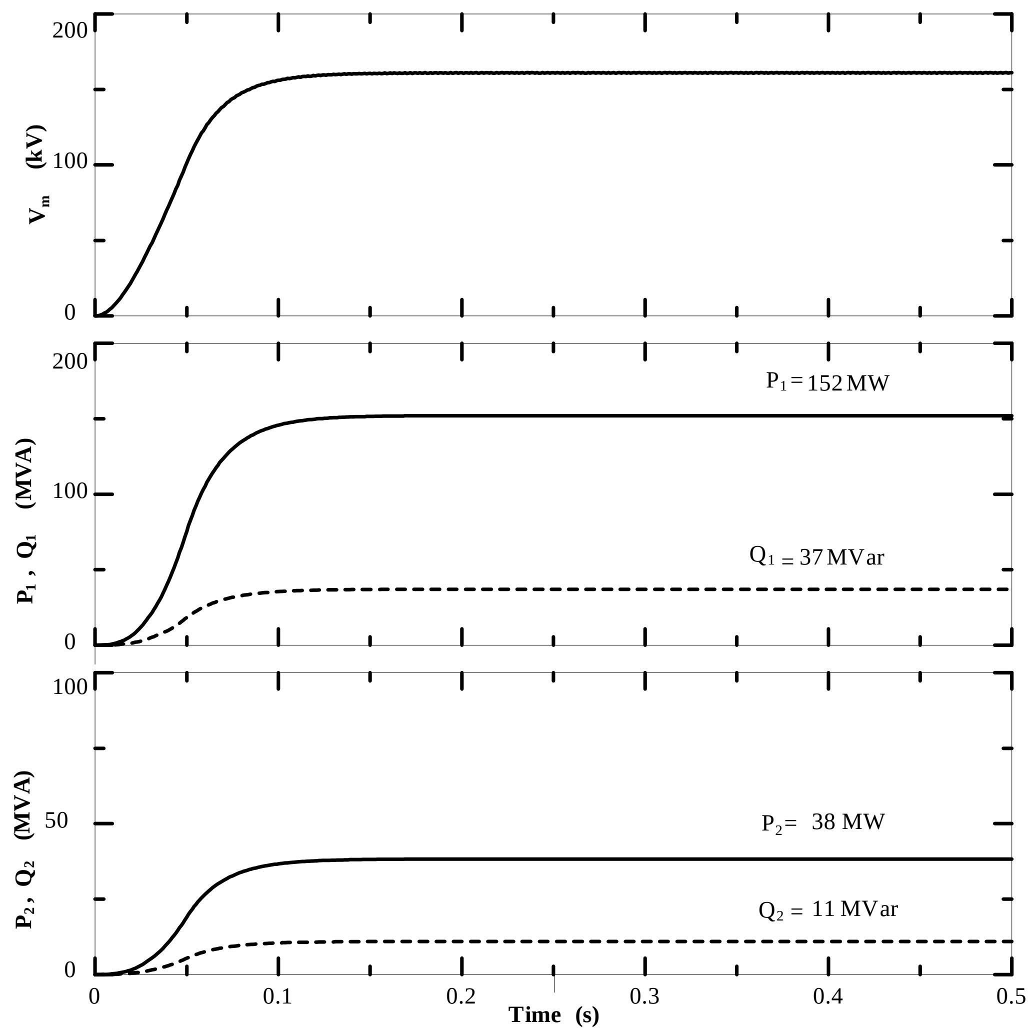


Figure 4-5
Simulation Showing Real Power and Reactive Power of Parallel Connected Transformers with Solution using a Series Connected Transformer

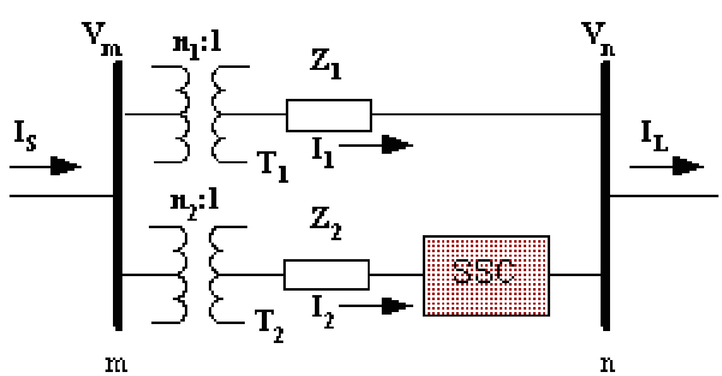


Figure 4-6
(a) Solid State Controller for Parallel Operation of Transformers

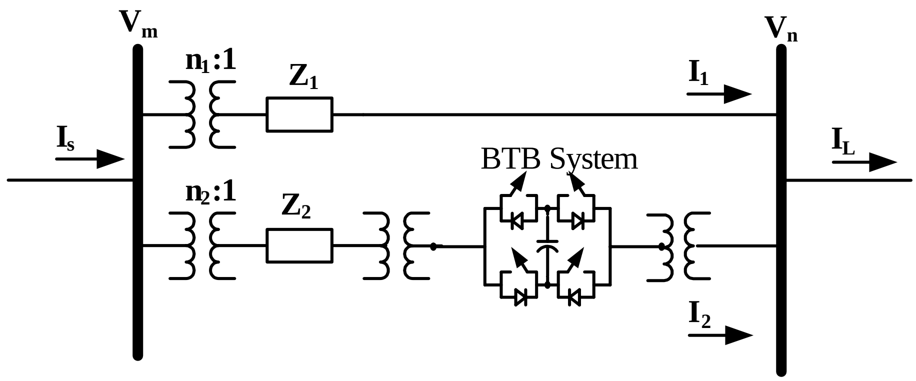


Figure 4-7
A Solution for Parallel Operated Transformer using a Back-Back System

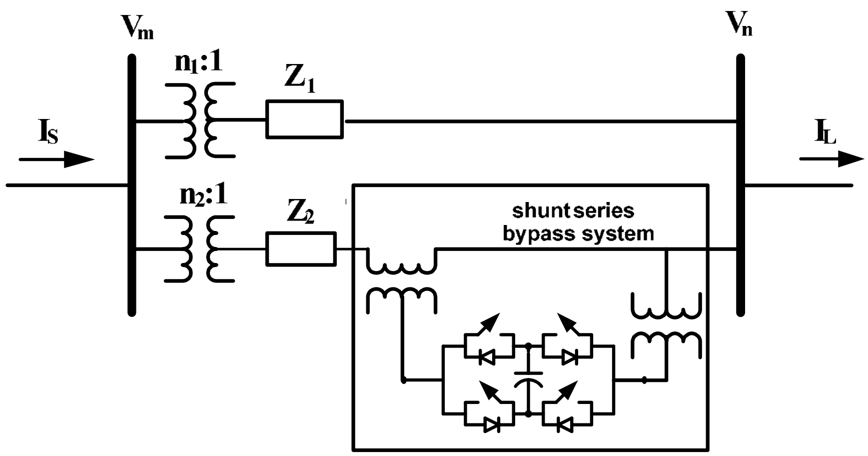


Figure 4-8
A solution for Parallel Connected Transformer using a Shunt/Series Bypass System

$$I_1 = \left(\frac{1}{n_1} - \frac{1}{n_2}\right)\frac{V_m}{Z_1 + Z_2 + Z_{eq}} + \frac{Z_2 + Z_{eq}}{Z_1 + Z_2 + Z_{eq}} I_L \quad \textbf{Eq. 4-4}$$

$$I_2 = \left(\frac{1}{n_2} - \frac{1}{n_1}\right)\frac{V_m}{Z_1 + Z_2 + Z_{eq}} + \frac{Z_1}{Z_1 + Z_2 + Z_{eq}} I_L \quad \textbf{Eq. 4-5}$$

It can be seen from (4-4) and (4-5), that if $n_1 = n_2$, the condition $Z_1 = Z_2 + Z_{eq}$ that leads to adequate power balancing can be met by appropriately adjusting the value of the equivalent impedance, Z_{eq}. Considering that in general the impedance of transformers ranges from 5% to 10% indicates that the maximum value of Z_{eq} would be equal to 5%. Hence, the SSBS is designed to have the MVA ratings of only 5% of the second transformer (S_2^{rated}), thus being more suitable than the BTB system in terms of size and cost.

Furthermore, the equivalent impedance, Z_{eq} is generally inductive. Therefore, the direction of the power flow is from the shunt converter to a series converter. Therefore a diode rectifier may be used as the shunt converter, leading to a more economical and reliable compared solution.

Summary

In summary, transformer capacity addition in substations in a plug and power manner may be realized using incremental installation of power electronic converters in the system, but would require further engineering studies, detailed design and laboratory scale demonstrations.

5
ELECTRONIC CLUTCH TO MITIGATE CAPACITOR SWITCHING TRANSIENTS

Classical Solutions for Mitigating Utility Capacitor Switching Transients

A number of methods have been proposed and used to ameliorate transient phenomenon due to capacitor energization. Adding a damping resistor or inductor in series are the most common and simple methods often used in power utilities.

Pre–Inserted Inductor

Pre-inserted inductor illustrated in Figure 5-1 (a) can nominally provide over-voltage control and also limits inrush currents. The concept is that the surge impedance of the circuit can be increased by the intentional addition of inductance. The addition of inductance within the capacitor bank circuit can also help reduce stress among other transmission level devices that are not associated with the capacitor bank. Pre- inserted inductor has been discussed as one of the most economic methods in mitigating capacitor transients; however, it may be ineffective for certain system conditions, depending on line length, system's healthiness and capacitor size. In addition, inserting an inductor into the capacitor bank is not a perfect solution for an opening operation because an abnormal voltage across the switch can result when the capacitor bank is disconnected.

Pre–Inserted Resistor

Circuit breakers with resistor pre-inserted in series with the capacitor bank circuit during switching has been used for a long time to mitigate capacitor bank switching transients. The added resistor absorbs energy unless it is shorted out after the capacitor bank is switched on. With the pre-inserted resistor method, shorting out requires a second switch, which increases cost and complexity of the switching device, and the second switching may cause another transient.

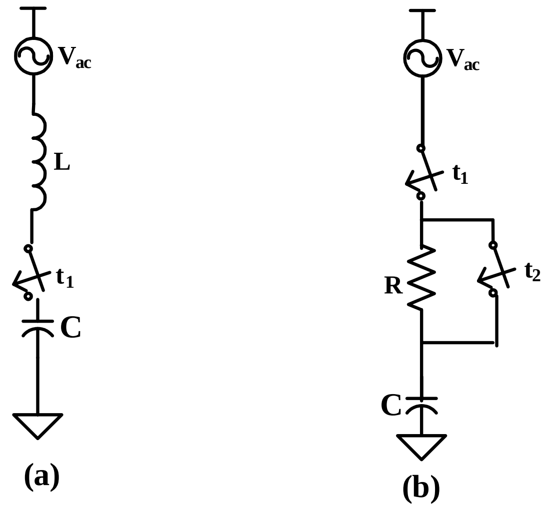


Figure 5-1
Two Common Methods to Minimize Capacitor Switching Transients (a) Pre-Inserted Inductor (b) Pre-Inserted Resistor

Pulse Width Modulation Switching

A suitably designed SSC (Solid State Controller) device applied in conjunction with an existing or classical capacitor bank can prevent all the problems associated with capacitor switching transients by acting as a 'clutch' to modulating the energy flow during switching. A schematic of a realization of such a device using a Pulse Width Modulated (PWM) Switch is illustrated in Figure 5-2.

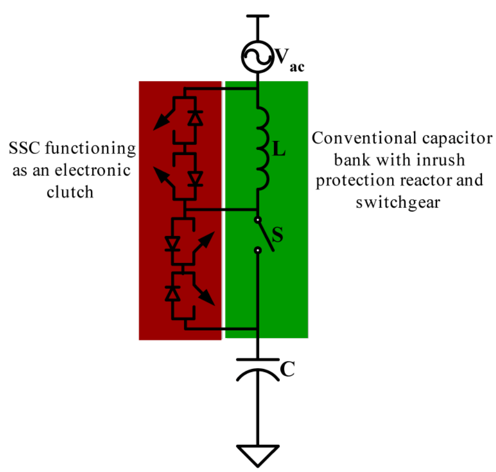


Figure 5-2
A PWM Switch for Capacitor Switching in Conjunction with the Existing Capacitor Bank

The realization of the PWM switch consisting of four IGBTs, or an equivalent semi-conductor device is illustrated in Figure 5-3. This device may be designed to operate by detecting, the utility voltage, V_{ac}, the inductor current, I_L , or the capacitor voltage, V_c.

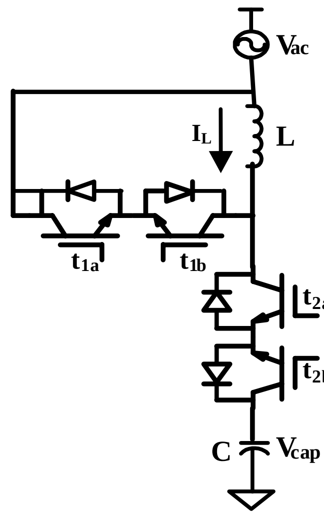


Figure 5-3
Schematic of the Realization of a PWM Switch for Capacitor Switching

PWM Switch Control Strategies

To demonstrate control strategies for the PWM switch, a simplified representation of substation illustrated in Figure 5.4 was simulated. The candidate three phase system simulated using Power System Computer Aided Design (PSCAD) consists of a 345kV utility voltage, a 345/115kV transformer, and a 50 MVAr capacitor bank for power factor correction (PFC), and a 11MVA inductive load. In this system, it is assumed that a three phase to ground fault occurs and cleared subsequently. At t = 0.9s, three phase to ground fault occurs, and at t=1.0s the breaker opens to clear the fault, finally, at t=1.5s, the fault is completely eliminated, and the breaker closes. Figure 5.5, shows voltage transients in the system during the switching event in the absence of any specific control of the PWM Switch.

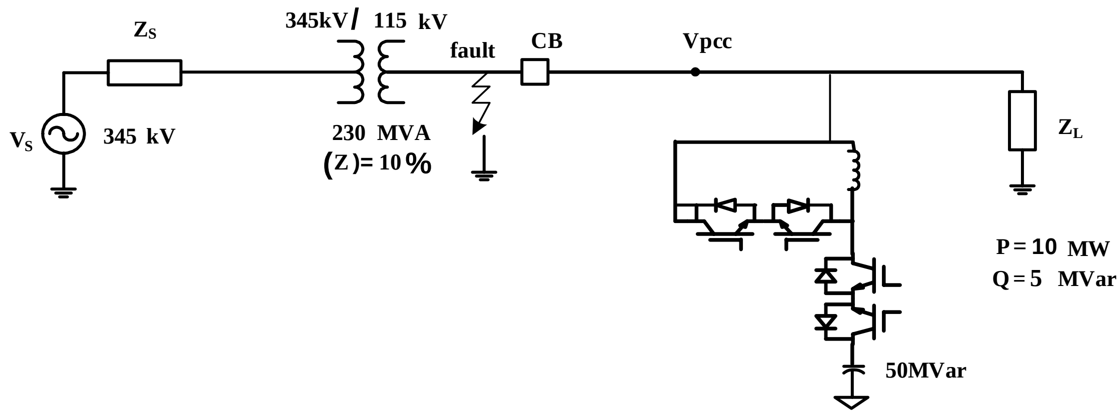


Figure 5-4
Simplified Representation of a Simulated 345kV Power System

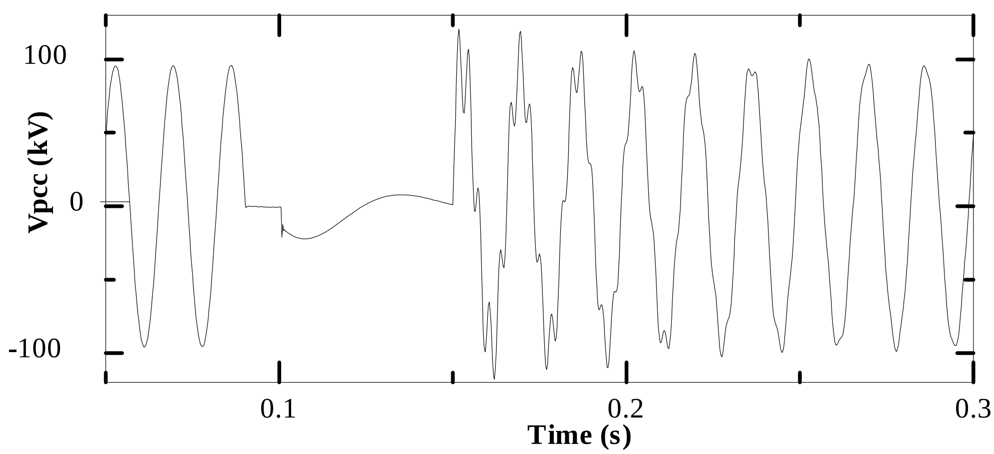


Figure 5-5
Simulation Results without Any Control Method

Ramp-up Duty Ratio Control Method

In the ramp–up Duty Ratio control method, the PWM switch is treated as a buck converter and control its duty ratio appropriately. In this application, when the duty ratio is equal to zero, the average voltage across the inductor during one switching cycle is zero, whereas when duty ratio is equal to one, the average voltage equals the difference between the utility voltage and the capacitor bank voltage. By using this scheme, the resonant current that results from the capacitor bank re-energization after the fault has cleared is suppressed by forcing the duty ratio to increase from zero to one slowly. This is an "Open Loop" control strategy; hence it is easy to control. However, during a fault, the capacitor bank voltage may not be zero, but the resonant current during a fault would be dependent on the ramp–up time. Figure 5-6 shows simulation results when the ramp-up duty ratio control method was applied. When the breaker is initiated at t=1.5s, the duty ratio changed from 0 to 1 slowly during one cycle. Although the voltage, V_{pcc} contains some switching ripples caused by the AC switching, the voltage transients are suppressed after one cycle.

Instantaneous Reactive Power Control Method

Instantaneous reactive power control method compensates a fluctuating reactive power caused by resonant current. In steady state, the instantaneous reactive power, Q is constant. However the current that result from capacitor switching contains a resonant component, this causes instantaneous reactive power to fluctuate. Hence, to compensate this fluctuating component of reactive power, we propose a control method to realize this. Figure 5-7 shows a block diagram that realizes this control scheme.

To detect the instantaneous reactive power, a P-Q transformation is applied to the utility voltage, V_{ac} and the current, I_{C}, flowing into the capacitor. The mean reactive power, Q is computed using a low-pass filter (LPF). Hence, the fluctuated component of the reactive power is obtained from subtracting the mean value, Q, from the instantaneous power, q. If the mean value of the reactive power is equal to the instantaneous power, the duty ratio DR is set to one. The duty ratio, DR, is therefore determined by multiplying the instantaneous power, q by the proportional gain, k, and adding a constant value one.

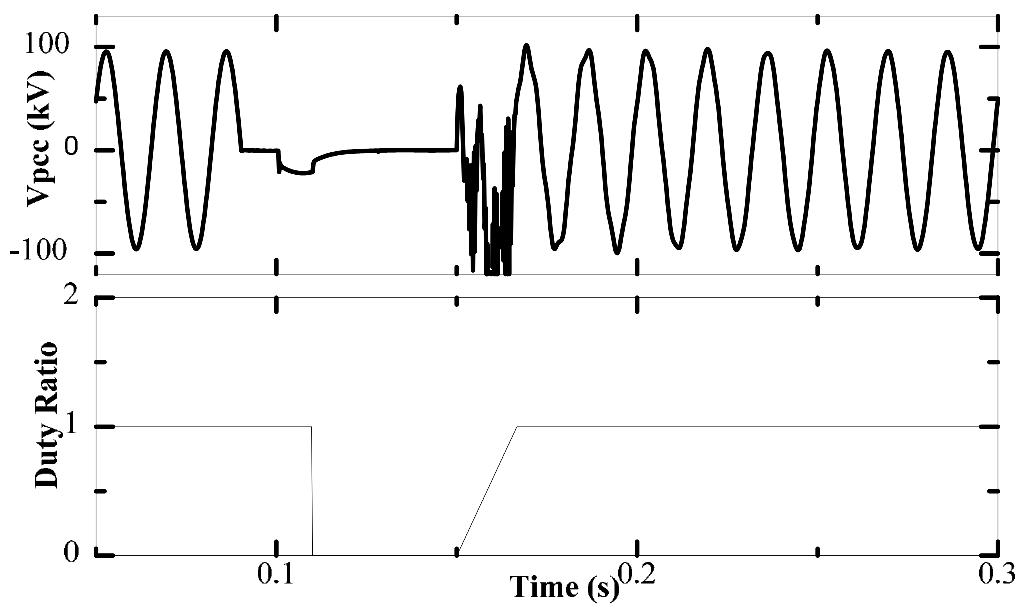


Figure 5-6
Simulation Results using the Ramp- Up Duty Ratio Control Method

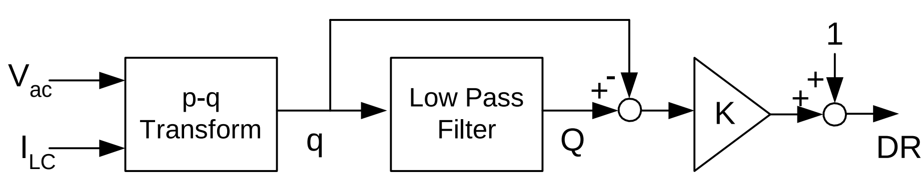


Figure 5-7
A Block Diagram for the Instantaneous Reactive Power Control Method

Figure 5-8 shows simulation results using the instantaneous reactive power control method. During the capacitor bank re-energization, resonant current flows into the capacitor bank. This resonant current creates a fluctuation in reactive power. In this control scheme, the PWM switch was controlled in order to minimize the reactive-power fluctuation. The duty ratio changed after t=1.5s, this is the time the breaker has interrupted the fault, and the resonant current was completely minimized in less than one cycle.

Based on the simulation results illustrated above, and estimates on the the switching stresses, losses and the complexity of the system, sensors and control, this approach was found to be unfavorable for further studies. An SCR or thyristor based device that is in shunt with the capacitor using a damping resistor is illustrated further as a more attractive approach for an electronic clutch.

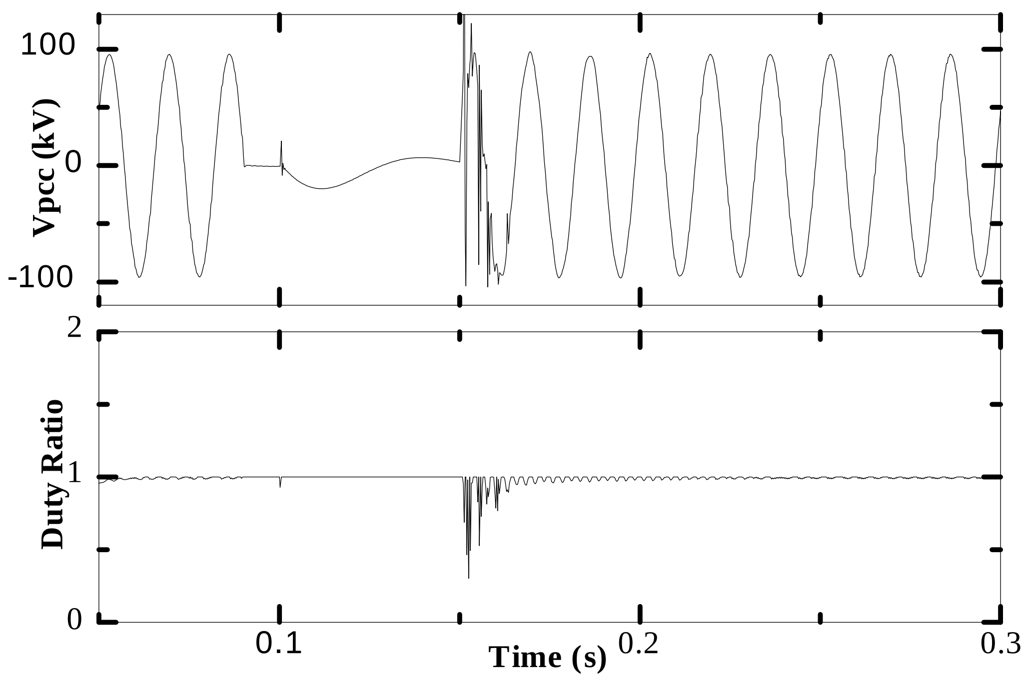


Figure 5-8
Simulation Result with the Instantaneous Reactive Power Control

Electronic Clutch Using Cycle Completing Switch

Simplified realization of an electronic clutch using an SCR or thyristor switching and a damping resistor is illustrated in Figure 5-9. The damping resistor is engaged in parallel with the capacitor during the switching operation. A suitably selected damping resistor absorbs the energy exchange between the system impedance and the switched capacitor and hence limits the overvoltages during switching transients. Soon after the switching transient is completed, the SCRs are turned off and the resistor is removed from the circuit at the subsequent zero crossing of the current.

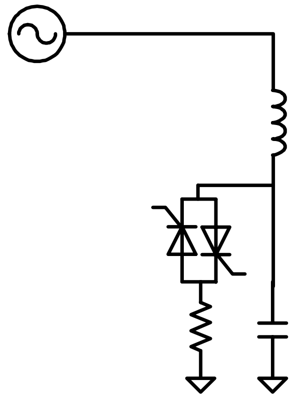


Figure 5-9
Schematic of the Proposed Electronic Clutch

In order the study the effectiveness of the proposed approach, the system was benchmarked against other approaches for mitigating overvoltage transients including (a) Full-time inductor (b) Pre-insertion inductor (c) Zero-crossing switch and (d) Pre-insertion resistor using computer simulations. The results are presented further using a low voltage system example that is further verified using laboratory experiments.

Benchmarking Simulation Results

Table 5-1 provides the parameters used in the computer simulation of the system illustrated in Figure 5-10 as single line diagram in PSCAD modeling environment.

Table 5-1
Parameters Used in the Simulation of Capacitor Switching Approaches

Quantity	Value	Units
Power Supply	230	V
Line reactance	9	mH
Capacitor:	7	μF
Parasitic inductance	5	mH
Full-time inductor	2, 1	mH, mΩ
Pre-insertion inductor	20, 0.2	mH, Ω
Zero-crossing breaker	1	ms
Pre-insertion resistor	50	Ω
Dumping resistor	50	Ω

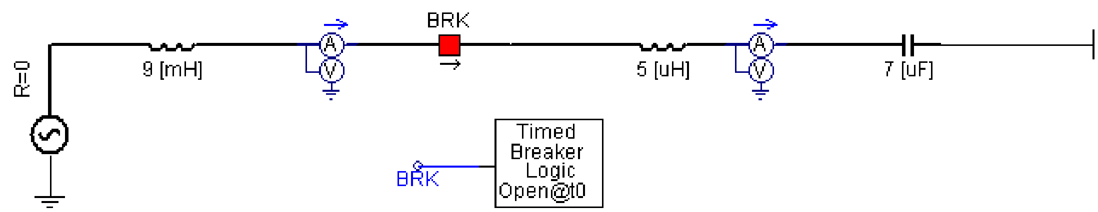


Figure 5-10
Single Line Diagram of the Benchmark Simulation

The three phase line to neutral voltage waveforms and capacitor voltage and current waveforms from each of the simulations are shown in Figure 5-11: Baseline capacitor switching; Figure 5-12: Full-time inductor, Figure 5-13:Pre-insertion inductor; Figure 5-14: Zero-crossing switch; Figure 5-15: Pre-insertion resistor; and Figure 5-16: Electronic clutch respectively.

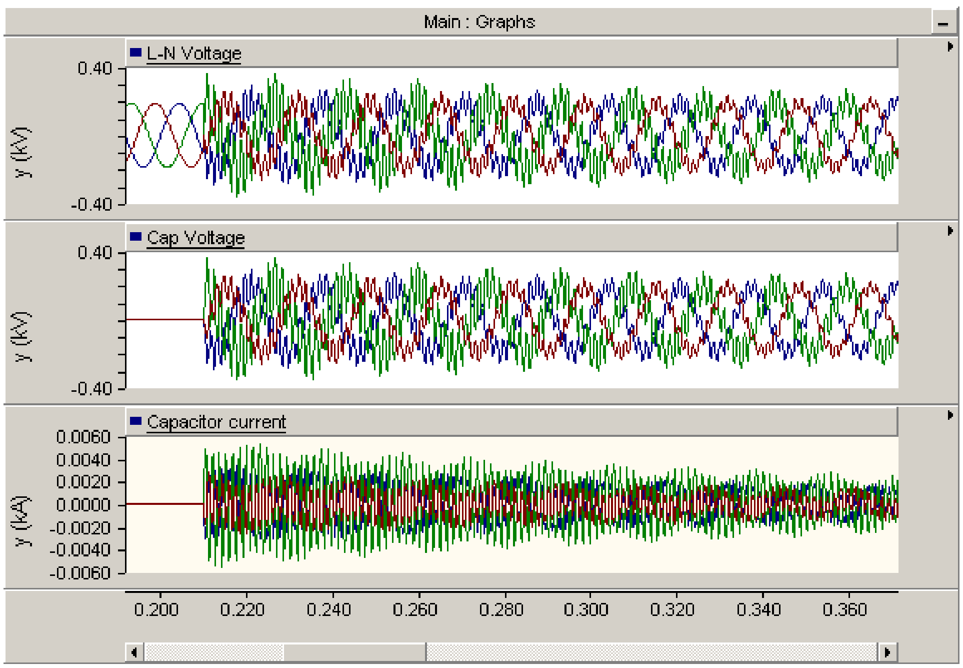


Figure 5-11
Simulation Waveforms from No Transient Limiting Case

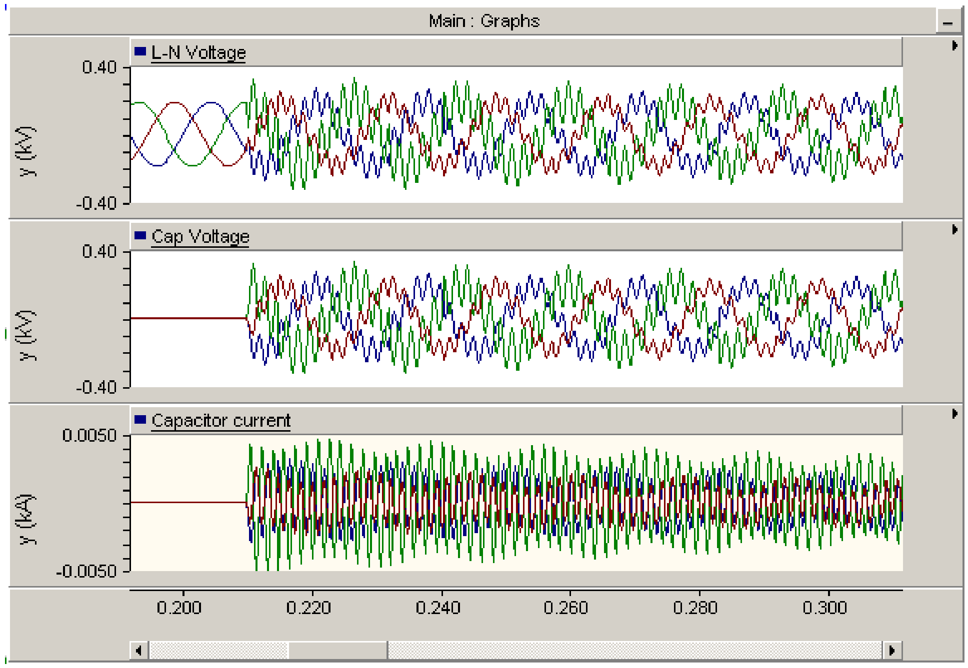


Figure 5-12
Simulation Waveforms using Full-Time Inductor Case

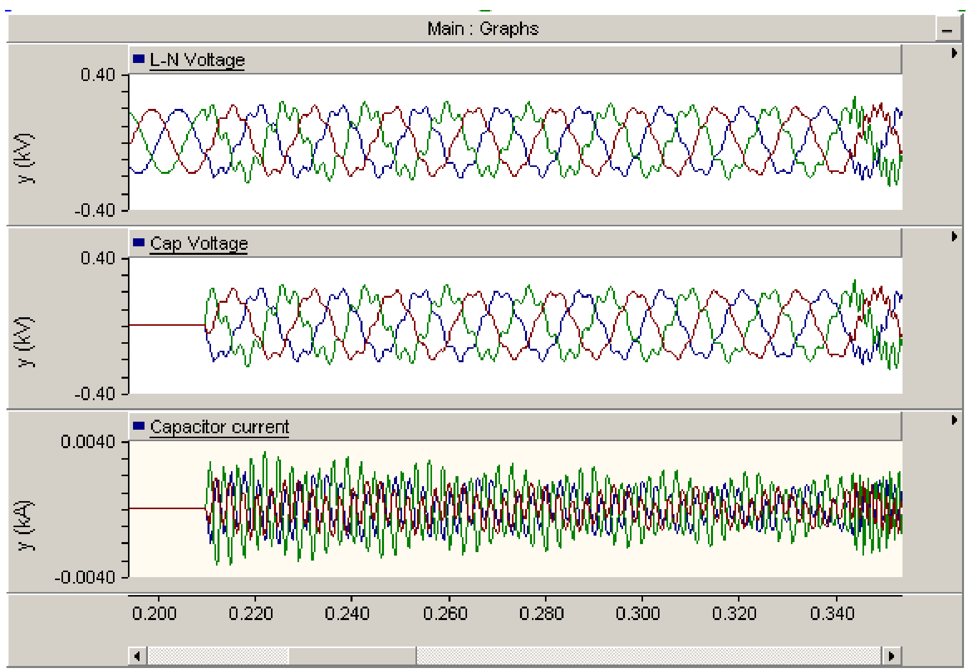


Figure 5-13
Simulation Waveforms using Pre-Insertion Inductor Case

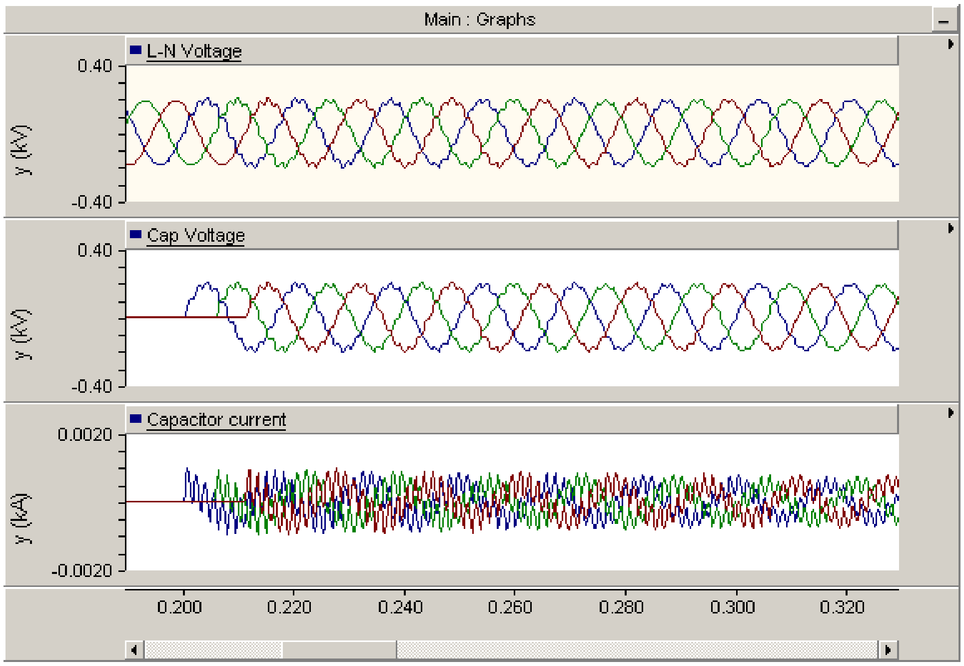


Figure 5-14
Simulation Waveforms using Zero-Crossing Switch Case

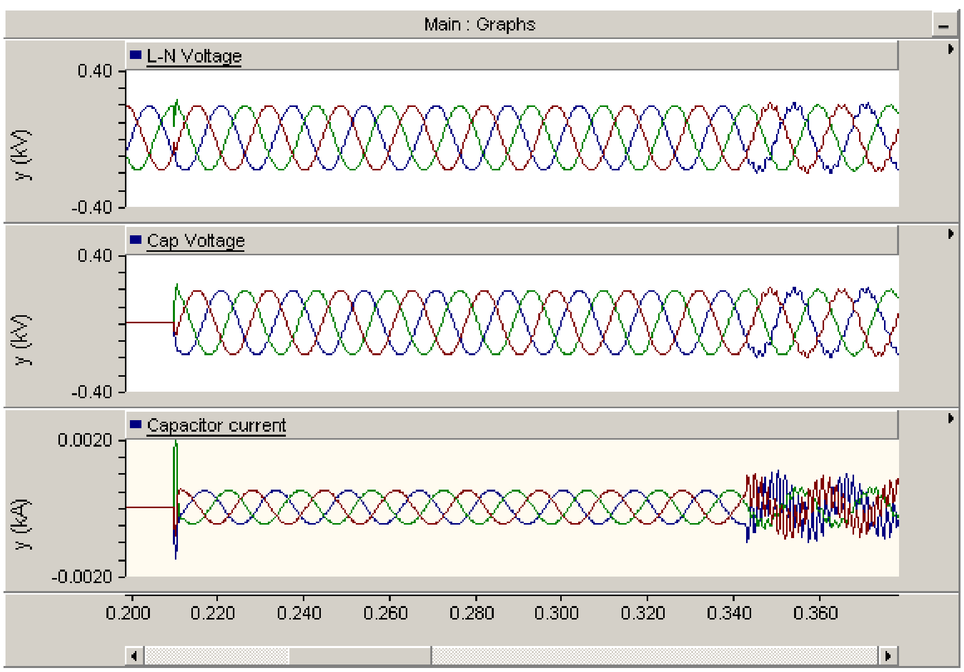


Figure 5-15
Simulation Waveforms using Pre-Insertion Resister Case

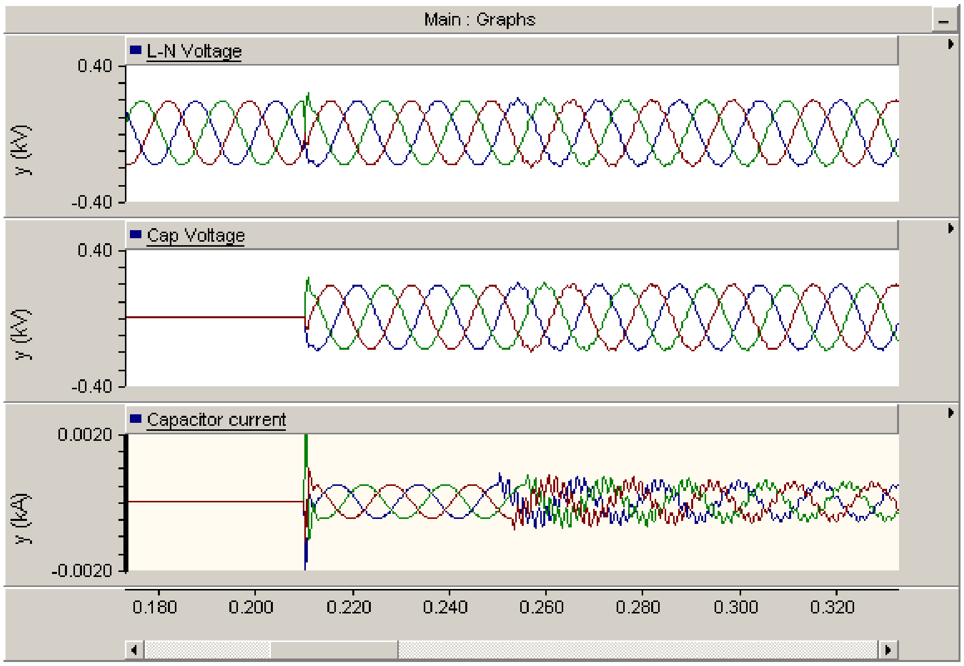


Figure 5-16
Simulation Waveforms using Electronic Clutch Case

The results readily demonstrate the functional performance of the electronic clutch against the state of the art benchmark devices. A laboratory scale experimental prototype of the system was developed and the results are presented further.

Benchmarking Experimental Results

A schematic of the laboratory experimental set-up used to verify the functionality of the electronic clutch is shown in Figure 5-17. As a low voltage system, the source impedance of the lab scale grid is highly resistive and provided more damping than the computer simulation environment. Besides that, the laboratory scale system and the computer models have identical parameters.

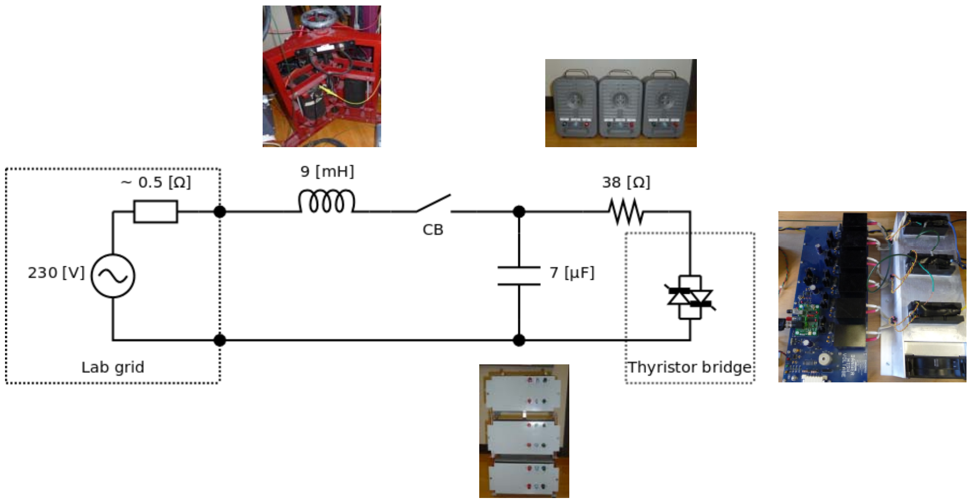


Figure 5-17
Schematic of Laboratory Scale Experimental System with Photographs of Major Components

Waveforms of the three phase capacitor voltage during the switching transient and an expanded view of the one of the phase voltages are illustrated in Figure 5-18 and Figure 5-19 for the baseline capacitor switching case and the application of the electronic clutch during switching respectively. The functional effectiveness of the electronic clutch is readily evident by comparing the two figures.

Having established the functionality of the proposed approach, a discussion of application considerations is presented further.

Application Considerations

Capacitor switching devices in utility distribution systems and substations have a long established field experience. The non-vacuum type switching devices are rated to have about 5000 switching operations. A majority of them maybe assumed to have about 200-250 operations per year. This yields about 20 to 25 years of operating life. If their application and installations in distribution systems typically took place in the 1970s and 1980s, a majority of them may be near their rated lifetime and slated for upgrade or replacement. Thus, technologies such as the proposed electronic clutch that can extend their lifetime or ease the stresses on them would be highly valued in systems.

Among the state of the art advanced switching solutions, the approach of using pre-insertion resistor is claimed to be effective at a lower cost compared to alternate solutions in the 69kV class of solutions according to a study by Progress Energy of Florida.

The application of pre-insertion resistors and inductors with existing switches or with new switches require breaking the circuit up-stream for de-energizing the system. This leads to circuit shut-down, consistent with utility safety protocols and maintenance practices. They have also been reported to have premature failures in the field.

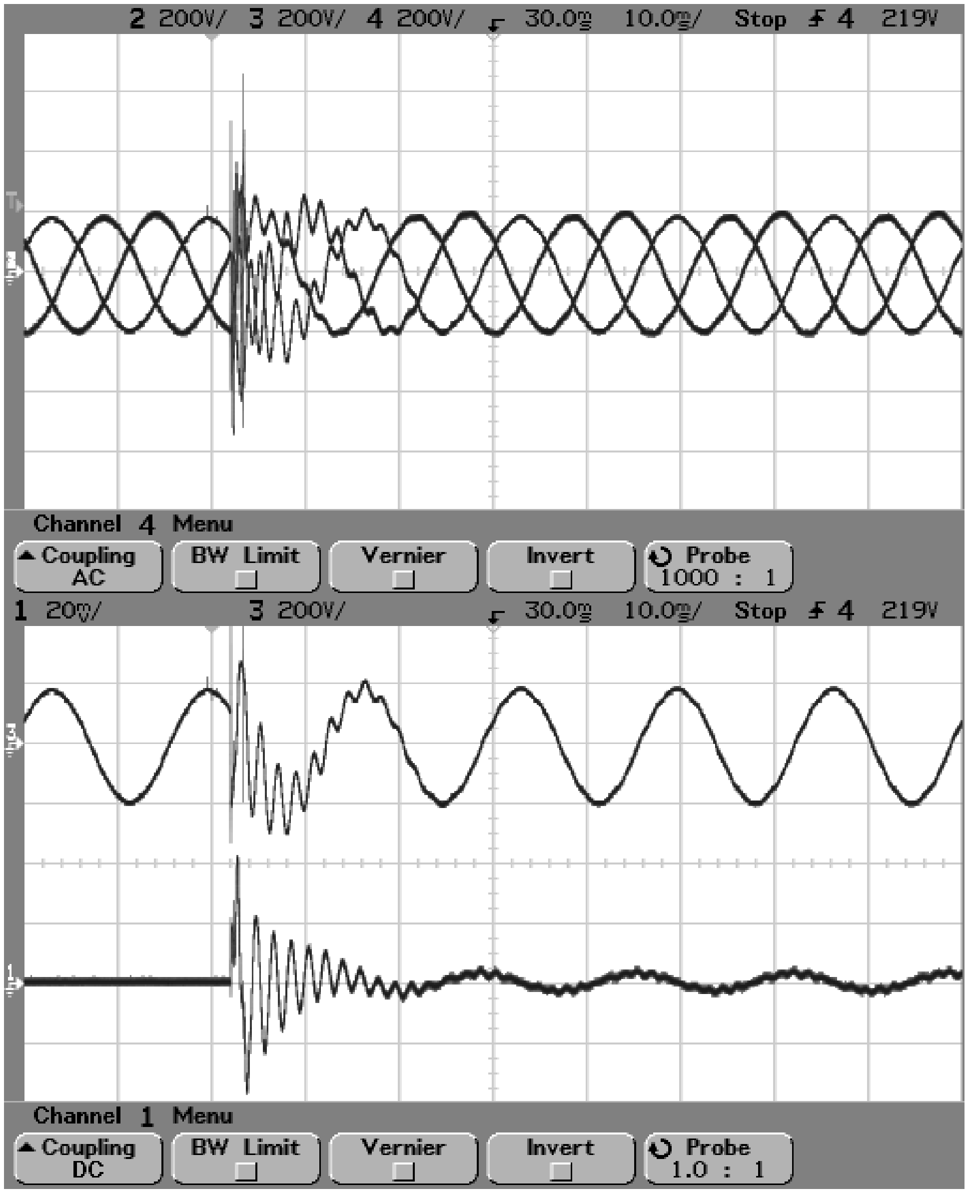


Figure 5-18
Three Phase Capacitor Voltage Waveforms and Expanded Views of Capacitor Voltage and Current Waveforms of One Phase from the Laboratory Scale Experimental Results of the Baseline Case of Capacitor Switching

On the other hand, use of zero voltage switch option requires a Vacuum or SF6 switches to provide adequate controlled dielectric withstand control during turn-on operation of the switch. This leads to additional cost in comparison to using classical break switches. Furthermore, they also require tuning and/or drift and sensitivity environmental factors.

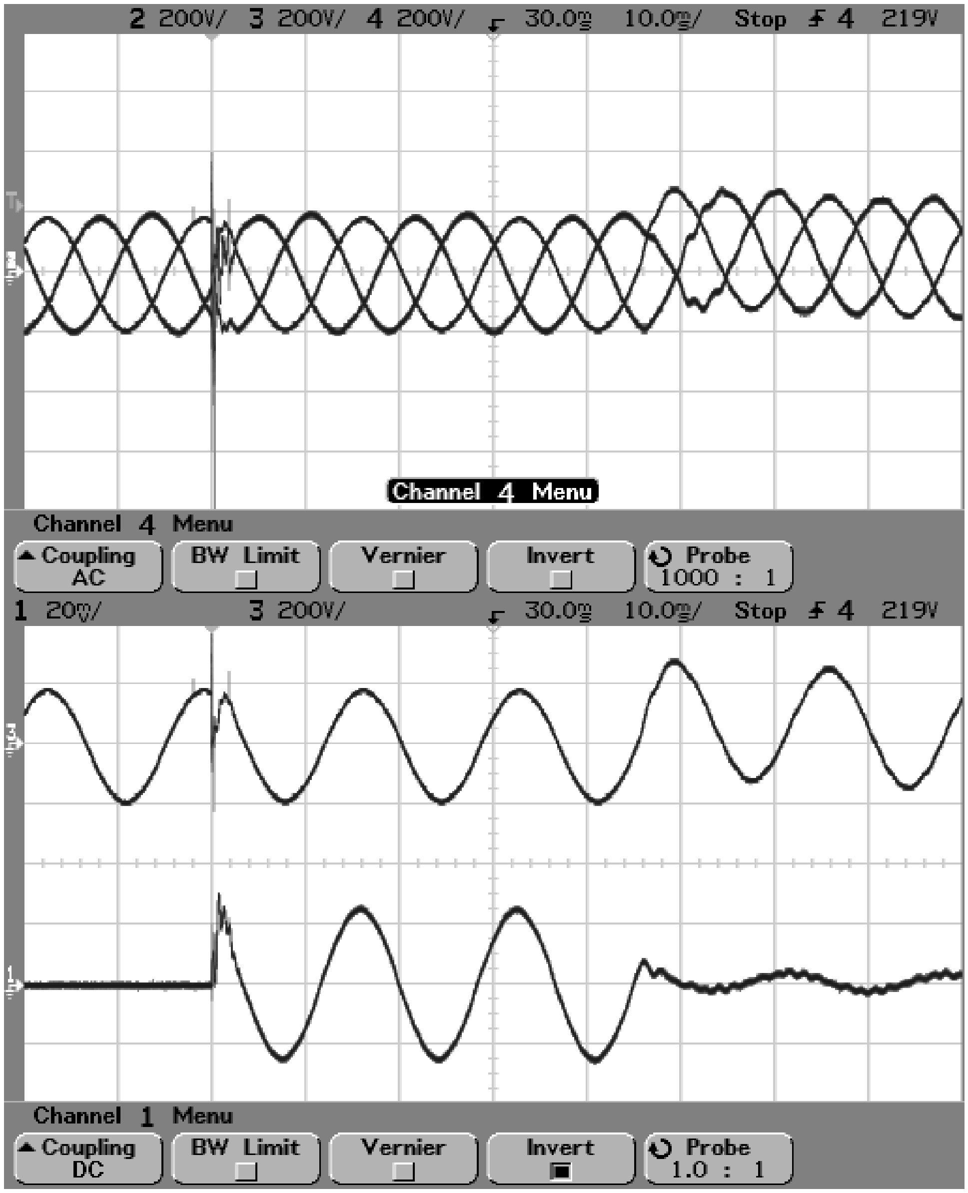


Figure 5-19
Three Phase Capacitor Voltage Waveforms and Expanded Views of Capacitor Voltage and Current Waveforms of One Phase from the Laboratory Scale Experimental Results of Capacitor Switching with Electronic Clutch

In contrast the proposed electronic clutch has the following attractive features:

- Limits overvoltages effectively
- Retrofit existing capacitor bank
- Shunt application of the solution across the capacitor bank
- Does not require circuit shut-down
- Existing circuit and controls unaffected

- Does not require additional sensors
- Switching coordination with existing control
- No sustained additional power loss
- Solid-state switch is short term rated
- Uses SCRs for solid state switches that are readily available at high power ratings
- Uses a damping resistor incorporating classical technology
- Can be realized in 4.1 kV, 13.8 kV and 69 kV systems
- Can be serviced easily without affecting circuit in case of mal-operation
- Can be applied selectively when necessary
- Controlled overvoltage transient switching completed within 2 cycles

Substation Application Study

In order to study the effectiveness of the proposed approach in a 345kV/115kV scale substation application, further simulations were conducted. Figure 5-20 illustrates the schematic of the substation environment model, while Figure 5-22 illustrates the schematic with the electronic clutch. The corresponding capacitor voltages are shown in Figure 5-21 and Figure 5-23 respectively. These transients correspond to the reclosing the capacitor switching device following its tripping during a fault at one of the buses as indicated in Figure 5-20 and Figure 5-22.

Summary

Based on the computer simulation results, experimental results and preliminary assessment of application issues, the electronic clutch has the potential to become a competitive commercial product.

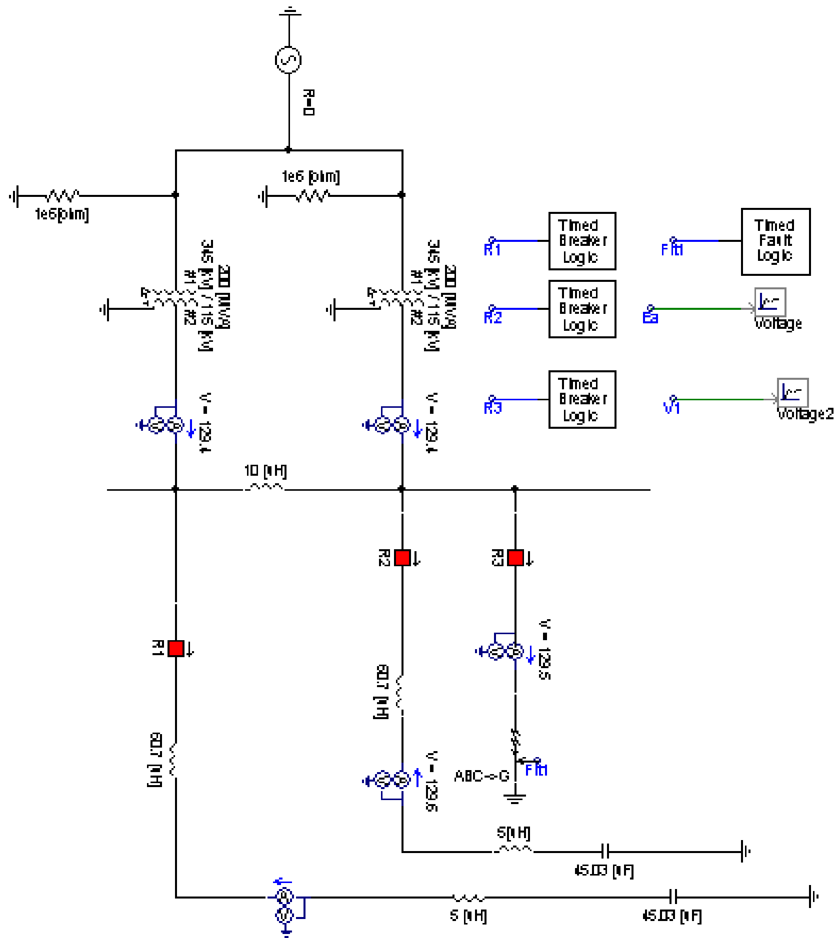


Figure 5-20
Single Line Diagram of the Benchmark Simulation of Capacitor Switching in a Substation

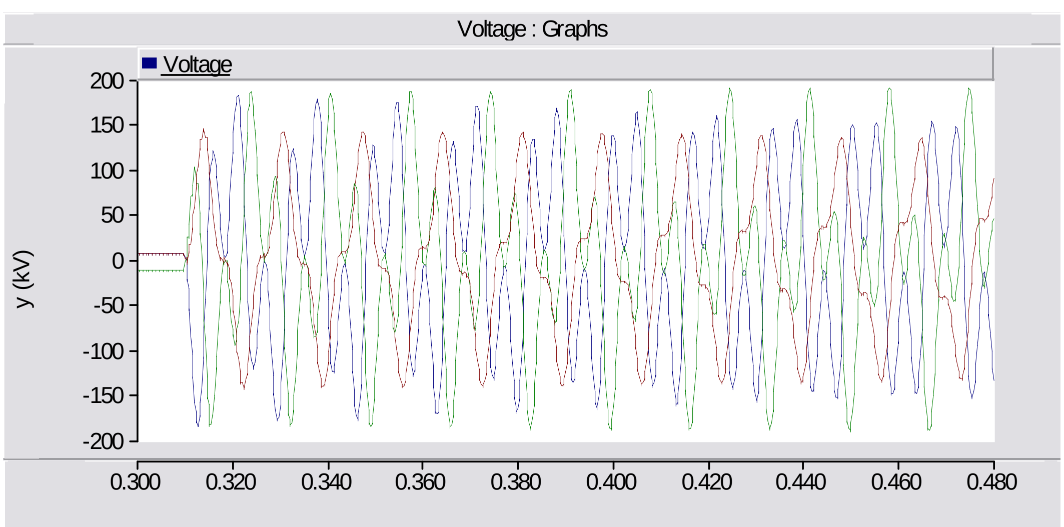


Figure 5-21
Capacitor Voltage Waveforms Following the Reclosing Event under Baseline Conditions

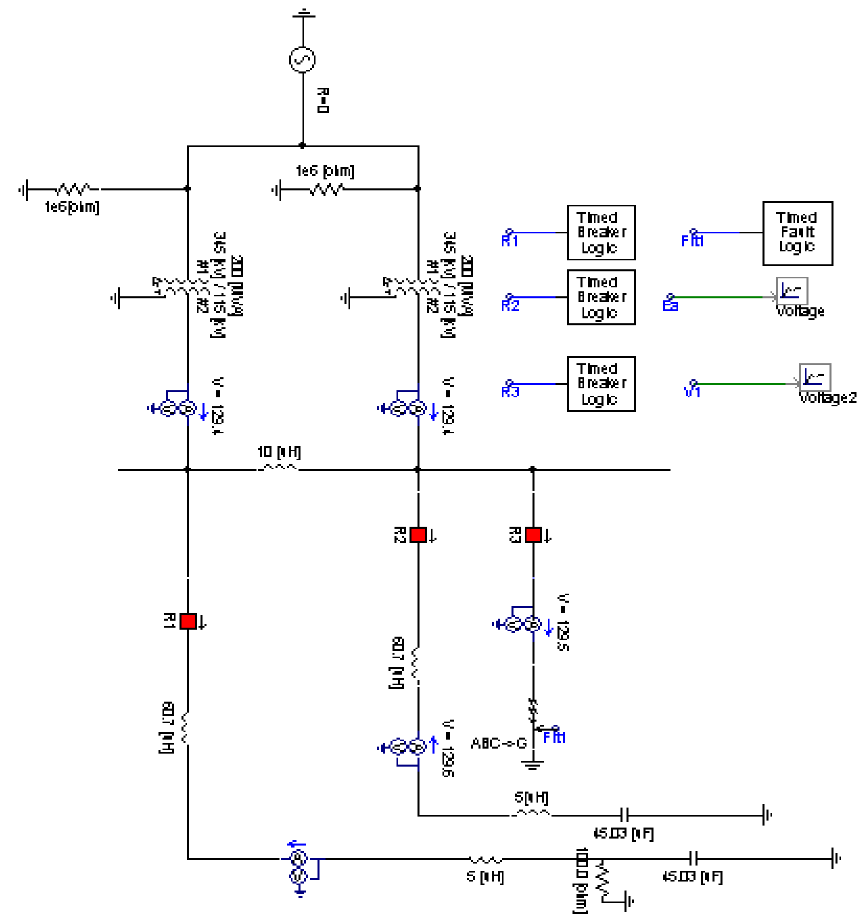


Figure 5-22
Single Line Diagram of Capacitor Switching in a Substation of a with Electronic Clutch

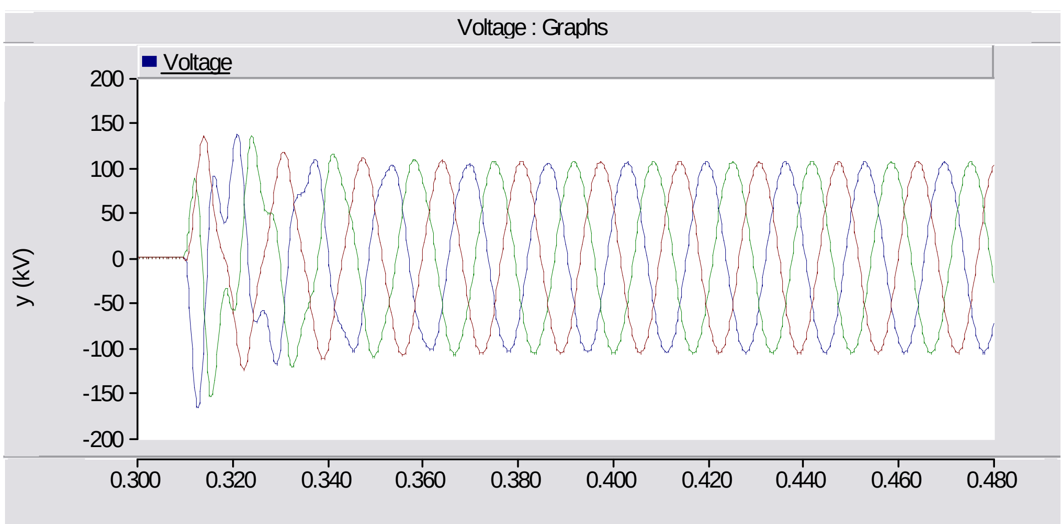


Figure 5-23
Capacitor Voltage Waveforms Following the Reclosing Event a with Electronic Clutch

6
CONCLUSIONS

Substations represent critical points in the backbone of power delivery systems and are points at which control actions and corrective actions during contingencies take place. They are the points of aggregation where switching actions that maintain the operational reliability and security of system are executed during normal and abnormal operating conditions. They primarily contain transformers for matching voltages between various segments of the transmission systems, along with various switchgear elements such as circuit breakers and sectionalizers, control elements such as load tap changers, reactive compensators and protective relaying systems.

A review of pertinent literature presented in the introduction indicates that lifetime extension, maintenance, demand growth and power quality are among the more significant concerns that prompt developments and improvements focusing on substations in the near future. On the other hand, a majority of recent developments on the application of power electronic controllers in electric utility systems under the rubric of FACTS have focused on developing equipment installed at substations to improve the operation and controllability of the entire transmission system. This establishes the scoping study on the application potential of power electronics controllers focused on improving the operability of the substation components as the main focus of this project.

A critical and comparative study of the capabilities of established and emerging solid state switching devices against classical mechanical-contact power switching devices identifies the main challenges in developing effective and competitive solutions for substation applications. The following specific applications scenarios were identified to be among the most apt for developing near term solutions. Some of the applications are illustrated in the schematic of a generic substation as different blocks, labeled solid state controllers (SSC) at various buses in Figure 6-1. A summarizing description of these devices follows:

Solid State Fault Current Limiter

Limiting the overcurrent seen by the transformers and circuit breakers using power electronics during various utility fault events lead to an increased lifetime as well as reduced maintenance requirements. Thus, the development of solid state fault current limiting devices forms a major thrust in the application of advanced power electronics in substations. Ongoing EPRI projects address this development.

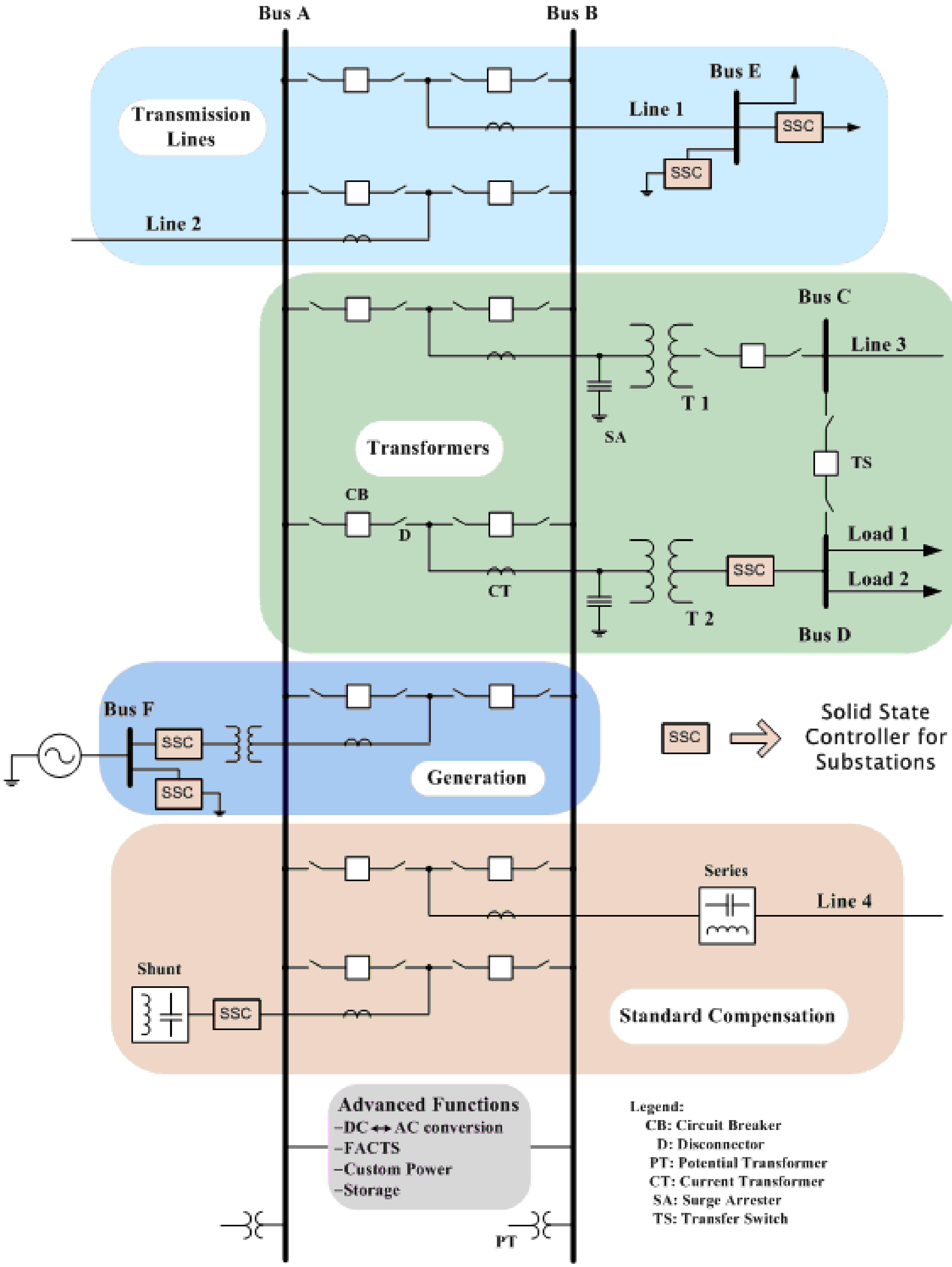


Figure 6-1
Schematic of a Substation Incorporating Advanced Power Electronics Controllers

Solid State Load Tap Changer

Load tap changers that are used in voltage regulating and phase shifting transformers contain mechanical contact switching devices that have a limited lifetime and pose recurring maintenance expenditure in power delivery systems. The technology of solid state switching devices for these applications has been known for several decades. Although a competitive solution addressing this issue remains elusive, the potential for effectiveness remains untapped. An ongoing EPRI project addresses this development.

Solid State Distributed Generation Expander

While distributed generation is being considered seriously to meet increasing growth of demand, their application in congested networked load centers such as urban locations becomes problematic due to constraints arising from short circuit current levels, protection design, and stability concerns. Therefore, development of power electronic devices that make it easier to incorporate distributed generation and reduce the cost of upgrading existing equipment will enable easier management of demand growth. The shunt and series SSC devices located at Bus F in Figure 6-1 have the potential to address this solution.

Electronic Flicker Controller

Power quality problems arising from varying loads like arc furnaces and varying sources like wind generators continue to lead to voltage flicker. With increasing penetration of wind generation, such problems become more widespread. Development of economic solutions to address voltage flicker will lead to improved power quality levels at specific problem instances in substations. The shunt and series SSC devices located at Bus E in Figure 6-1 have the potential to address this solution.

Transformer Capacity Expansion Controller

Replacement of transformers at substations is a common occurrence to meet demand growth in power delivery systems. Development power electronics technologies that allow an incremental approach towards capacity expansion will lead to better asset utilization, cost savings and investment deferral. The SSC located at Bus C in Figure 6-1 addresses this solution.

Operations of parallel transformer to meet demand growth in power delivery systems have been considered in detail. In parallel operated transformers, the active powers flowing through each parallel connected transformer may be unbalanced due to mismatched ratio of the transformer impedances.

The technical update has presented the use of a series balancing transformer, Back-to-Back (BTB) configuration and Series/Shunt Bypass (SSB) configuration. A preliminary comparative evaluation among these solutions leads to the following observations:

The series balancing transformer used as a solution is effective for balancing active and reactive powers among the parallel connected transformers. However, the turn ratio of the series common transformer needs to be tuned to the ratio of the MVA rating of the parallel-connected transformers.

The solution utilizing a BTB configuration requires two sets of a step-down transformer and ac/dc power converters that would have 100% MVA rating of the parallel transformers. Thus this topology is bulky and very expensive to realize. On the other hand, the control strategy employed in this scheme is easy and is independent of the transmission line and transformer impedances.

The SSBS can be controlled to produce impedance by injecting a voltage in series to the utility grid through its inherent series transformer. Hence, the SSBS is designed to have the MVA ratings of only 5% of the second transformer. This topology is less expensive when compared to the Back-Back configuration.

Electronic Clutch for Capacitor Switching

Capacitor switching transients are among the most common events that occur in a substation that routinely lead to overvoltages and various power quality issues. The development of an 'electronic clutch' that is able to engage the switching of the capacitor in a controlled manner can prevent all the transient problems associated with capacitor switching. The SSC device located at Bus A in Figure 6-1 will address this solution. This solution has been examined further through detailed computer simulations and laboratory experiments. The functional feasibility has been established and preliminary application considerations have been discussed.

Summary

The application of selected of the advanced power electronic controllers listed above for solving a substation challenges have been studied in the context of emerging power semiconductor devices. A focused study of the electronic clutch as a solution that has the potential for commercial scale development has been completed.

7 RECOMMENDATIONS

Switching operations of high voltage capacitor banks for reactive power or voltage support in substations can produce significant transients. Transient phenomenon related to capacitor bank switching includes high magnitude and frequency inrush currents, over- voltages at the switched capacitor bank as well as magnified transients across the power system, and fast transients coupled through transformers.

State-of-the-art approach to mitigate capacitor switching overvoltage problems such as full-time inductors, pre-insertion resistors, pre-insertion inductors and zero voltage switching devices do not always provide a cost effective solution the problem. Based on detailed device development study of an electronic clutch to manage overvoltage transients, an alternative solution that has the potential to be applied as a cost effective retrofit has been identified. Laboratory scale experiments and computer simulations have validated the feasibility of the approach.

Continuing investigations of the electronic clutch aimed at the development of a full-scale commercial prototype for field trial is recommended. A collaborative project involving a utility, commercial manufacturer of power switchgear and university investigators will form an ideal partnership for the development.

8
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A

COMMERCIALLY AVAILABLE POWER SWITCHING DEVICES

Table A-1
Power Devices

Diodes	V (V)	I(A)
Eupec D2601N90T	9000	2240
ABB 5SDD10F6000	6000	1235
ABB 5SDD50N5500	5000	4700
Semikron SKN400	3000	400
ABB 5SDD60Q2800	2000	7385
Fuji 6Ri75P-160	1600	75
Mitsubishi FD5000AV-100DA	1200	5000
Semikron SKN6000	600	6000
Mitsubishi FD602AV-88	400	4400

Thyristors	V (V)	I(A)
Mitsubishi FT1500AU-240	12000	1500
Dynex DCR2400B85	8500	2370
Eupec T2871N80TOH	8000	2680
ABB 5STP12N8500	8000	1200
ABB 5STP52U5200	4400	4120
Semikron SKT1400	3600	1400
ABB 5STP50Q1800	1800	6100
Semikron SKT2400	1800	2400
Mitsubishi FT5000AP-8	400	5000

GTOs	V (V)	I(A)
ABB SGA40L4501	6000	6000
Mitsubishi FG6000AU-120D	3800	1030
ABB 5SGT30J6004	2800	1000

IGBTs	V (V)	I(A)
Eupec FZ600R65KF1	6500	600
ABB 5SNA0600G650100	6500	600
Dynex DIM400XSM65-K	6500	400
Eupec FZ1200R33KL2C_B5	3300	1200
Eupec FZ3600R17KE3	1700	3600
ABB 5SNA3600E170100	1700	3600
Dynex DIM3600ESM17-E	1700	3600
Mitsubishi CM1000DU-34N	1700	1000
Fuji 6MBI450U4-170	1700	450

IGCTs/GCTs	V (V)	I(A)
ABB 5SHY30L6010	3600	1300
Mitsubishi GCU15CA-13	3600	500

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