COMPARATIVE ANALYSIS OF DATACENTER ELECTRICAL DISTRIBUTION ARCHITECTURES

by

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This thesis analyzes the propagation of voltage transients within datacenter facilities. Two datacenter distribution architectures are modeled. The first architecture represents the standard AC approach to distributing electric power within a datacenter. This AC system model contains power electronic circuits representing the various components of the system. The second architecture distributes 380 V DC throughout the datacenter facility. This system model also contains power electronic circuits representing the behavior of the various pieces of datacenter equipment. Both architectures are modeled using the PSCAD software package. The datacenter equipment modeled includes AC and DC uninterruptible power supplies, AC and DC server power supplies, equipment used for protection and isolation, as well as the server electronics.

In both cases, the datacenter facility is serviced with electric power through a modeled utility distribution network. This network includes a medium voltage substation model. The substation contains a medium voltage feed, as well as a switched shunt capacitor bank. During the simulation, the capacitor bank is actively connected to the substation bus through the closing action of a circuit breaker. This action creates a voltage transient which propagates through the distribution network.

This voltage transient is introduced to the entrance of each datacenter facility. Measurements are taken at various points throughout the distribution architectures, observing the propagation of the transient through the various power electronic devices. At the input terminals of the AC and DC server power supplies, the voltage deviations are measured for comparison against applicable manufacturing standards. This is done to assess whether the transients in each architecture fall within acceptable limits.

The analysis shows that each architecture has its specific concerns, with regard to transients, and demonstrates the importance of transient research for datacenters.

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1.0 INTRODUCTION

Global industries, governments, organizations, and institutions rely on the operation of datacenters in order to successfully meet their day-to-day objectives. The increased reliance on datacenters combined with the shear growth of the industry sector has led to more careful considerations for datacenter design. Historically, datacenters have sprouted where needed, and have increased capacity as demand for data services has increased. However, many datacenters are currently operating at or near capacity, and are not able to expand under the restraints of their facility electrical distribution systems [1].

For the reasons stated, stakeholders in the datacenter industry have begun to consider alternative electrical distribution systems that provide greater reliability and operating efficiency, as well as lower capital costs and ease-of-installation. Among the many alternatives proposed, facility-level DC distribution, at a voltage near 400 V DC, has emerged as the option providing the most benefit [2]. A number of studies have shown that DC distribution provides savings, in terms of energy efficiency, space utilization, and required cooling within a datacenter. However, the issue of transient propagation has not been fully defined or quantified [2].

This thesis analyzes the power conversion stages utilized in order to deliver power to the server processor in a datacenter facility. A PSCAD simulation model is used to compare the effect of voltage transients, originating from the utility distribution grid and propagating throughout the datacenter facility, using an AC and DC distribution architecture. Both distribution architectures, as well as the utility distribution network, are modeled using PSCAD/EMTDC. A voltage transient is generated from a capacitor bank switching event. The transient is analyzed as it propagates through both the AC and DC architectures, through each of the modeled conversion stages. It is shown that the AC architecture provides inherent protection against transients, at the cost of low efficiency, a high parts count, and poor space utilization. The DC system is vulnerable to transients. More research is required in order to safely capitalize on the benefits of DC distribution.

1.1 DATACENTERS IN THE MODERN ECONOMY

Datacenters are physical facilities that house information technology (IT) equipment. The main function of the datacenter is to provide reliable power, security, cooling, and network connectivity to computer equipment [3]. Compared to the electrical loads which have traditionally dominated the electric grid, IT equipment is more sensitive to fluctuations in the electric power supply. For instance, the same voltage sag that would cause lights to dim in a facility would result in a complete loss of equipment functionality in a datacenter [4]. The equipment outage would persist for hours, resulting in large sums of lost revenue [4]. Given the sensitivity of the equipment, datacenter facilities have strict requirements for their design and operation.

1.1.1 Context for Considering Datacenter Design

Computing technology has revolutionized human society. Since the first commercial machines were introduced in the 1950's, computers have increased human productivity (with the exception of Facebook), enabling people to do more by working smarter, instead of working harder.

The first business computing machines were introduced in the 1950's [5]. These machines were primitive in their capabilities, even compared to many of the embedded computers that are common today. These mainframe computers operated on punch card instructions, requiring programming by specialized operators [6]. By the 1960's, mainframe computers were able to support operating systems and high level programming languages [7]. The personal computer was introduced in the 1970's, enabling end users to utilize word processing and simple spreadsheet programs [8]. In the 1980's and 1990's, server technology advanced, with the application of virtualization, allowing multiple users to access resources and computing environments simultaneously from the same server [9]. This layer of abstraction, coupled with the development of internet protocols, greatly expanded the applicability of computing technology, and brought enterprise scale computing resources to remote locations [7].

The growth in the IT market in demonstrated in Figure 1 below. As shown, investment in IT equipment has steadily increased since the commercial introduction of the technology. The only exception was in the early 2000's, following the burst of the dot com bubble [7].

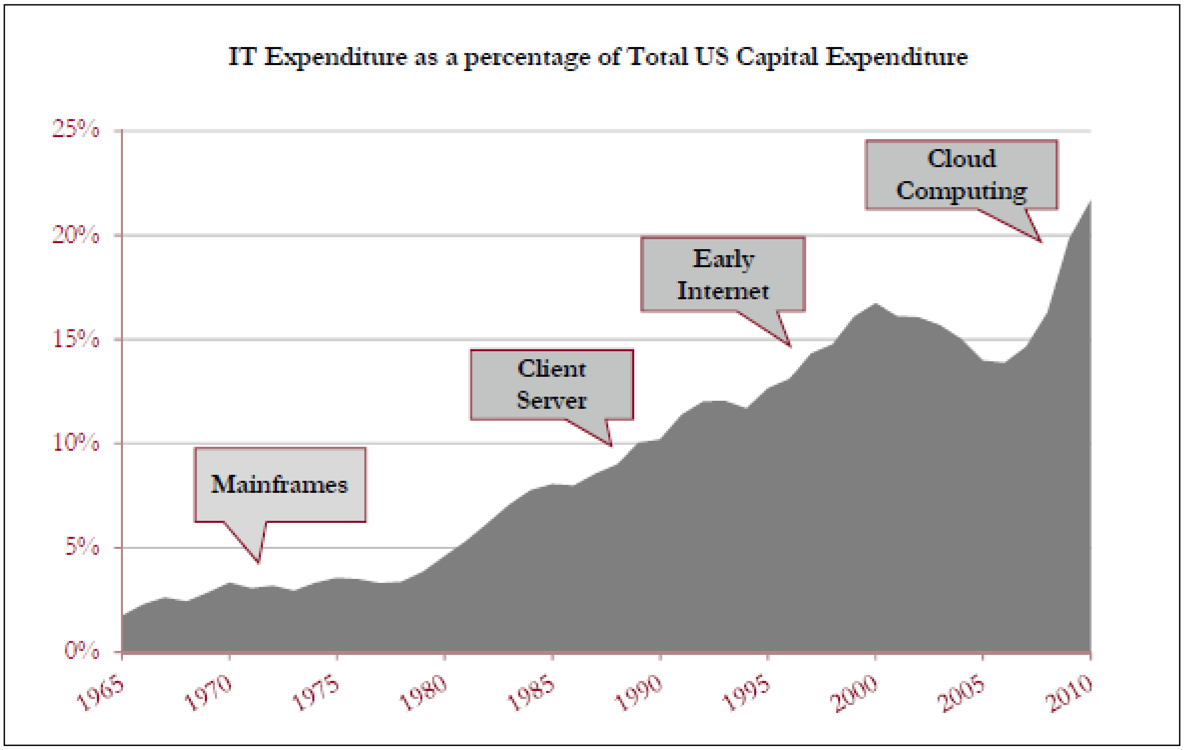

Figure 1: IT Investment Historical Trend [7]

Research has shown that IT investment impacts on economic growth and productivity. This happens in a number of ways. IT investment increases capital deepening and increases Total Factor Productivity (TFP) [7]. Capital deepening refers to an increase in computer hardware, software, and communications equipment per worker within the economy [7]. Capital deepening increases business efficiency by reducing the functions performed by labor. IT solutions have allowed companies to outsource non-essential business functions and focus on core activities [10]. This further increases the ratio of business output to required labor [7].

Total Factor Productivity is an economic term that represents growth in business output, not accounted for by growth in business inputs [11]. This implies that the economy has become more efficient, a trend which is attributed to increases in technology within the economy. There are many cases that show a positive correlation between IT and TFP [12] [13].

Apart from capital deepening and TFP, economists have discovered that IT services positively impact efficiencies in several ways [14]. These can be referred to as spillover effects, and include: (1) increasing productivity by outsourcing non-core activities, (2) promoting growth by fostering innovation, (3) increasing flexibility and competitiveness, (4) improving business intelligence capabilities, and (5) promoting new businesses while fostering growth in small and medium businesses [7].

In short, it is shown that increases in IT investment and utilization contribute to economic growth by increasing business efficiency. Statistics have shown that “80% of computing power and 65% of storage capacity is not efficiently utilized, where a single company privately owns dedicated machines” [15]. In the modern economy, businesses are increasingly moving their IT resources into datacenter facilities, in order to more fully realize the benefits of their technological assets [3]. With the increase of datacenter utilization and the benefits that IT services bring to the economy, it is important to address issues concerning datacenters and their operation. Figure 2 clearly demonstrates the levels of investment in datacenter equipment over the last 15 years, the increase in the installed base of datacenter equipment, as well as the increasing power and cooling requirements required to support this infrastructure.

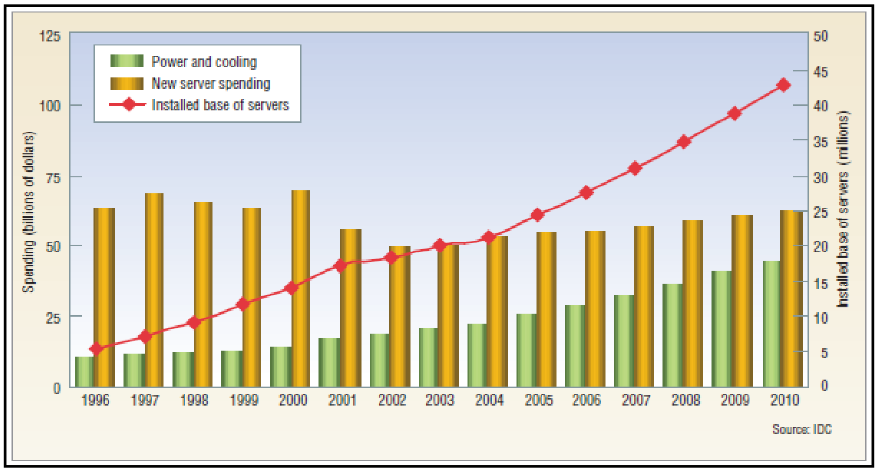

Figure 2: The Cost of Powering and Cooling Servers [16]

1.1.2 Power Consumption in Datacenters

Datacenter facilities are growing in size and power consumption level, rivaling the electrical capacity of manufacturing facilities. Given the amount of power that these facilities consume, locating datacenters requires planning in conjunction with utility power distributors.

Datacenters have received a great deal of criticism for their power consumption. Some of this criticism is legitimate, while many of the claims concerning datacenters have been exaggerated. For instance, a report by the Greening Earth Society claimed the internet was responsible for 8% of US electrical consumption in 1998, and that this percentage would grow to become 30 to 50% of US consumption by 2020 [17].

Later studies showed that this figure was inaccurate [18]. Studies show a more representative figure being 3% of US power consumption in 1999/2000 [19]. A 2005 study by the chip manufacturer AMD showed that US data centers accounted for 5 GW of energy [20]. Distributed across the 320 US datacenters, the average US datacenter accounts for 15 MW of power [21].

Considering the large consumption levels of datacenter facilities, and the large costs associated with powering these facilities, datacenters are often located in areas in which electrical costs are low. Unfortunately, these areas typically have low electrical costs due to an abundance of fossil fuel generation in the local area. For example, a planned US National Security Agency (NSA) datacenter is planned for construction in the Camp Williams region of Utah [22]. This 1.5 million square foot, 65 MW facility will benefit from an electrical rate of 7 cents per kWh, 30% lower than the national average [22].

Mike Bullock, CEO of Transitional Data Services, a Massachusetts based datacenter consulting firm, commented on the matter, saying, "The reason the electricity is so cheap is because 98 percent of Utah's electricity is powered by coal and natural gas. That's not very carbon friendly, and with pending cap-and-trade legislation, Utah's electricity costs will most definitely increase. How much? Who knows? But whatever it is, the taxpayer (that's you) will be paying for it" [22].

An example from the UK includes the headquarter building of the Met Office, the national weather service of the UK. In mid-2009, several outlets in the UK press highlighted the excessive energy consumption of the facility, as well as the facilities contribution to environmental pollution. The irony is that the excessive consumption can be attributed to an IBM supercomputer, used within the facility for climate modeling [22].

SMART 2020, a 2008 report by The Climate Group, stated that Information and Telecommunications Technology (ICT) has its largest influence "enabling energy efficiency in other sectors" and that ICT "could deliver carbons savings five times larger than the total emissions from the ICT sector in 2020" [23]. An analysis by Intel Labs concluded that, "trying to arrest data center growth would be the exact wrong thing to do" [23]. At the same time, datacenter operation is extremely inefficient and "there is no reason that we have to accept the current level of inefficiency in data center power distribution" [23].

Figure 3 illustrates the way power is used within the datacenter facility. Keeping in mind the purpose of the datacenter, which is to process information within the server processors, one can see that datacenter facilities are highly inefficient in achieving this task. Figure 3 shows that only 30% of the incoming facility power is delivered to the server cards. The server cards themselves contain additional electronics apart from the server processors. In fact, processors only account for 19% of the power delivered to the server cards.

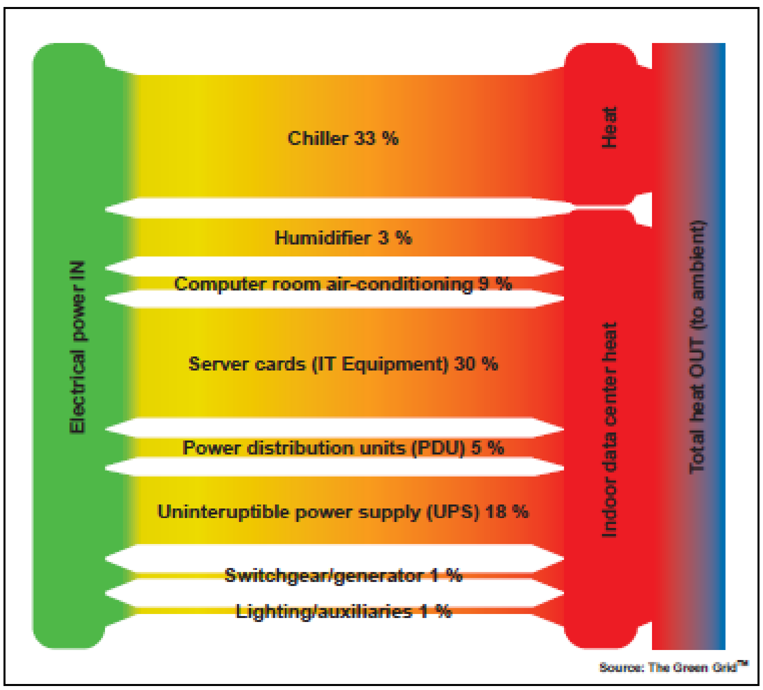

Figure 3: Power Utilization Within a Datacenter Facility

The development of faster chip technology resulted in higher heat density in smaller processor geometries [2]. This means that modern processors require extensive cooling infrastructure for operation. Considering the nature of the datacenter business, wherein profits rely on the ability to process high amounts of information, datacenters are designed to fit considerable amounts of equipment into highly dense space. The average power density of datacenter computer rooms is approximately 50 W per square foot [3].

Table 1 below is provided for comparison. A 2007 study by the Indiana University Sustainability Taskforce sought to benchmark the energy consumption of several types of facilities over the course of a year [24]. A subset of their findings is shown in Table 1, manipulated mathematically to show the information in terms of power density in watts per gross square foot. As shown, most buildings tend to have power densities on the order of 1.2 to 3.3 watts per square foot [24]. Datacenters greatly exceed this standard rating, necessitating the use of an intensive cooling infrastructure.

Table 1: Power Densities in Various Facilities

		Electrical Use Per Gross Square Foot		
Building Type		BTU	Watt*h	W/gsf
Classroom/Office				
Average:		39,379.00	11,540.84	1.316574197
Median:		39,580.00	11,599.75	1.323294312
Office Areas				
Average:		45,153.00	13,233.03	1.509618698
Median:		44,022.00	12,901.57	1.471805513
Research Laboratories				
Average:		99,214.00	29,076.75	3.3170622
Median:		93,556.00	27,418.55	3.127895974
Residential Facilities				
Average:		38,336.00	11,235.17	1.281703152
Median:		36,039.00	10,561.99	1.204906612

Although the magnitude of the energy required for facility cooling is significant, in most datacenters, the power lost in energy conversion and conditioning equipment is even more significant. Figure 4 below, produced by Intel, shows the conversion losses for a given computational load in a datacenter room. This information can be summarized in this observation made by Lawrence Berkeley National Lab, “for every watt of power utilized to process data, another 0.9W is required to support power conversion. In addition … another 0.6 to 1 watt (or more) of power will be required for each watt utilized to cool the power conversion equipment” [2].

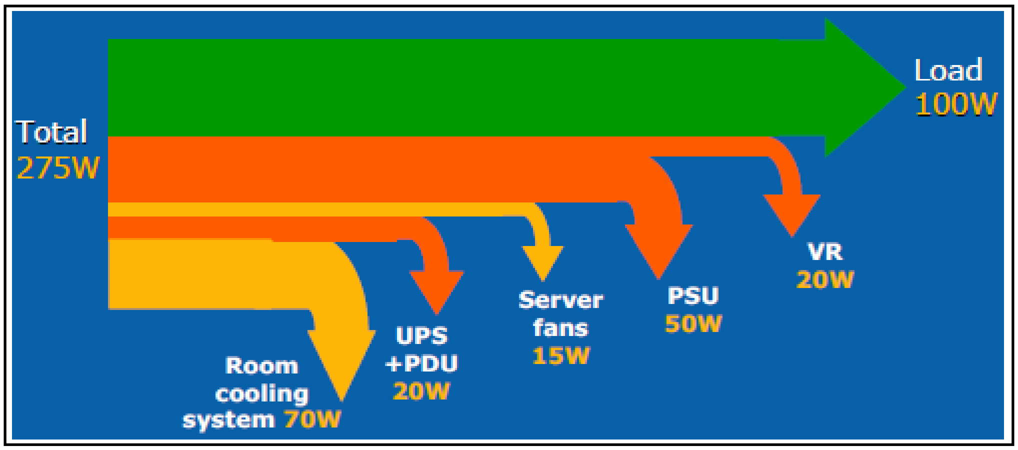

Figure 4: Conversion Losses [2]

As demonstrated, datacenter facilities suffer from very low efficiency operation. Efficiency has always been considered secondary in datacenter design. Due to the high costs associated with downtime (time in which the server processors are inoperable), reliability has been the key parameter in datacenter electrical distribution system design. The importance of uptime will be explored in the next section.

1.1.3 Reliance and Downtime

Datacenters have become an integral part of the modern economy. Many of the information services and financial transactions that we utilize and perform on a daily basis relay on datacenters. In fact, many operations performed by the central governments of many developed nations rely heavily on datacenters to perform their daily operations.

The Public Administration Select Committee of the UK Cabinet Office underwent a study in May 2011, for the purpose of identifying the datacenters owned by, or crucial to, the operation of public services [25]. Engineering and Technology Magazine, the official publication of the Institution of Engineering and Technology in the UK, reported that the central government relied on 220 datacenters for its functions [25]. When local government and wider public sector services are accounted for, the dependence extends to over 600 datacenter facilities [25].

Figure 5 below shows the location of major datacenter facilities in the US. In 2000, it was estimated that there were approximately 320 data center hosting facilities in the United States [21]. There are 16 major cities in the US with five or more planned or current data center facilities [3]. Silicon Valley, California is the largest of these cities, hosting approximately 54 data center facilities, or 17% of all major hosting facilities in the US [3]. Estimates from 2000 showed there were nearly 9.5 million square feet of data center computer rooms in the United States [26].

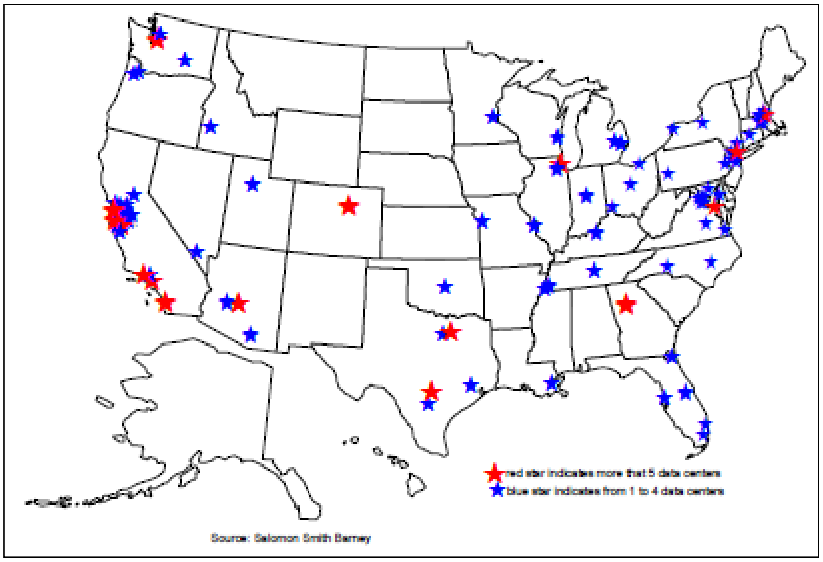

Figure 5: Locations of Major Datacenter Facilities in the US [3]

The economic dependence on datacenters is best illustrated through the costs associated with downtime. When datacenters become inoperable, due to interruptions in the electrical supply, business operations are halted, resulting in a loss of sales and services. These losses are well recorded and tabulated for the various industries that utilize datacenter facilities.

The following chart, Table 2, shows the cost of downtime in different industries. As shown, downtime in datacenter facilities can have a significant financial impact. In a study by Emerson Network Power, the importance of datacenters and downtime were examined. If all 509,147 of the world's datacenters experienced 2.5 outages for a duration of 134 minutes, that would equate to 2,842,737 hours of downtime [27]. The outage time was calculated using an average, representative figure. The cost of this downtime would equal $426 billion per year [27].

Table 2: The Cost of Downtime [28]

Industry	Average cost of downtime (US $/hour)
Cellular communications	41,000
Telephone ticket sales	72,000
Airline reservations	90,000
Credit card operations	2,580,000
Brokerage options	6,480,000

2.0 TRADITIONAL DATACENTER DESIGN

Due to the high costs associated with downtime, as shown in the prior section, the main focus of traditional datacenter design has been ensuring reliability in datacenter operations [29]. Datacenter electrical distribution architectures must ensure that computer processing equipment always has an appropriate electrical supply. By appropriate, it is meant that the electrical supply must be uninterrupted, and without fluctuation in the supply voltage.

2.1 BASIC DATACENTER STRUCTURE AND FUNCTION

Datacenter facilities are fed electrical power from a utility provider. In the US, the utility supplies electrical power, typically, at 480 V AC, three phase [2]. To ensure reliability, datacenters are typically fed from redundant, isolated feeds from within the utility distribution network [29]. In this manner, the datacenter can operate continuously, even during a disturbance or outage in a particular region of the utility network.

In addition to the redundant utility feeds, datacenters are equipped with onsite generation. In the event of a complete utility outage, onsite generation guarantees continuity of operation. Most commonly, datacenters utilize diesel generators for backup generation [29]. Diesel generation offers the most economic backup solution [30]. However, diesel generator emissions are often unregulated, furthering the reputation of datacenters as irresponsible power consumers [30].

The measures listed above ensure that the datacenter always has a continuous power supply. However, fluctuations can be seen at the server level when switching from one power feed to another [29]. In addition, during regular operations, the utility distribution network experiences voltage transients, often from lightning strikes and capacitor banking switching events at distribution substations [31]. In order to mitigate the effects of these supply inconsistencies, an uninterruptible power supply is employed [29]. UPSs allow uninterrupted transfer between power feeds [32].

The UPS supplies server racks with a high quality AC power input. Each server is equipped with a Power Distribution Unit (PDU), a device which provides galvanic isolation from the power input and protection in the event of a supply-side fault. Power from the PDU is fed directly into the server Power Supply Unit (PSU). Within the server power supply, the AC input voltage is rectified and conditioned, creating a voltage signal suitable for use by the DC-powered electronics within the server. Figure 6 below demonstrates the power conversion stages typical of an AC datacenter facility.

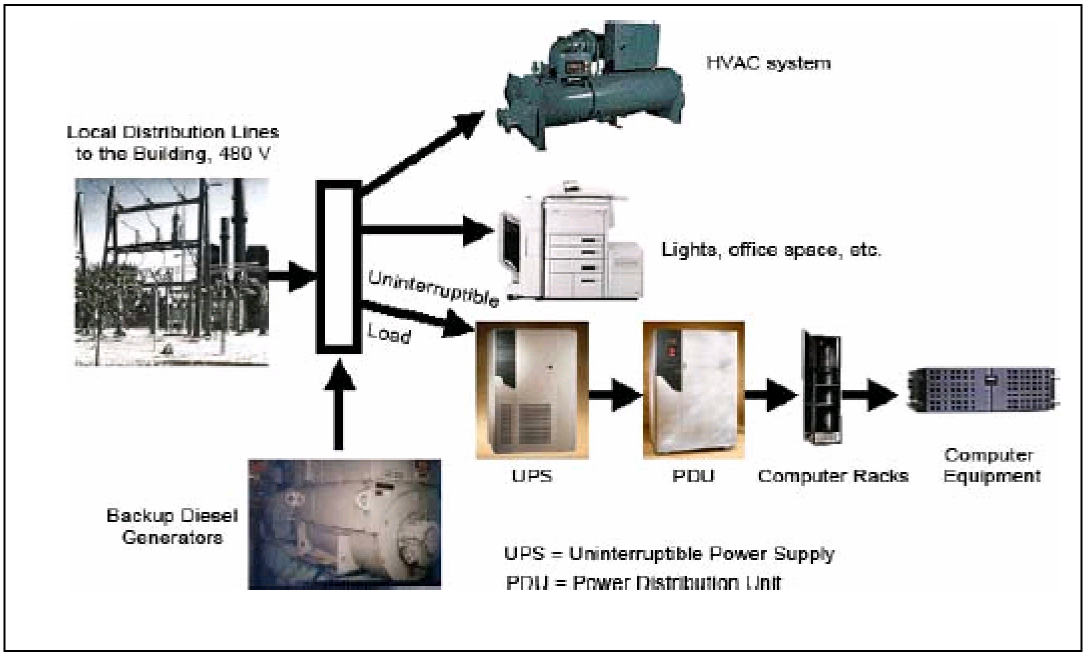

Figure 6: Typical Datacenter Power Distribution Architecture [2]

2.2 DATACENTER EQUIPMENT

This section provides details on the equipment mentioned in the previous section. Equipment descriptions and topologies will be introduced for the main components of the traditional datacenter; namely, the UPS, the PDU, the PSU, and the server electronics.

2.2.1 The UPS

UPSs provide power conditioning and backup power for critical loads within datacenter facilities [33]. UPS systems generally consist of a form of energy storage, coupled with a power electronics device. The energy storage device is usually an electrochemical battery, but flywheels have been used in some circumstances [2]. IGBT inverters are used to produce a high quality AC feed for the sensitive electronic equipment [34].

There are several types of UPS configurations, each offering differing benefits. Three UPS topologies are recognized by the international standard IEC 62040-3 [35]. These topologies are passive standby, line interactive, and double conversion.

The passive standby topology is shown in Figure 7 below. In this topology, the load is normally supplied by the utility directly [35]. In the event of a utility outage, the load is fed by battery storage, through the inverter [35]. This topology has the advantage of simplicity and low cost [35]. However, during regular operation, there is no isolation between utility disturbances and the datacenter distribution system [35].

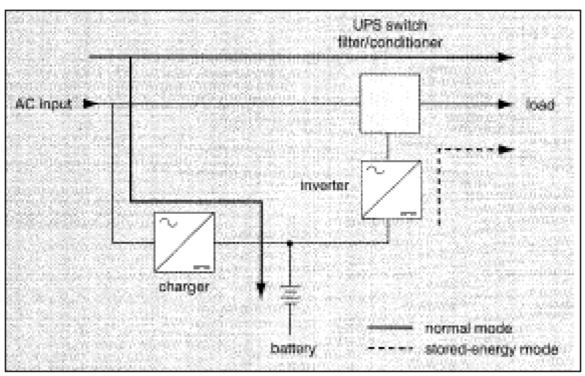

Figure 7: Standby UPS Topology [35]

The line interactive topology is shown in Figure 8 below. In this topology, the UPS is connected in parallel with the utility feed [35]. The inverter is used interactively to modify the utility feed, correcting disturbances [35]. The inverter also acts as a synchronous rectifier, charging the batteries when necessary [35]. In the case of a utility outage, the inverter alone supplies power to the load, either until the utility is restored, or until the backup generators are brought online. A line interactive UPS may have lower cost than a double-conversion UPS of the same rating [35]. However, the line interactive topology has several disadvantages. Firstly, the topology relies on the utility feed as a frequency reference [35]. This makes the topology ill-suited for powering sensitive loads with medium to high power ratings [35]. Furthermore, the topology does not offer true isolation from grid disturbances. The ability of the inverter to provide regulation is limited by the fact that the inverter is also used to charge the batteries [35].

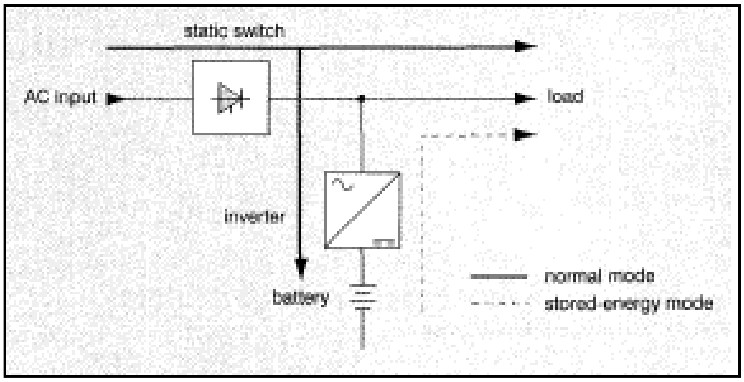

Figure 8: Line-Interactive UPS Topology [35]

The double conversion UPS offers the highest protection, compared to other topologies. The double conversion UPS is illustrated in Figure 9 below. In this topology, the power electronic devices are connected in series with the utility supply [35]. A diode rectifier is typically used to establish a DC bus internal to the UPS [35]. From this DC bus, the batteries can be recharged when needed [35]. The inverter is also powered by this DC bus. Under normal operation, the AC utility supply is rectified, then inverted, providing a high level of isolation from transients [35]. When the utility supply is unavailable, the batteries supply the load through the inverter [35]. This topology provides the highest level of reliability and has become a standard for protecting IT equipment with power ratings above 5 kVA [33].

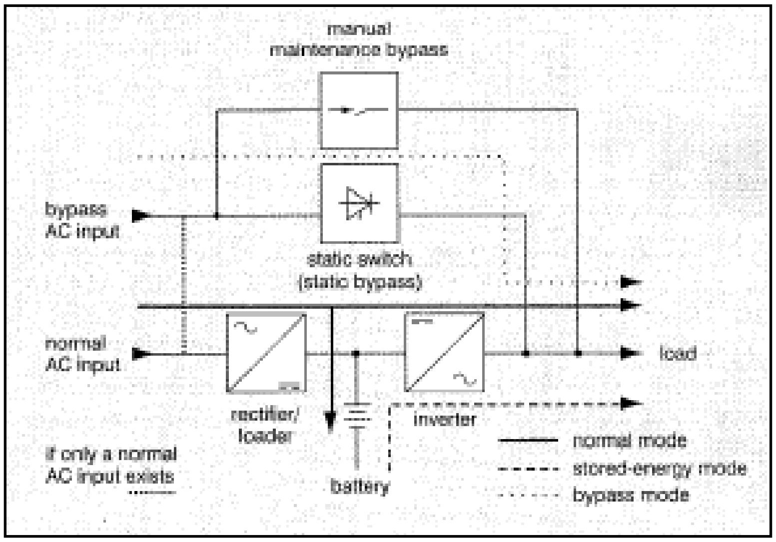

Figure 9: Double Conversion UPS Topology [35]

2.2.2 The Power Distribution Unit

The Power Distribution Unit serves several purposes within the datacenter facility. The PDU utilizes a transformer to provide galvanic isolation between the datacenter loads and the incoming supply. This provides an additional layer of protection against transients and fault on the utility side of the system. This transformer can also provide voltage transformation, stepping the output voltage of the UPS down to a lower level for distribution within the facility [2]. In some instances, the output voltage of the UPS remains 480/277 V, three-phase [2]. This voltage can be fed to a 480/277 to 208/120 transformer within the PDU, allowing for lower voltage distribution within the facility [23]. It is not necessary that the PDU transformer perform the voltage transformation. In some instances, the UPS itself is designed such that the inverter stage produces a 120/208 output, and the PDU transformer is used to convert the voltage feed from a three phase input, to multiple, separate single phase outputs [36]. The exact configuration and use of the PDU is determined by the power needs, voltage ratings, and physical configuration of the datacenter facility and servers [3].

Apart from providing isolation, and providing voltage transformation where needed, the PDU provides protection through the inclusion of circuit breakers [36]. PDUs deliver power to a number of loads, connected in parallel. This can be seen in Figure 10 below, where the PDU is depicted as a transformer, in series with switch panel. Each output of the PDU can be individually connected/disconnected through an internal circuit breaker, in the event of a local fault or disturbance [36].

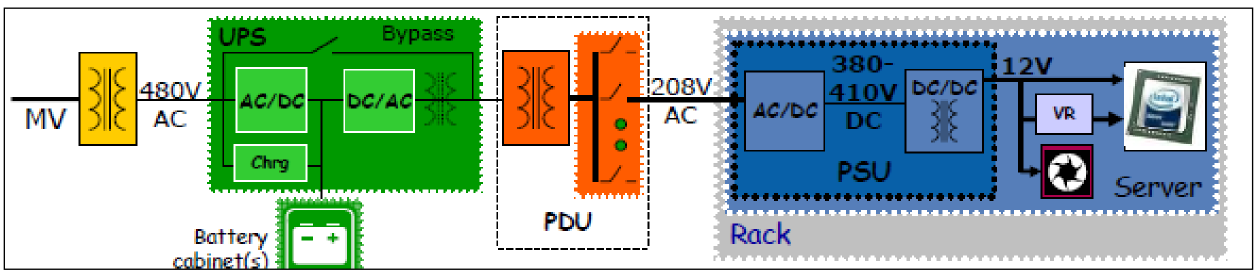

Figure 10: Illustration of AC Architecture Showing PDU Functionality [37]

As with most equipment within a datacenter, PDUs are often fed from redundant power supplies. In the case of the PDU, this means that two parallel UPSs are used. This allows for continued operation while one UPS undergoes maintenance, and also guarantees continuity of operations during a fault condition on one UPS.

2.2.3 The Power Supply Unit

The Power Supply Unit is responsible for converting and conditioning the AC supply voltage, creating a DC voltage suitable for use by the electronics within the server. Servers contain a number of different pieces of internal electronic devices, including disk drives, processors, and fans. These devices require different amounts of power and differing supply voltages. In addition, modern processors operate have precise voltage supply requirements, and cannot tolerate fluctuations [2]. This requires that voltage regulation circuitry be located directly next to the processor [2]. For these reasons, the server power supply is used to set up an intermediate DC voltage; this voltage is typically 12 V DC [2]. Voltage regulators are then used to condition the power required by the individual electronic devices within the server [2].

The power supply unit typically contains a power-factor-correction (PFC) circuit, a diode rectifier, a DC/DC buck-converter, and an electromagnetic interference filter [23]. A picture of a server PSU is shown in Figure 11 below. The figure describes the PFC circuit as being 'no longer needed.' This applies to an alternative DC distribution architecture, and will be described later in this thesis.

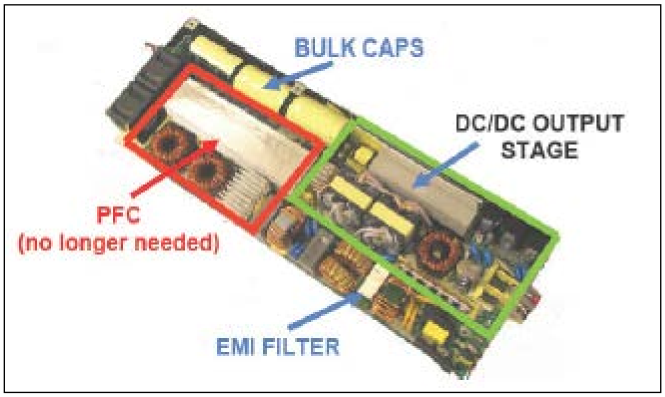

Figure 11: Example Server Power Supply Unit [23]

2.2.4 The Server Electronics

The Power Supply Unit is responsible for converting and conditioning the AC supply voltage, creating a DC voltage suitable for use by the electronics within the server. The server electronics are typically mounted on a printed circuit board (PCB). The entire PCB with all of its components, is generally referred to as a server card. A typical dual processor server card utilizes 450 W of power [29]. The common electronics typically included in a server card, as well as their relative power consumption levels are shown in Figure 12 below.

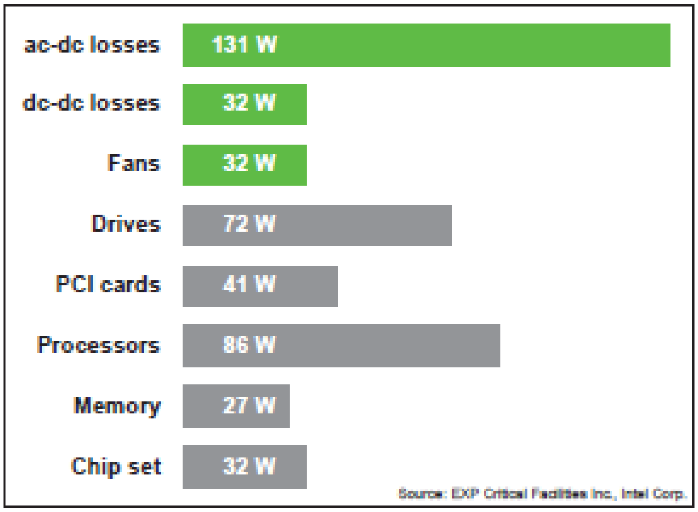

Figure 12: Server Electronics and their Power Consumption Levels [38]

This thesis investigates the power conversion stages between the datacenter facility voltage supply, and the server processor. Therefore, the processor is most important, amongst the many electronic devices mounted on the server card. The power requirements of modern processors will be analyzed in further detail.

Server processors have grown significantly, in terms of their energy efficiency per unit of processing power [23]. For instance, in March 2007, Intel introduced two 50-watt server processors. These servers exhibited a 35 – 60 percent decrease in power consumption, compared to Intel's prior models, representing a nearly ten-fold improvement in power consumption per core, in only a 1.5 year span [23]. In 2008, Intel introduced a new line of 45nm quad-core processors, delivering up to a 67 percent performance increase per watt [23]. This represents a growth of 1.67 times performance per watt, in just one year [23]. These figures demonstrate the great improvements that have been made in improving processor efficiency.

Processor voltages have decreased over time [39]. Modern processors operate at very low voltages (near 1 V DC) and high currents (near 100 A) [2].

3.0 ALTERNATIVE DATACENTER DISTRIBUTION ARCHITECTURES

The rising costs of electricity, coupled with the international push toward achieving sustainability, international efforts to combat global warming, and the possible development of a carbon tax penalties and incentives, have all forced datacenter designers to consider the merits of alternative electrical distribution architectures. This chapter explores two common alternative architectures for distributing electrical energy through datacenter facilities. The AC versus DC comparison study done in the subsequent chapters only considers the facility-wide DC distribution architecture. The hybrid architecture is not modeled or used for comparison. However, this architecture has its merits, and is mentioned in this chapter for completeness.

3.1 FACILITY-WIDE DC DISTRIBUTION

In a typical AC datacenter distribution architecture, the facility supply voltage undergoes no less than four voltage conversions (from AC to DC, DC to AC, etc.) before reaching the server electronics [2]. In order to mitigate the conversion losses, DC power is distributed throughout the building, directly from the rectifier stage of the UPS. By using a high DC voltage, resistive losses can be mitigated by delivering large amounts of power using lower current values. Based on input from a number of stakeholders within the datacenter market, a standard for 380 V DC distribution is emerging as the facility-wide distribution voltage of choice [2].

The facility-wide DC distribution architecture is shown graphically in Figure 13 below. This is the architecture, as prototyped by Lawrence Berkeley National Lab and other industry partners, in their 2008 study.

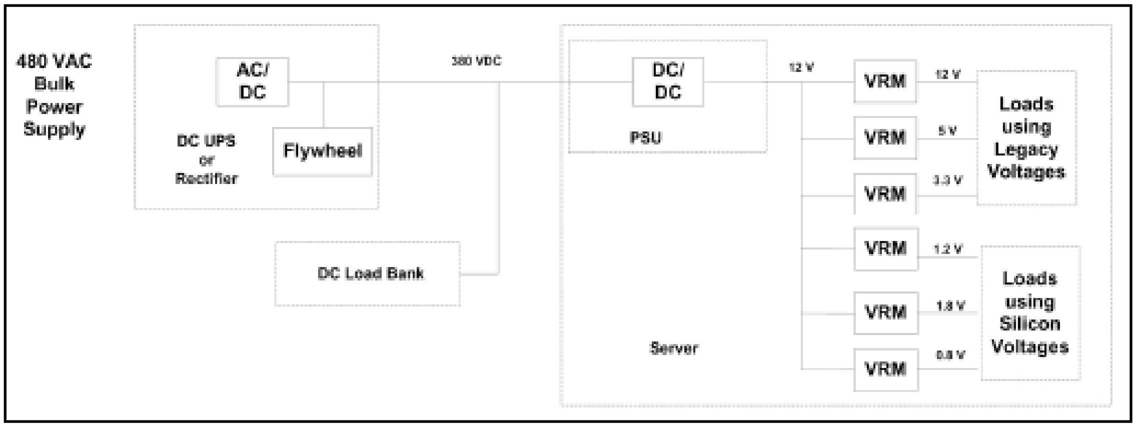

Figure 13: Facility-Level DC Distribution Architecture [2]

A second representation of the architecture is seen in Figure 14 below. Shown below, this representation highlights the use of electrochemical batteries for providing energy storage. In addition, this representation shows that DC, transformerless PDUs can be used to provide protection in the DC architecture.

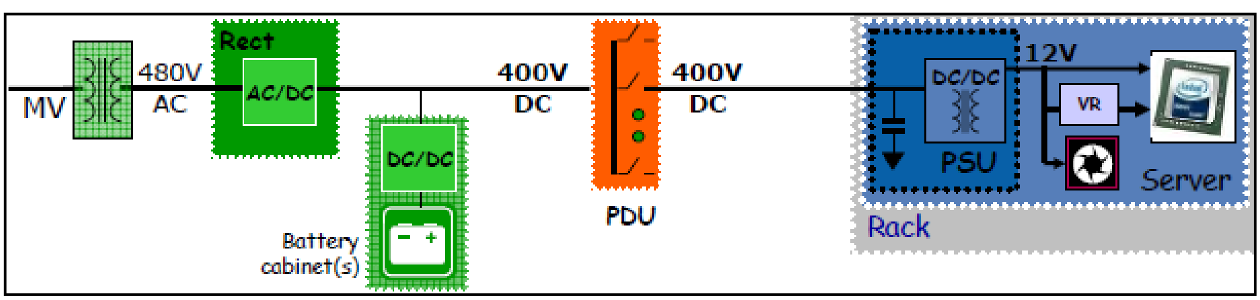

Figure 14: Alternative Representation [37]

The facility-wide DC distribution architecture offers many benefits. When Figure 14 is compared with the standard AC architecture shown in Figure 10, one can see some immediate benefits. Chiefly, there is a reduction in required equipment when utilizing the DC architecture. Figure 15, produced by Intel, highlights the equipment reductions using high voltage DC distribution.

In the DC system, the diode rectifier in the UPS is replaced by an active IGBT-based synchronous rectifier [34]. This active rectifier regulates the DC bus voltage, supplying the high voltage DC feed. The server power supply is greatly simplified, eliminating the need for power factor correction circuits, as well as the diode rectifier [23]. In the DC system, the server power supply functions simply as a filtered buck converter, establishing the internal 12 V DC voltage needed to supply the voltage regulators [23].

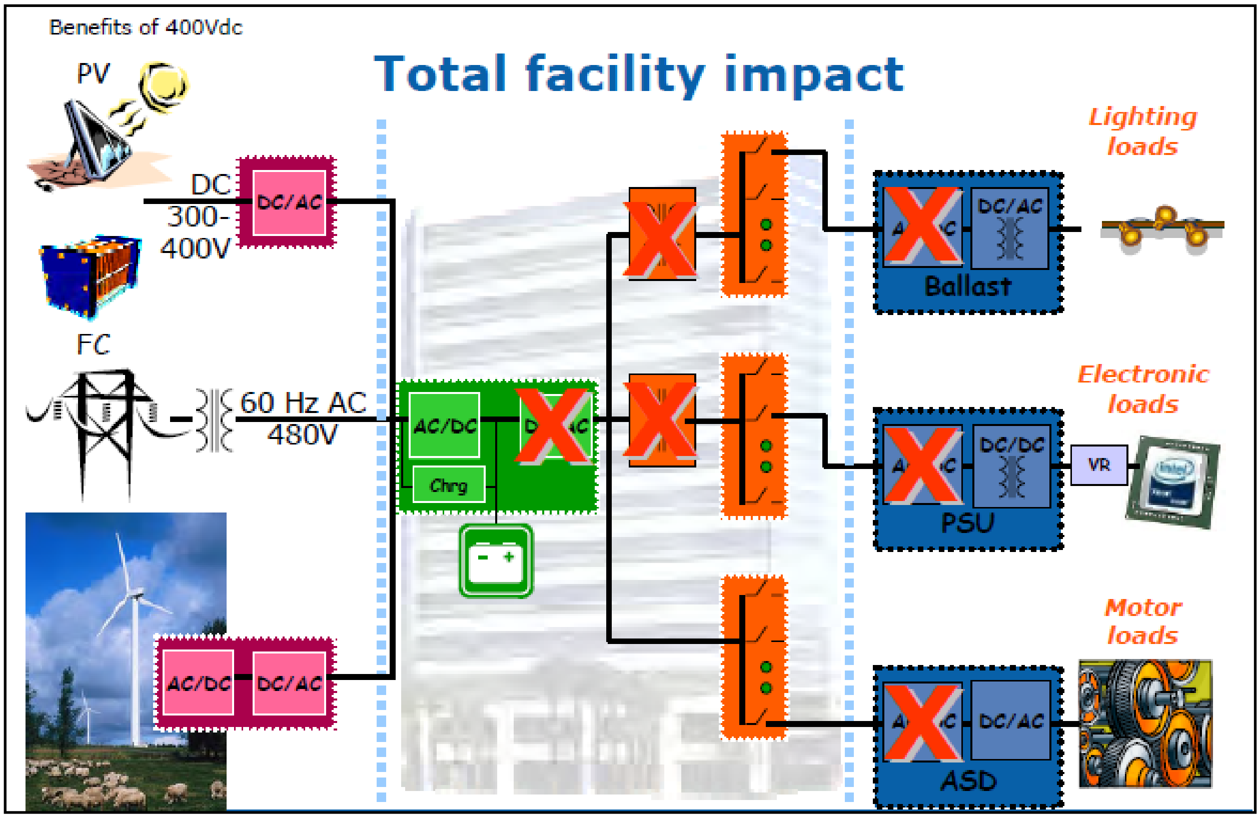

Figure 15: Equipment Reduction With DC Distribution [37]

3.2 RACK-LEVEL DC DISTRIBUTION

The rack-level DC distribution architecture is demonstrated in Figure 16 below. This architecture is a hybrid approach which distributes AC power throughout the datacenter facility, but rectifies the voltage, providing DC power at the server rack level. This approach allows current AC facilities to reap the benefits of using DC servers without rewiring an entire facility [2]. The hybrid approach can serve as a transitional technology, allowing for immediate adoption of DC distribution in datacenters.

The hybrid approach centralizes the rectification stage from the server power supplies. Modern server racks can hold up to 128 Blade servers per rack. With a rectifier in each server power supply, the power losses are localized, requiring local cooling [2]. By centralizing the rectification, the heat can be dealt with in one central location, minimizing the cooling infrastructure required within the server [2].

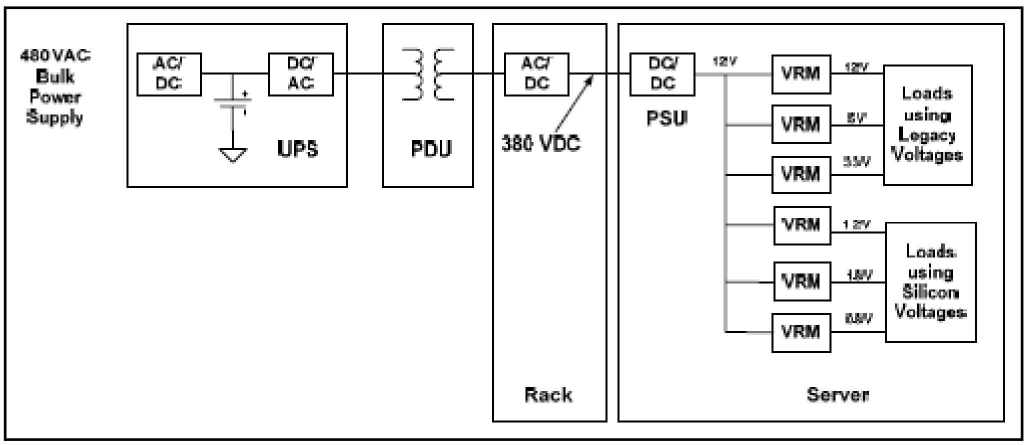

Figure 16: Rack-Level DC Distribution Architecture [2]

Table 3 below demonstrates the distribution of servers by building type within the US. Although this thesis has placed an emphasis on enterprise datacenter facilities, one can see that the majority of servers are located in other facilities. Despite the significant growth in the datacenter industry, there is a significant amount of IT equipment still being housed in non-enterprise class datacenter facilities. Therefore, the hybrid approach is one that has significant merit for practical application and quick deployment within existing markets.

Table 3: Servers by Building Type [32]

Type	Server Closet	Server Room	Localized Data Center	Mid-tier Data Center	Enterprise-Class Data Center
Scope	Secondary computer location, often outside of IT control, or may be a primary site for a small business	Secondary computer location, under IT control, or may be a primary site for a small business	Primary or secondary computer location, under IT control	Primary computing location, under IT control	Primary computing location, under IT control
Power/cooling	Standard room air-conditioning, no UPS	Upgraded room air conditioning, single UPS	Maintained at 17°C; some power and cooling redundancy	Maintained at 17°C; some power and cooling redundancy	Maintained at 17°C; at least N+1 power & cooling redundancy
Sq ft	<200sq ft	<500sq ft	<1,000sq ft	<5,000sq ft	>5,000 sq ft
US data centers (2009 est)	1,345,741 = 51.8%	1,170,399 = 45.1%	64,229 = 2.5%	9,758 = 0.4%	7,006 = 0.3%
Total Servers (2009 est)	2,135,538 = 17%	3,057,834 = 24%	2,107,592 = 16%	1,869,595 = 15%	3,604,678 = 28%
Average servers per location	2	3	32	192	515
					

Source Data Courtesy of EPRI ELECTRIC POWER RESEARCH INSTITUTE

4.0 DATACENTER DESIGN ARCHITECTURE SIMULATION MODELS

The following sections describe the simulation models used to represent the distribution architectures explored in this thesis. In each study, the means of delivering electrical power to the server load varies. However, in each case, the server load itself is identical. The server simulation model is described first within this section.

As mentioned earlier, this thesis work describes the process of power delivery from the building entrance to the server processor. This section describes the way in which the server processor is modeled. Figure 17 below shows the server load, as modeled in PSCAD. As shown, the server load consists of a 12 V DC buck converter, used to regulate the voltage at the server electronics. This converter is often referred to as a voltage regulation module [29]. The server processor is modeled as a linear, constant power load. Although the data processing requirements of data center facilities and equipment change over time, it has been shown that the power requirements remain constant, regardless of the network topology or data-flow quantity [40]. The server load is modeled as a constant 100 W load, drawing 100 A at a constant voltage of 1.0 V [2]. Power ratings between 85 and 120 W are typical of the quad-core servers commonly found in modern datacenter equipment [23].

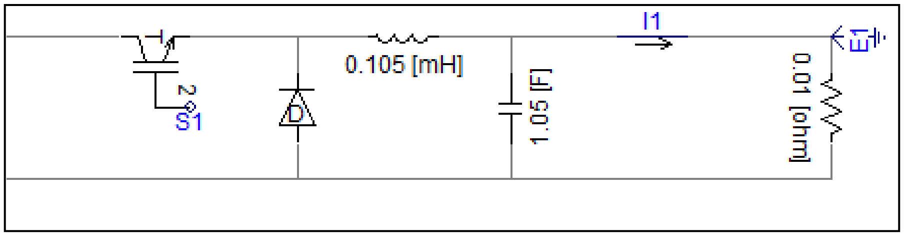

Figure 17: Server Processor Simulation Model

The following waveforms, in Figure 18, show the steady-state voltage and current of the server during the simulation.

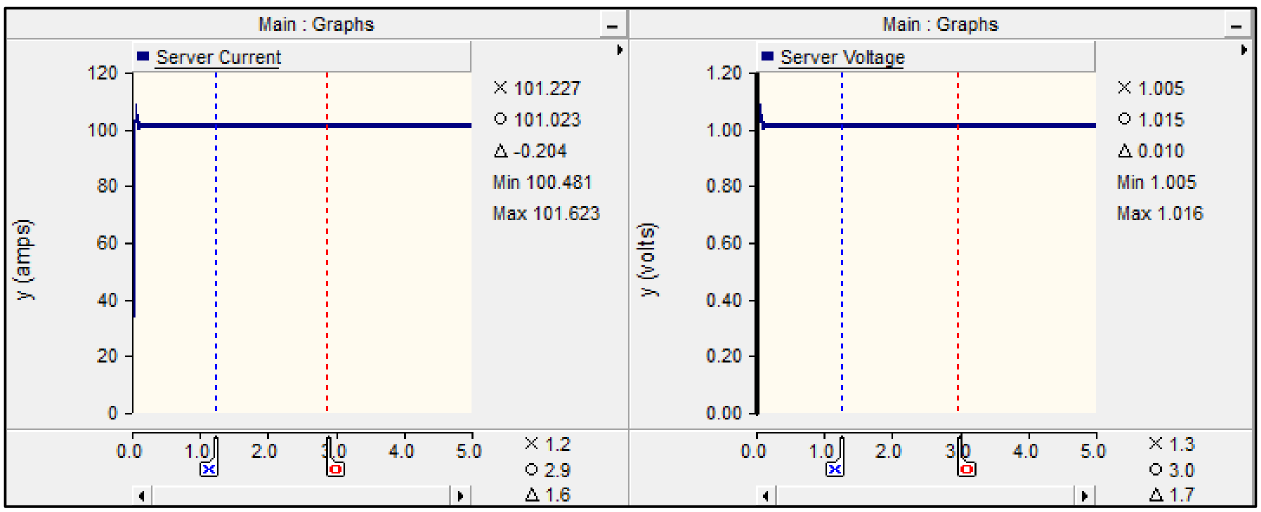

Figure 18: Server Load Voltage and Current

4.1 AC BASELINE SYSTEM MODEL

This section describes the simulation method used as a baseline in the following analyses. The baseline model provides a functional representation of a typical AC datacenter.

4.1.1 Description of Equipment Models

The equipment models utilized in the AC system model include the double-conversion UPS, the power distribution unit, the server power supply unit, and the server processor. The equivalent model used for each piece of equipment will be described in the following paragraphs.

The double-conversion UPS was modeled as a series connection of a synchronous rectifier and a two-level pulse-width modulated inverter [34]. The operation of the synchronous rectifier is described in [32]. The synchronous rectifier model will be described in more detail in the section concerning the DC UPS model. The synchronous rectifier was chosen due to its low harmonic injection, compared to a standard diode rectifier. Using the synchronous rectifier in conjunction with a pulse-width modulated inverter helped to limit the harmonic distortion of the UPS input and output.

The UPS inverter model is shown in Figure 19 below. This inverter topology is common in UPS applications, offering a lower cost compared to more complex topologies [34]. In this model, sinusoidal pulse-width modulation was used, because of its ease of implementation. SPWM does not offer the best harmonic performance, compared to other modulation techniques. To adjust for this, a 5th harmonic filter was sized to improve the harmonic output of the inverter. The following diagram shows the inverter during steady-state operation. Note that three separate PDUs are also shown at the output of the inverter.

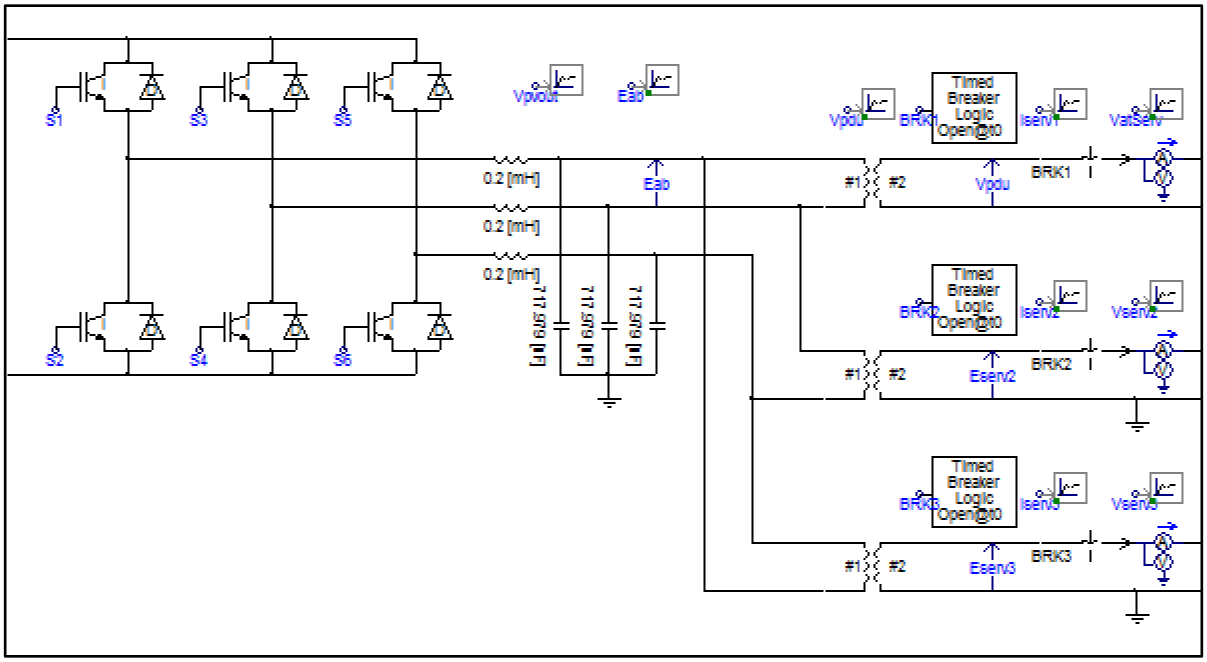

Figure 19: Inverter Circuit Diagram

The SPWM switching controls for the inverter circuit are shown in Figure 20 below.

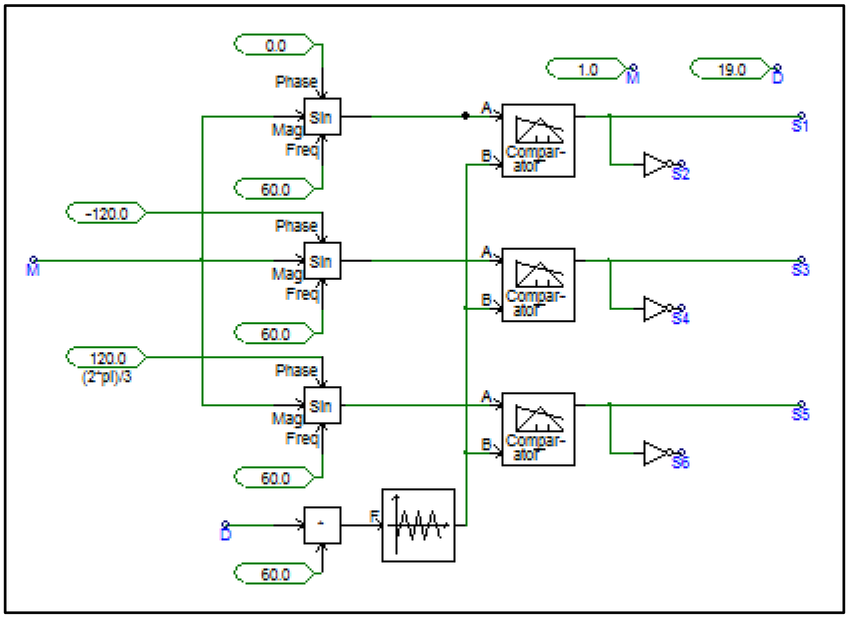

Figure 20: SPWM Switching Controls

The line-to-line output voltage waveform for the inverter is shown in Figure 21. Also shown is the output voltage waveform for the power distribution unit. The power distribution unit was modeled as a transformer and circuit breaker. In this study, the PDU transformer was to provide galvanic isolation. A 4:1 transformer was used, feeding 120 V AC to the server power supply, from the 480 V AC output of the double-conversion UPS. Figure 21 shows the waveforms for the inverter output, as well as the PDU output.

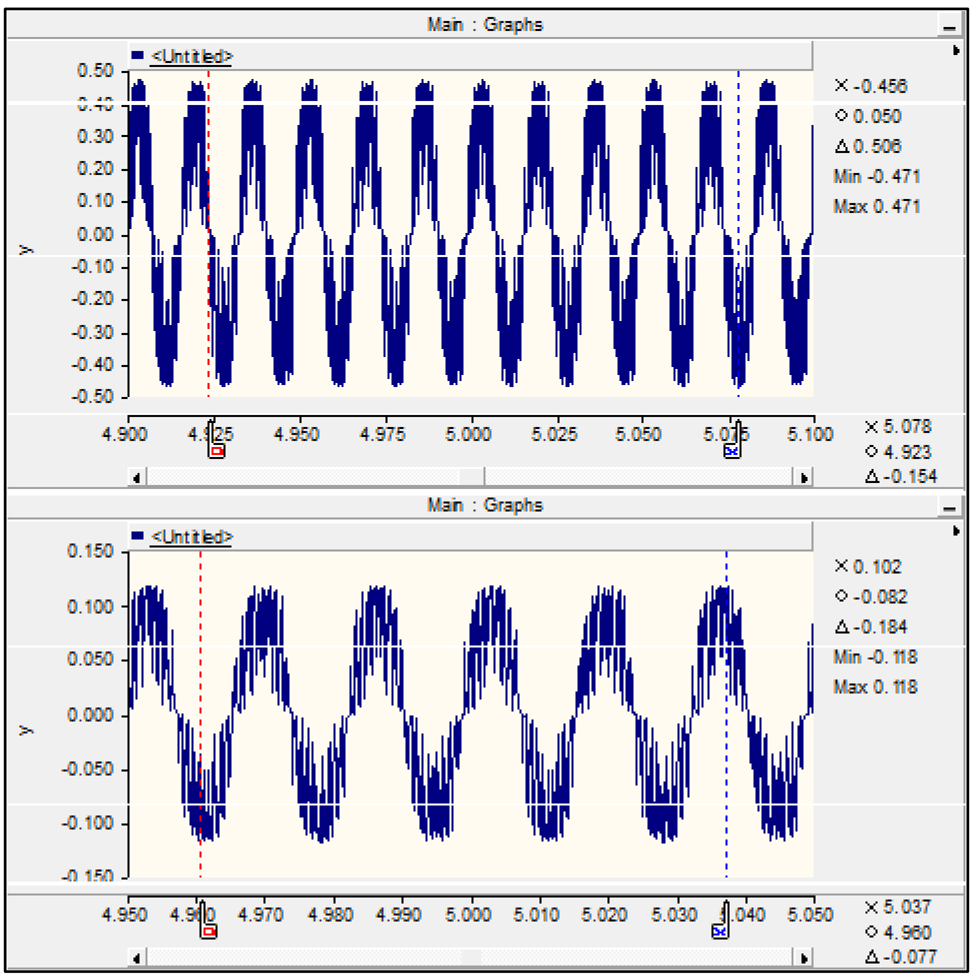

Figure 21: Output Waveforms for UPS and PDU

The server power supply was modeled as a diode rectifier, filter, and buck converter, all connected in a series arrangement. Figure 22 below shows the server power supply.

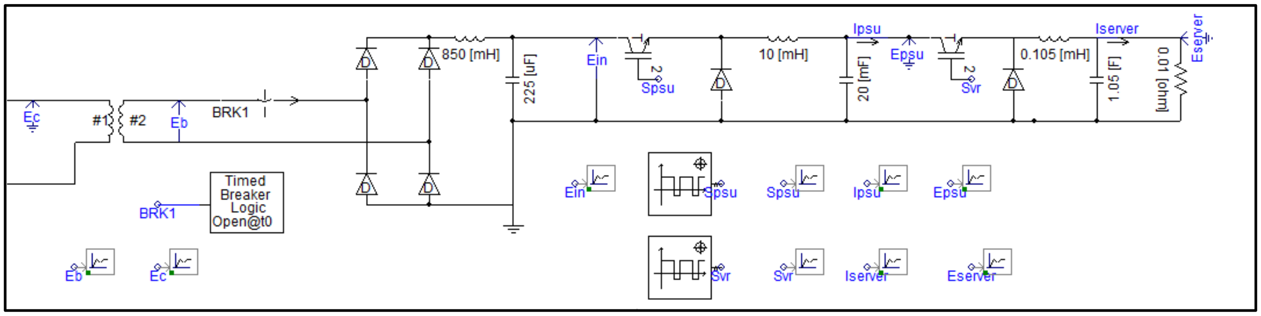

Figure 22: AC Server Power Supply Unit and Processor

The server power supply is designed to take the 120 V input voltage, and transform it into a regulated 12 V DC output. The steady-state operational waveforms for the circuit are shown in Figure 23 and Figure 24 below, demonstrating the correct functionality of the devices.

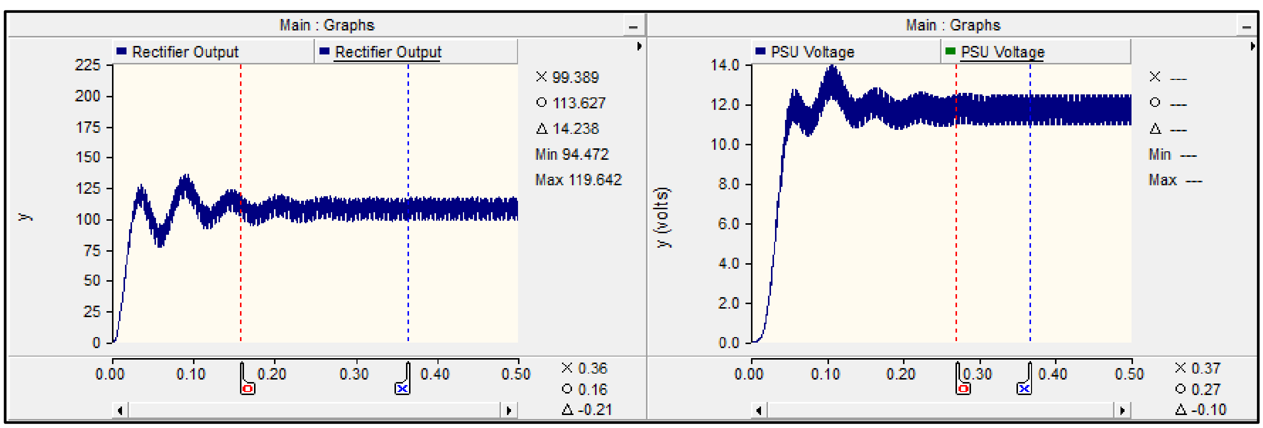

Figure 23: Rectifier and PSU Voltages

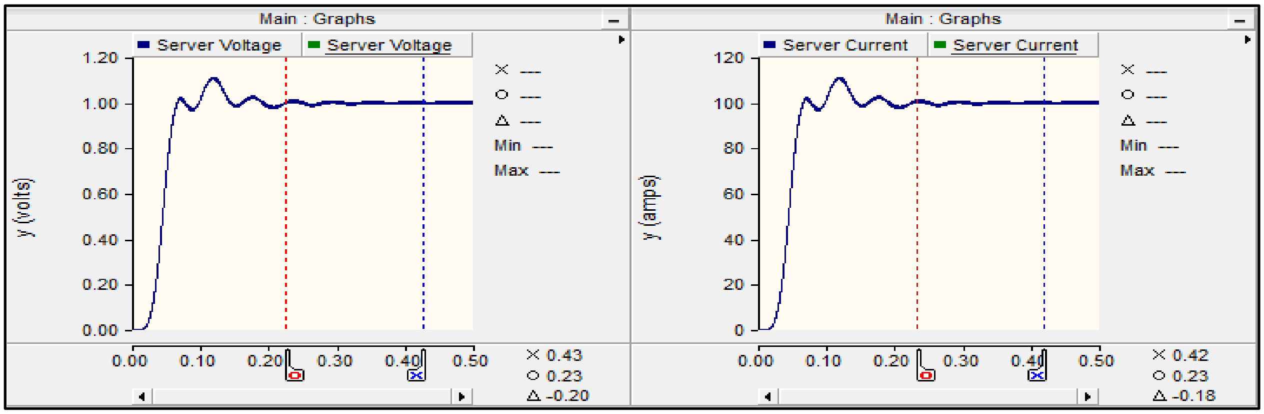

Figure 24: PSU and Server Processor Waveforms

The interconnected AC system model is shown in Figure 25 below. In the figure, three PDUs are shown. The first PDU feeds a server, as modeled above. The other two phases feed a lumped resistive load, sized to serve as an equivalent for the server load. This was done to ensure that the three loads were balanced at the inverter output.

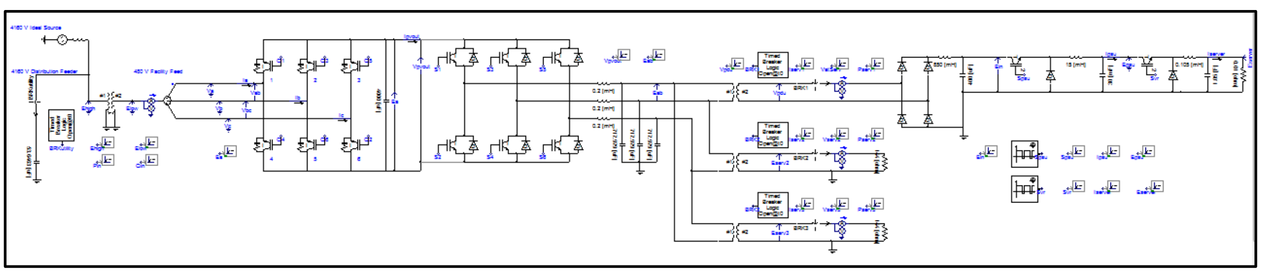

Figure 25: Interconnected AC System

4.2 FACILITY-WIDE DC SYSTEM MODEL

The following section describes the manner by which the DC architecture was modeled using the PSCAD software package.

4.2.1 Description of Equipment Models

The equipment models utilized in the DC system model include the DC UPS, the DC server power supply unit, and the server processor. The equivalent model used for each piece of equipment will be described in the following paragraphs.

The DC UPS was modeled as a synchronous rectifier. Figure 26 shows the rectifier as modeled in PSCAD.

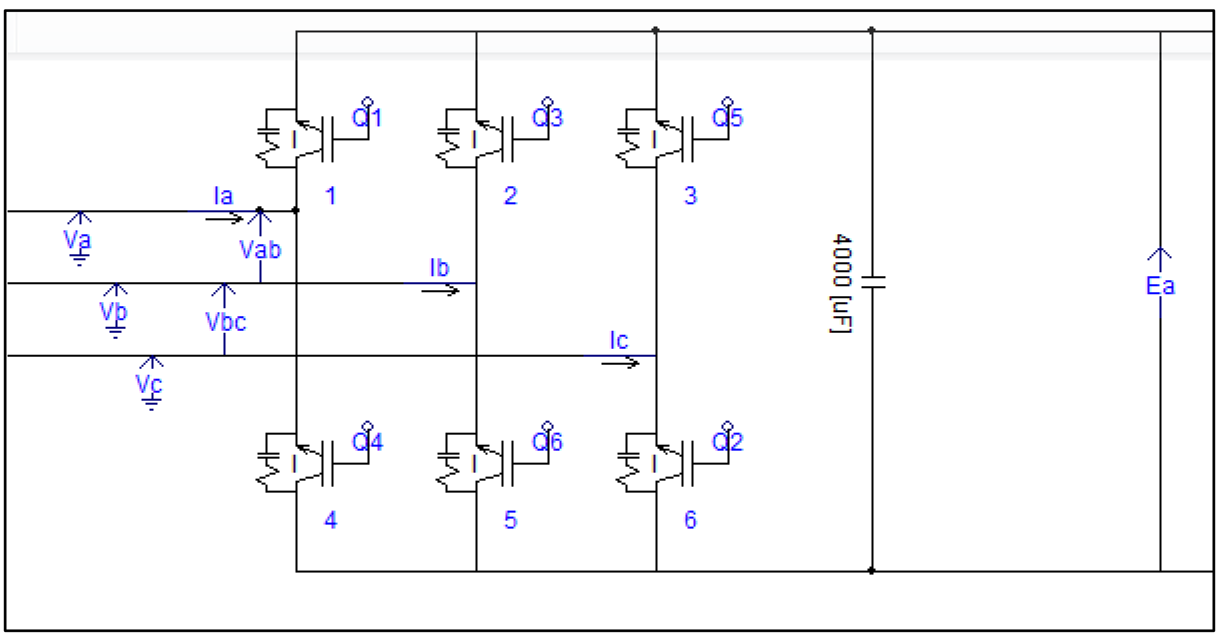

Figure 26: Synchronous Rectifier Simulation Model

The synchronous rectifier has been identified as an appropriate topology for use in DC UPS systems, due to their low harmonic injection [34] [32]. The synchronous rectifier operation is described in [32]. Synchronous rectifiers operate by gating semiconductor devices for select subintervals of an electrical AC voltage cycle. During the time period in which the devices are conducting, current flows in one direction, inhibiting flow in the reverse direction. The angle at which the devices are gated determines the DC output of the rectifier circuit. Denoting this firing angle by the letter alpha, the relationship between the line-to-line RMS input voltage and DC output voltage can be expressed using the following relationship.

$$V_{DC,\alpha} = 1.35 * V_{LL} * \cos(\alpha)$$

With an input voltage of 480 V AC, and a desired output of 380 V DC, the firing angle must be set to 54 degrees. Note that the output of the synchronous rectifier will exhibit a voltage ripple unless filtered. In the simulation case, the output was regulated with a capacitor, which had the effect of boosting the output voltage by a minor percentage. To compensate, the firing angle was reduced until the desired output voltage was reached.

Note that IGBTs were used in this simulation. Traditionally, synchronous rectifiers were developed using thyristors, which naturally commutate based on the phase separation of the line voltages [32]. Using IGBTs, it was necessary to specify both a firing angle, and a commutation angle. This was accomplished in PSCAD by calculating the desired duration of the gate pulse for the device. The waveforms shown in Figure 27 verify the correct operation of the device.

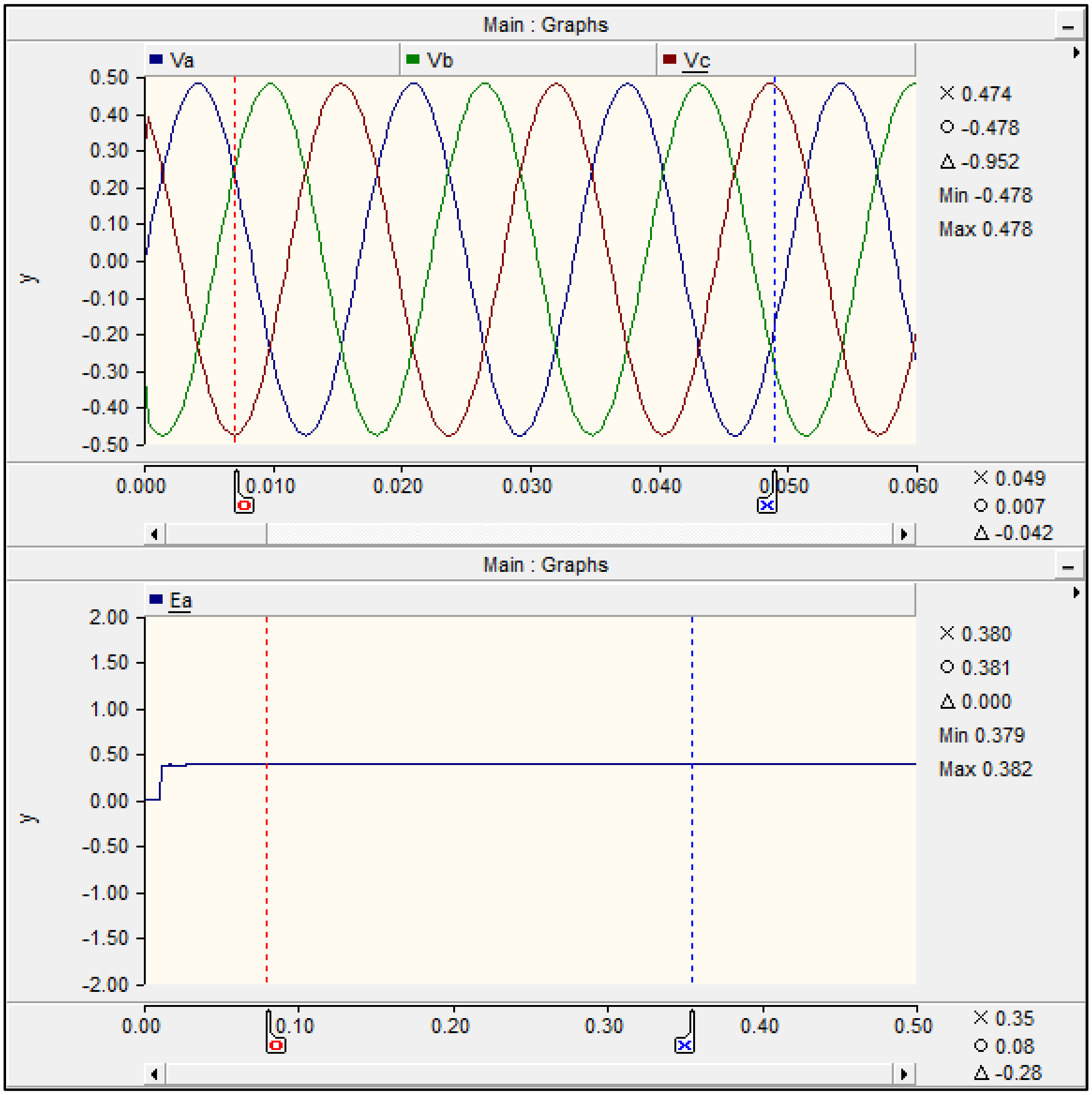

Figure 27: Synchronous Rectifier Input and Output Waveforms

The DC server PSU was modeled as a buck converter [2] [23]. Figure 28 shows the buck converter as modeled.

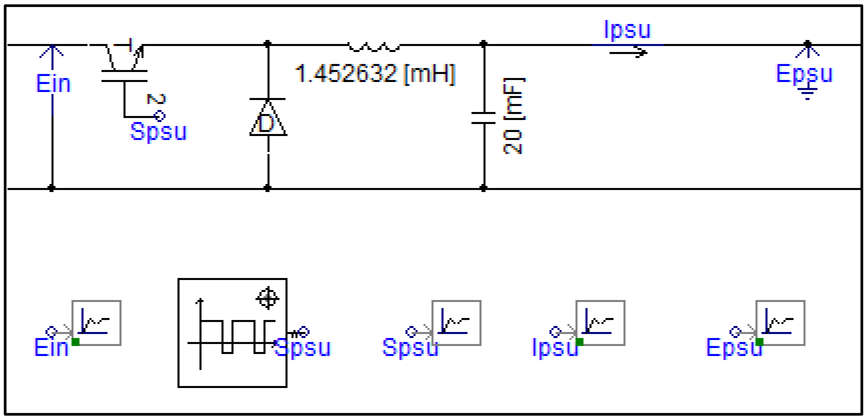

Figure 28: DC Server Power Supply Unit

In order to ensure a minimal ripple in the output voltage, filter inductor and capacitors were sized with the intent of limiting the voltage ripple in the steady state. The input and output waveforms for the PSU are shown in Figure 29 below.

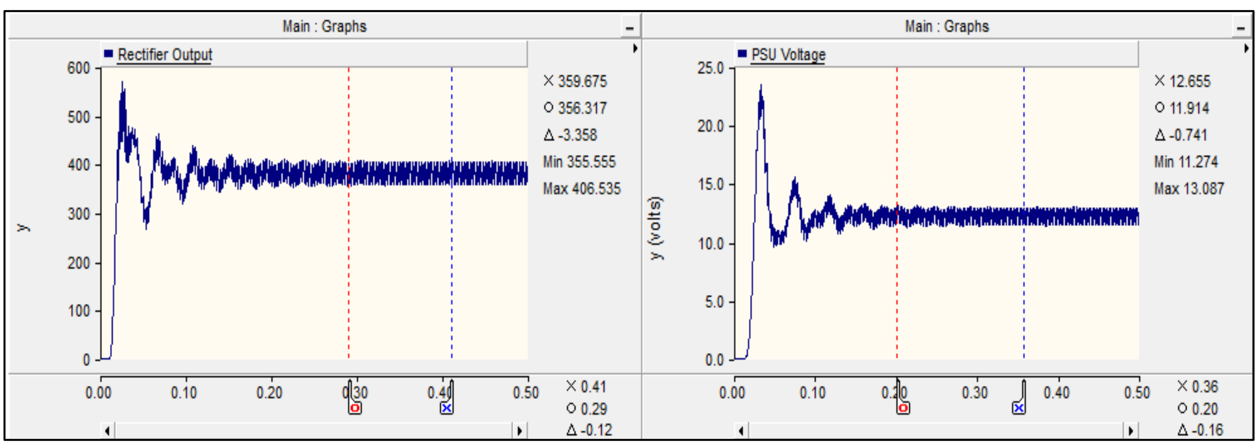

Figure 29: DC PSU Input and Output Waveforms

The server processor used in this simulation was common to all the simulation models, and was described in the introduction to this chapter. Figure 30 below shows the entire interconnected DC system, as modeled in PSCAD. As shown, the simulation model powers two separate servers. Note that this model includes the utility distribution network, which will be described in more detail in the Chapter 5 analysis.

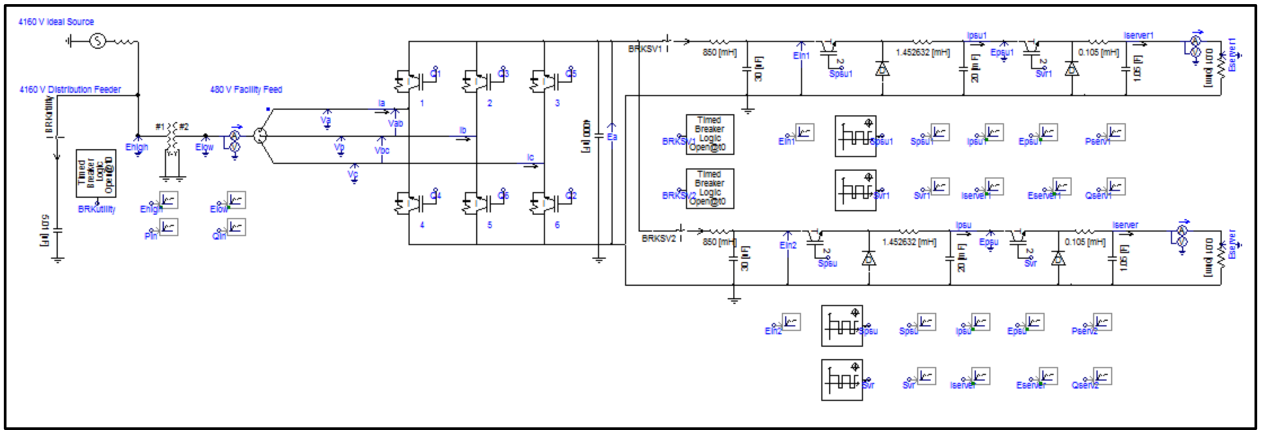

Figure 30: DC Architecture Simulation Model

5.0 TRANSIENT PROPAGATION STUDY

This section focuses on the manner by which voltage transients propagate through datacenter facilities. Both of the design architectures previously described were subjected to the same voltage transient. Voltage measurements were taken at various locations within each distribution system, measuring the percentage voltage deviations and the duration of the deviation. Deviations at the server level were compared to the ITIC standard for compliance.

5.1 STUDY PARAMETERS AND BASIC STRUCTURE

The transient overvoltage was simulated using a capacitor bank switching, a common source of transients on utility distribution networks [41]. The distribution network is sized with a short-circuit strength of 7 MVA, or nearly 1 kA. The capacitor bank is sized at 5% of the MVA capacity of the network equivalent. The utility distribution network, as modeled in PSCAD, is shown in Figure 31 below.

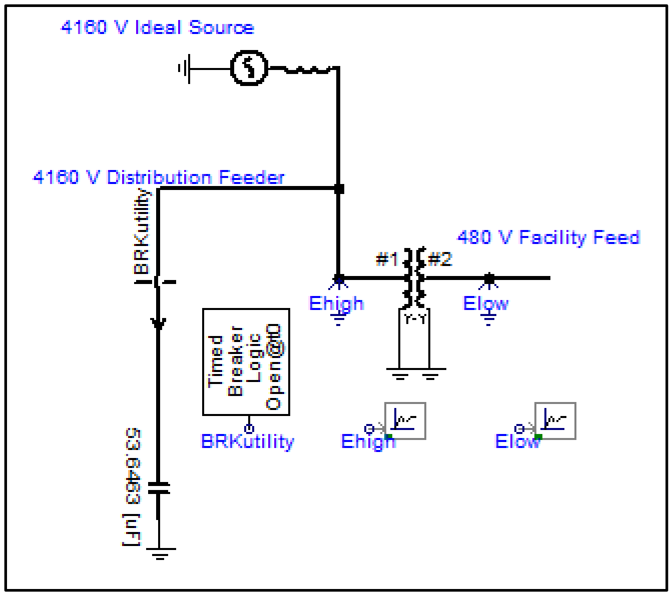

Figure 31: Utility Distribution Network Model

As shown, the high voltage transmission network is modeled using a Thevenin equivalent circuit, represented as an ideal voltage source behind a reactance. The ideal source provides power to a 4160 V AC substation bus. The bus feeds the datacenter load, but also contains reactive compensation in the form of a static capacitor (cap) bank. At the initiation of the simulation, the capacitor bank is uncharged and disconnected from the utility network. At three seconds into the simulation, the cap bank is energized through a circuit breaker, causing a voltage transient.

The distribution feeder terminates in a utility step-down transformer. This transformer converts the 4160 V feed to a 480/277 three phase feed for the datacenter facility. When the voltage transient occurs, measurements are taken at the high and low side of the transformer, in order to analyze the propagation, and the preservation of the transient characteristics. These characteristics are shown below.

Figure 32 below shows the high and low sides of the transformer during the duration of the simulation. As shown, a voltage transient occurs when the cap bank is energized at 3.0

seconds. Note that the transient natural decays in less than two seconds, bringing the system voltages to new steady-state values.

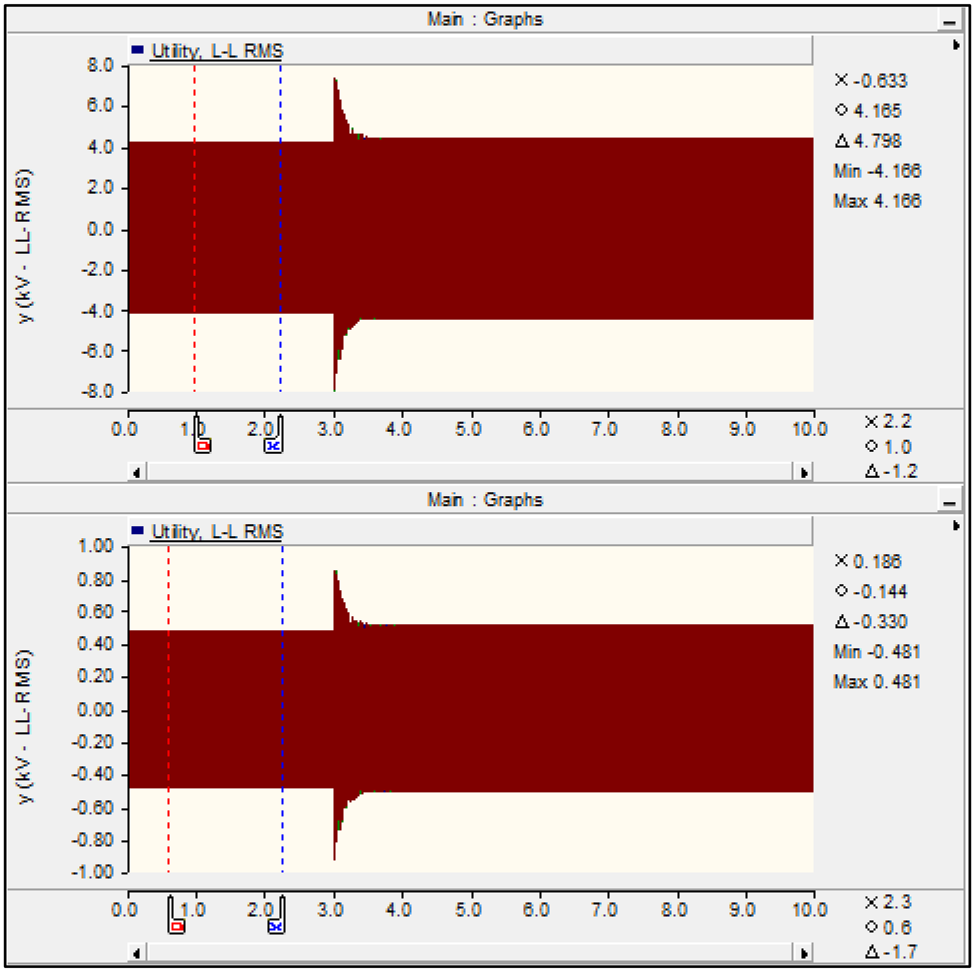

Figure 32: Utility Voltage During Capacitor Bank Energizing

Figure 33 below shows a close-up of a single phase of the utility voltage while the transient occurs. Since the voltage across the capacitor bank cannot change instantaneously, the utility voltage is pulled to the capacitor bank voltage at the time of the disturbance [31].

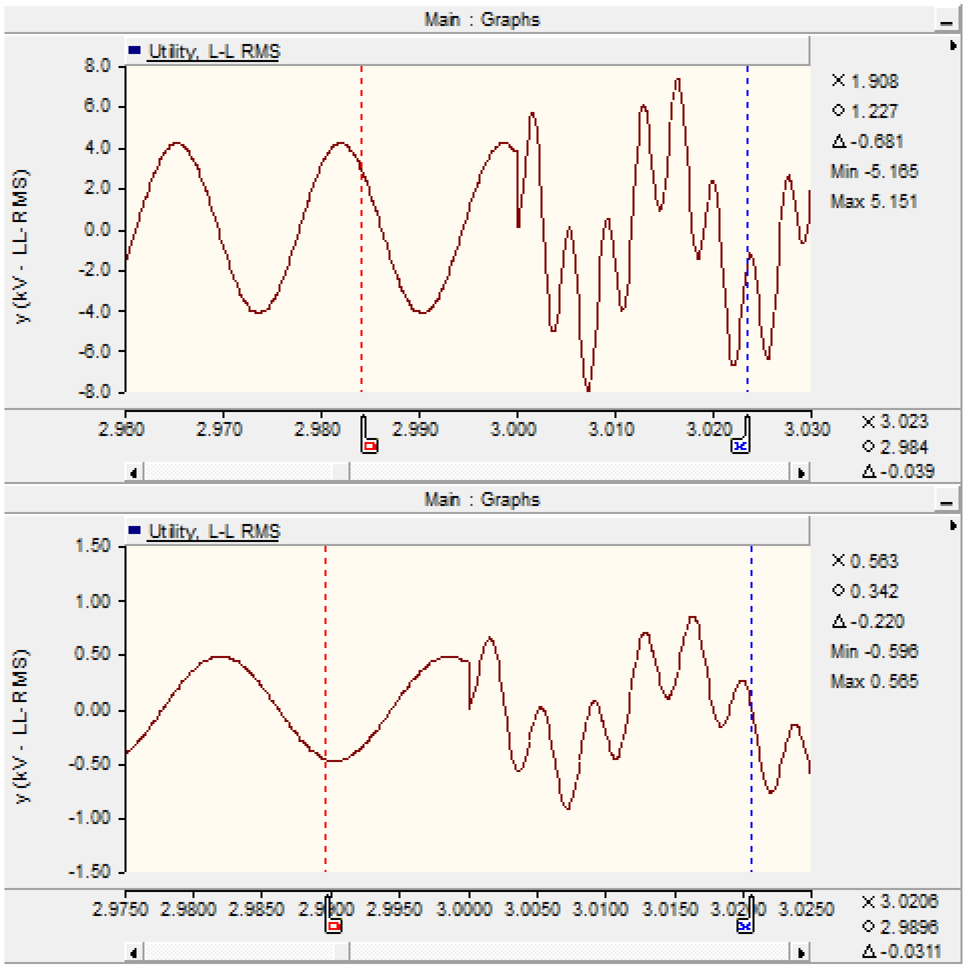

Figure 33: Close-Up of Voltage Transient

In each of the architectures, the voltage transient described above is introduced at the facility entrance. Each of the architectures is modeled as described in the prior chapter of this thesis. This study measures voltages at key points within the facilities, analyzing the effect of the voltage propagation through the facility.

The goal of the study is to compare the voltage deviation at the server power supply against the standards set forth by the Information Technology Industry Council (ITIC) and the Electric Power Research Institute (EPRI) [42]. Each organization has produced a standard curve which will be used in this analysis. One curve determines the acceptable limitations for AC equipment exposure to voltage transients. The second curve determines the acceptable limits for DC equipment.

The AC curve, developed by the ITIC, describes the voltage tolerance applicable to single-phase 120 V AC equipment [42]. The curve quantifies the percent deviation from nominal voltage, as well as the duration of the deviation in seconds. Depending on the depth of the deviation and its duration, information technology equipment is expected to respond without interruption, with service interruption but no physical component damage, or with damage to internal components [42]. Equipment manufacturers create components that meet or exceed the recommendations set forth by the ITI. AC server power supplies are designed according to this standard. The ITIC is shown below in Figure 34.

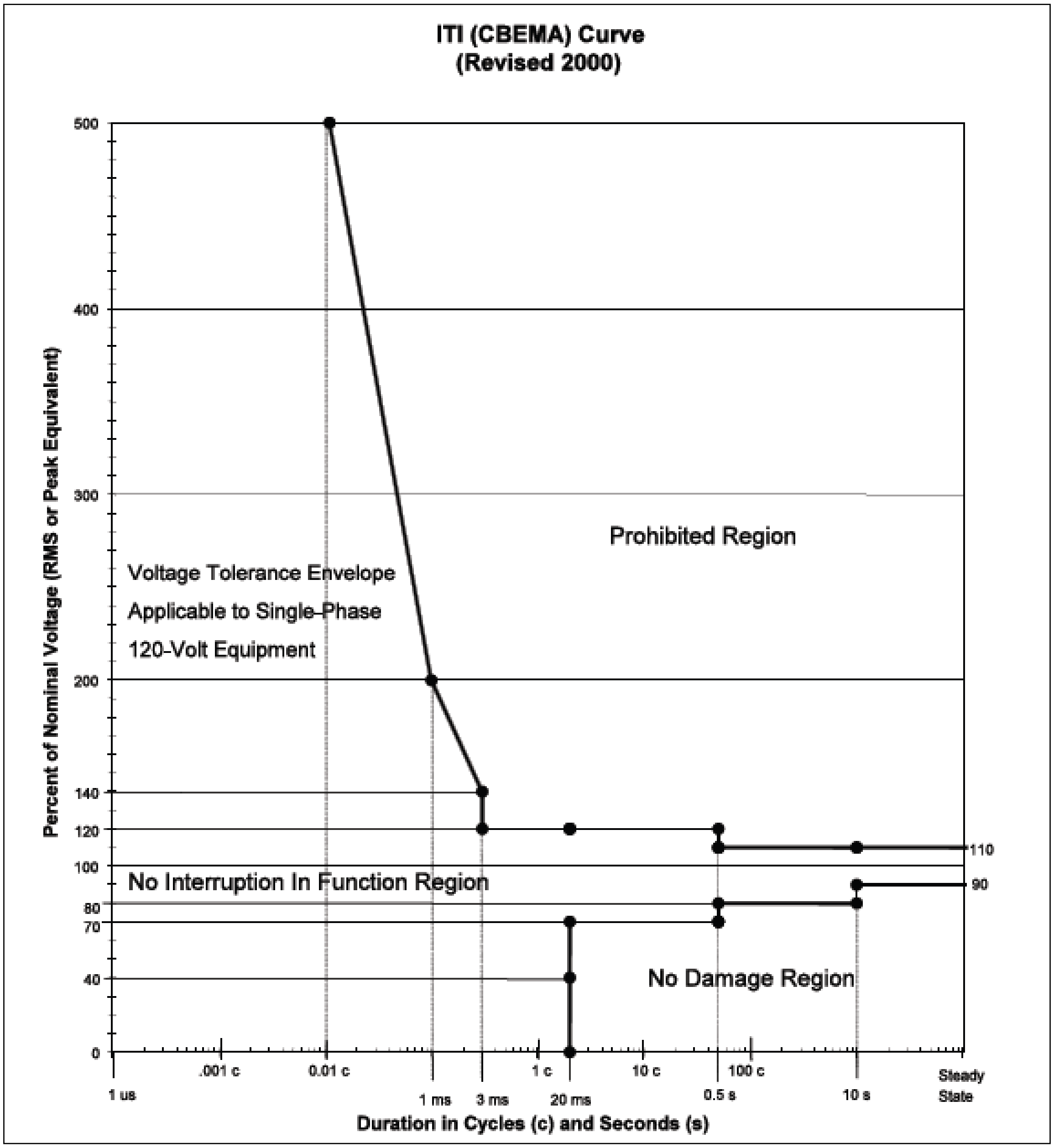

Figure 34: ITI Curve for AC Equipment [42]

The DC curve, developed by EPRI, describes the voltage tolerance applicable to DC server power supplies [38]. The curve quantifies the deviation from nominal voltage (measured in volts), as well as the duration of the deviation in seconds. Depending on the depth of the deviation and its duration, DC server power supplies are expected to respond without interruption, with service interruption but no physical component damage, or with damage to internal components. The EPRI curve for DC server power supplies is shown below in Figure 35.

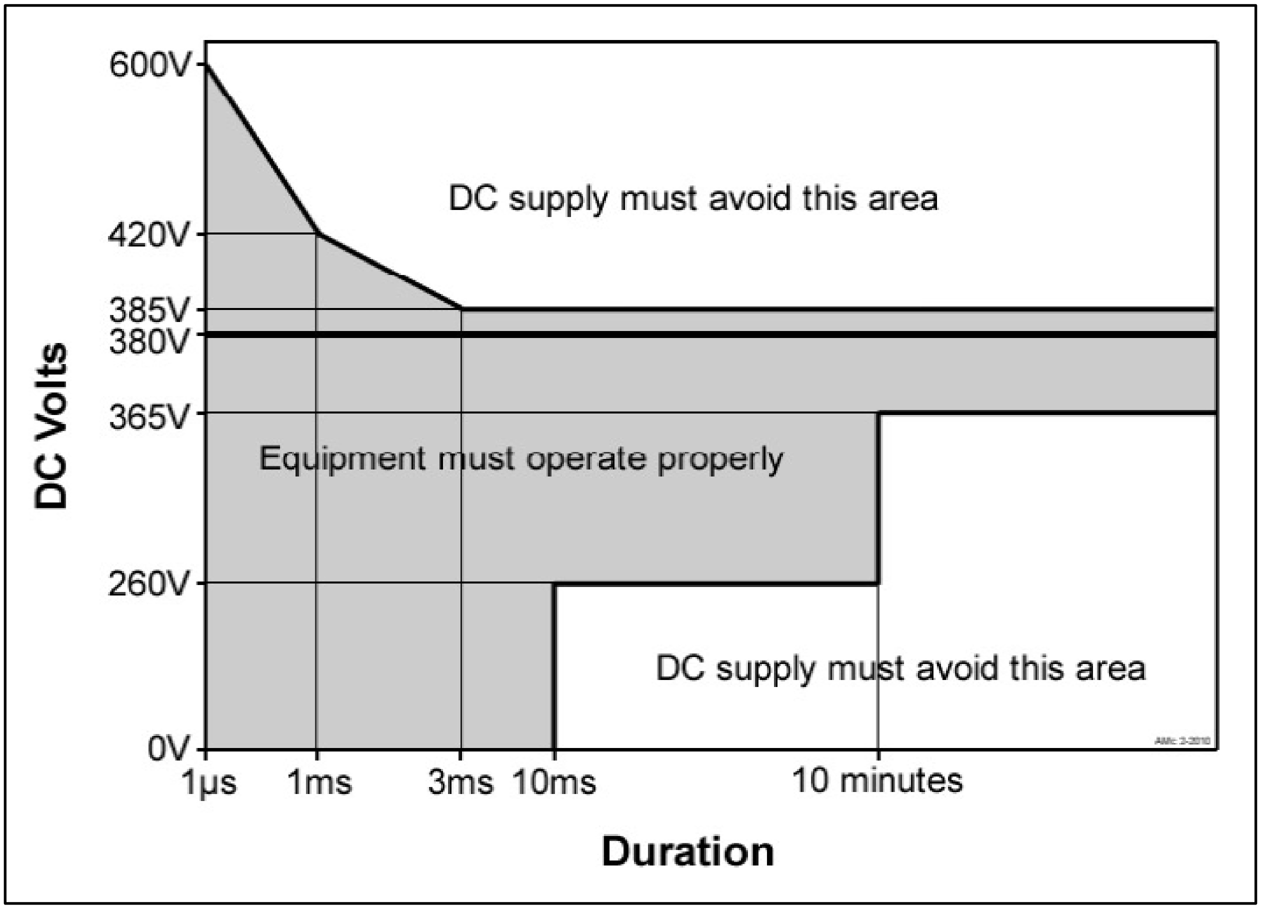

Figure 35: EPRI Standard for DC Server Power Supplies [39]

Note that the manufacturing standards apply to the design of the server power supply units. Therefore, the most significant voltage measurement, that which will be compared to a standard curve, is the voltage measured at the input of the server power supply in each architecture. Although voltage measurements will be shown at various points in the system, including the deviation at the server processor, it is the input to the power supply which is vital in this analysis.

5.2 TRANSIENT PROPAGATION IN THE AC SYSTEM

The following graphs demonstrate the voltage deviations in the AC system model during the course of the simulation. Figure 36 below shows the utility voltage on the high side of the distribution transformer during the simulation. The figure is shown twice, displaying the steady-state voltage prior to the transient event, as well as the peak value after the transient occurs. As shown, the pre-transient voltage is 4.16 kV line-to-line RMS. After the transient, the voltage reaches a steady-state value of 5.08 kV, with a peak voltage of 5.524 kV.

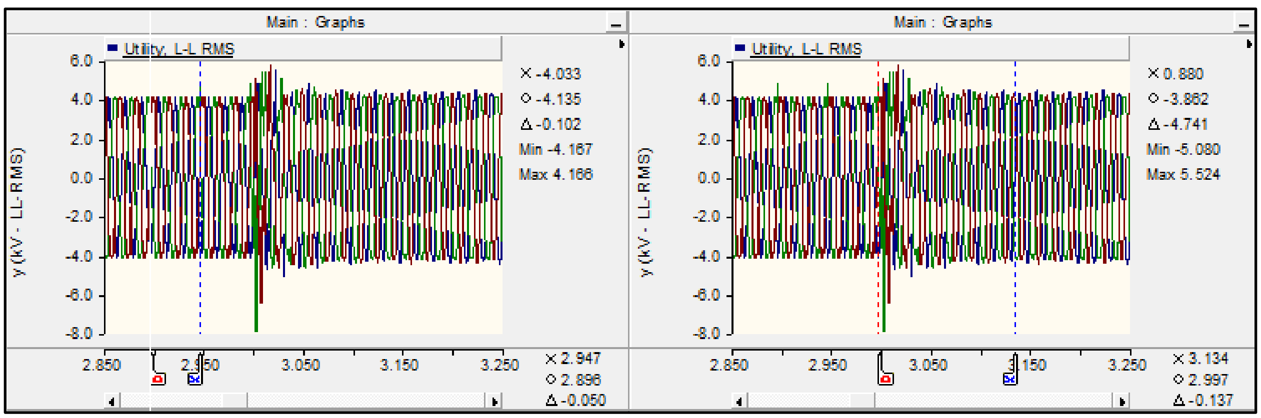

Figure 36: Utility Voltage During Simulation

Figure 37 below shows the voltage at the internal DC bus of the AC UPS. In the AC UPS, the synchronous rectifier was set to output a voltage of 648 V DC. This was done to simulate the effect of a three-phase diode rectifier. The waveforms show that the synchronous rectifier output exhibits ripple both before and after the transient. The pre-transient average DC bus voltage is 635 V. The post-transient DC bus voltage has an average value of 796.2 V.

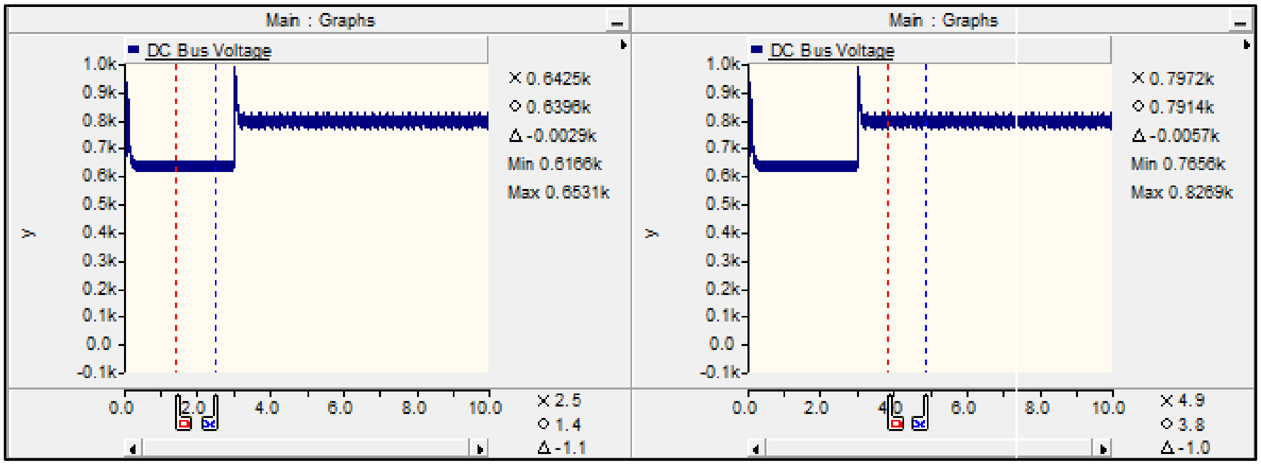

Figure 37: UPS Internal DC Bus Voltage

Figure 38 below shows the voltage at the inverter output during the simulation. Note that only the line-to-line voltage from phase A to phase B is shown. As shown in the figure, the pre-transient voltage has an RMS value of 484 V AC. After the transient, the average value settles at 740 V AC, with a peak transient overvoltage of 750 V.

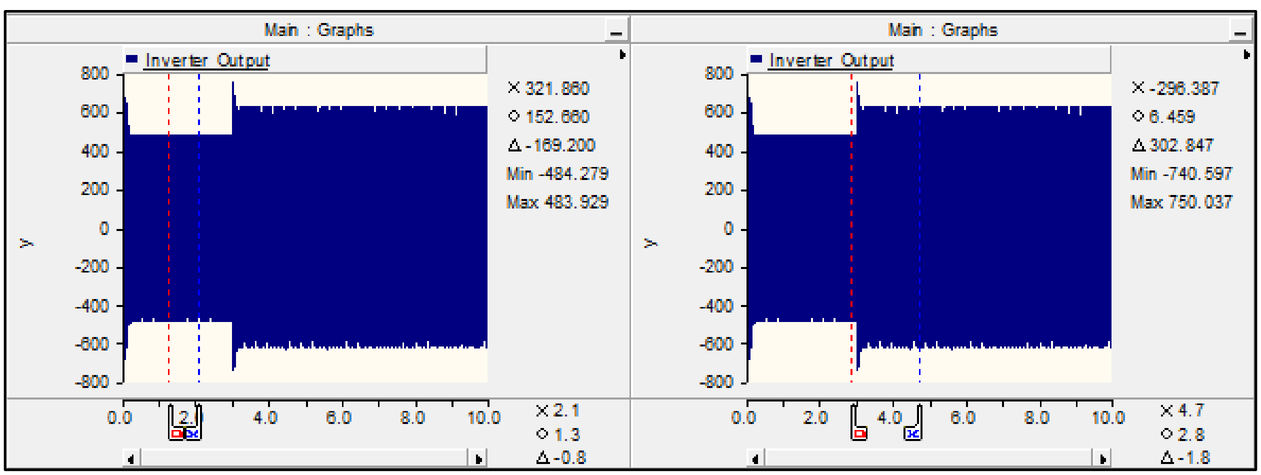

Figure 38: Voltage Seen at the Server Power Supply

Figure 39 below shows the voltage deviation seen at the output of the PDU. This is the voltage which was fed to the server AC power supply unit model. As shown in the figure, the pre-transient voltage has an RMS value of 121 V AC. After the transient, the average value settles at 185 V AC, with a peak transient overvoltage of 188 V. This transient represents a 52.9% increase in the operating voltage. According to the ITIC standard, a transient overvoltage of this magnitude should not be allowed to persist for more than 3 ms. In this simulation model, the transient persists for the duration of the simulation – a period of seven seconds. Note that this simulation utilized a feedforward control strategy to achieve the desired steady-state operating conditions. The duration of the transient can be reduced by employing feedback control methods to the operation of the UPS inverter.

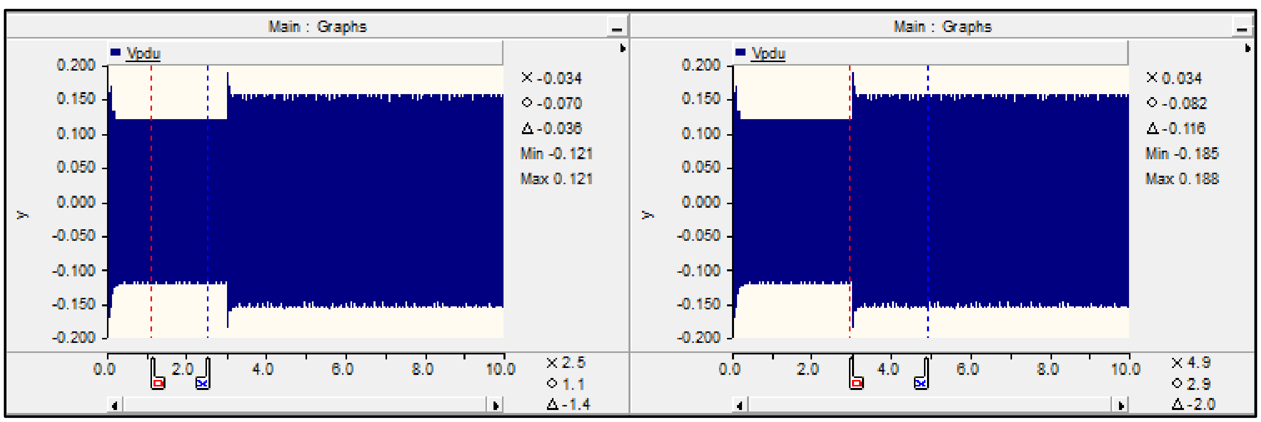

Figure 39: PDU Output Voltage

Figure 40 below shows the voltage deviations seen at the server power supply unit, as well as the server processor. As shown, the PSU and processor both reach their expected pre-transient values 12 V DC and 1 V DC. After the transient, both experience significant deviations that sustain over the course of the simulation.

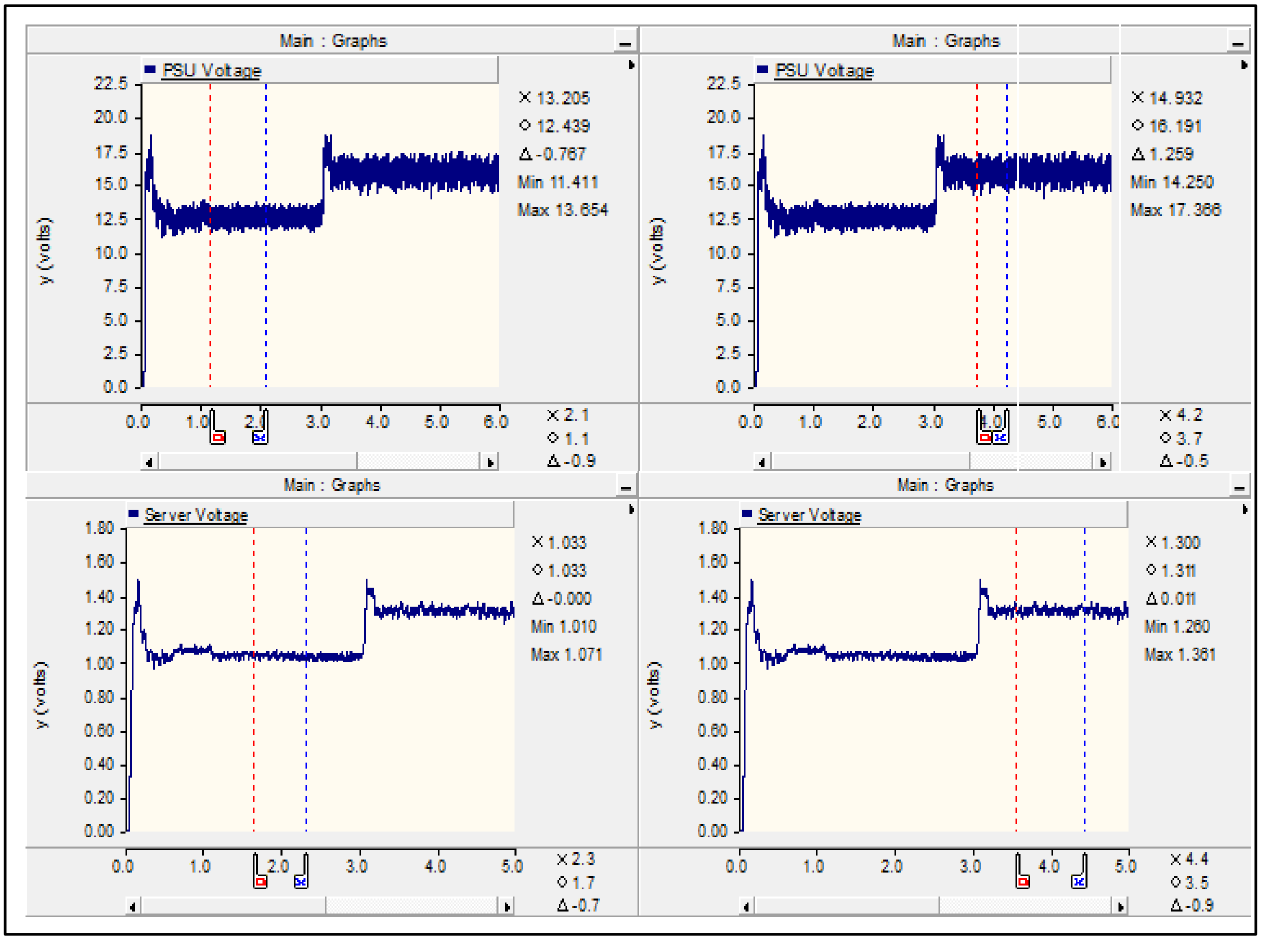

Figure 40: Server PSU and Processor Voltages

The AC benchmark analysis shows that voltage deviations occur as a result of the transient event. These deviations are measured at different points in the network. At the input terminals to the server power supply, the voltage transient exceeds the standards set forth by the ITIC. However, it is not the sheer magnitude of the voltage transient which is the issue. The true problem lies in the duration of the overvoltage condition. With proper feedback controls implemented, this issue can be resolved.

5.3 TRANSIENT PROPAGATION IN THE DC SYSTEM

The following graphs demonstrate the voltage deviations in the DC system model during the course of the simulation. Figure 41 below shows the utility voltage on the low side of the distribution transformer during the simulation. As shown, the pre-transient voltage is 480 V line-to-line RMS. After the transient, the voltage reaches a steady-state value of 556 V, with a peak voltage of 563 V.

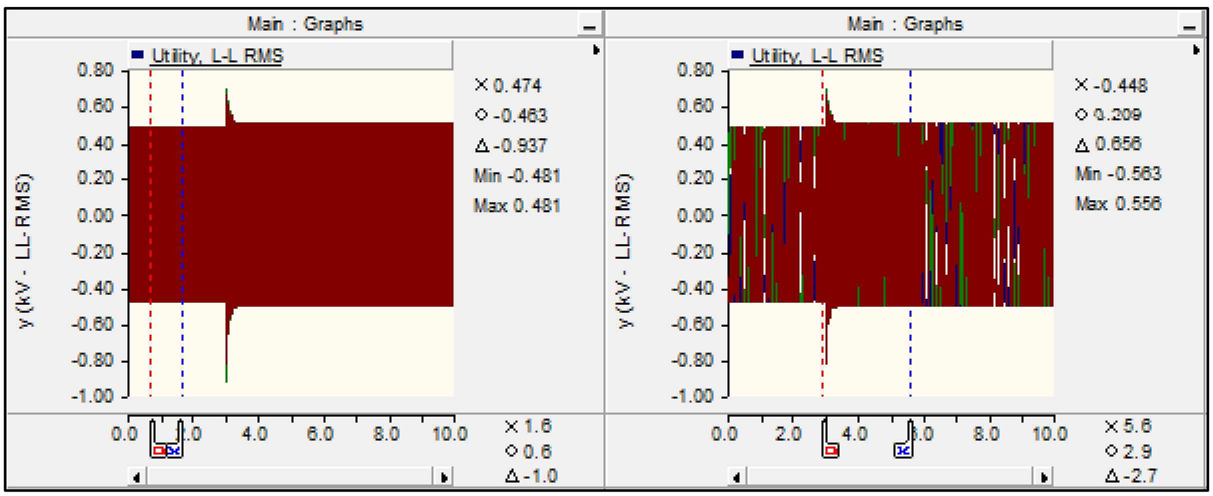

Figure 41: Utility Voltage During DC Analysis

The output of the synchronous rectifier is shown in Figure 42. As shown, prior to the transient event, the rectifier produces a DC voltage of 380 V. Once the transient occurs, the voltage increases to a peak value of 739 V. This represents a 194% increase in the operating voltage. This peak value exceeds the 600 V DC maximum value set forth by the EPRI standard. After 1.6 seconds, the voltage stabilizes at a new steady state value of 423 V. This value persists throughout the duration of the simulation. According to the EPRI standard, a transient of this value must not persist for more than 1 ms.

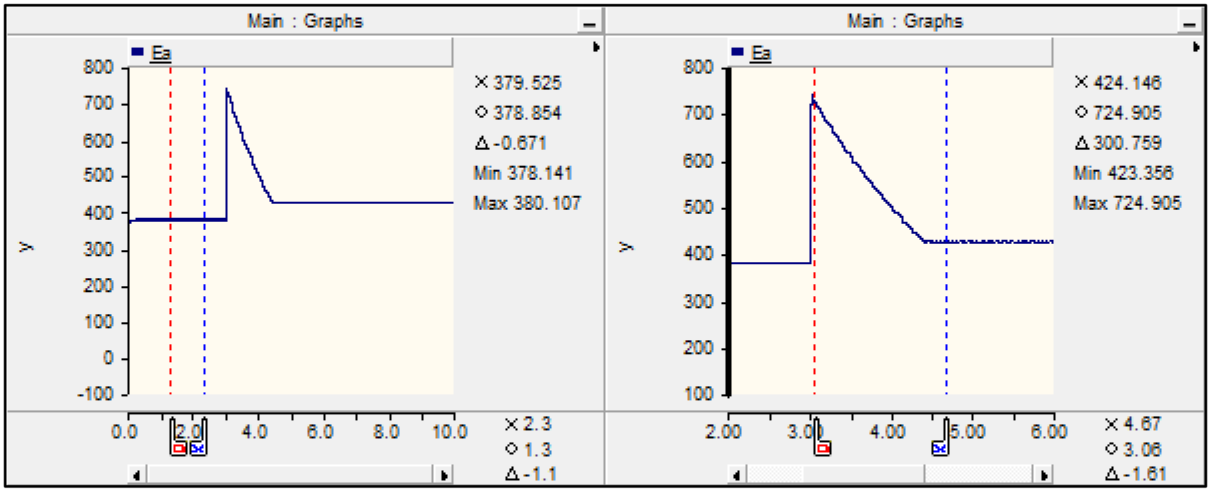

Figure 42: Synchronous Rectifier Output Voltage

The voltage deviations at the server voltage regulator input and server processor are shown in Figure 43 below.

In the case of the DC distribution architecture, it is seen that the voltage deviations at the server, caused by the capacitor bank switching transient, exceed the standard put forth by the Electric Power Research Institute. These overvoltages exceed the standard in terms of their sheer magnitude. Therefore, one cannot conclude immediately conclude that feedback controls can mitigate the problem, as was the case in the AC distribution architecture. Further research is required in order to determine the effect that closed-loop regulation would play in the DC architecture.

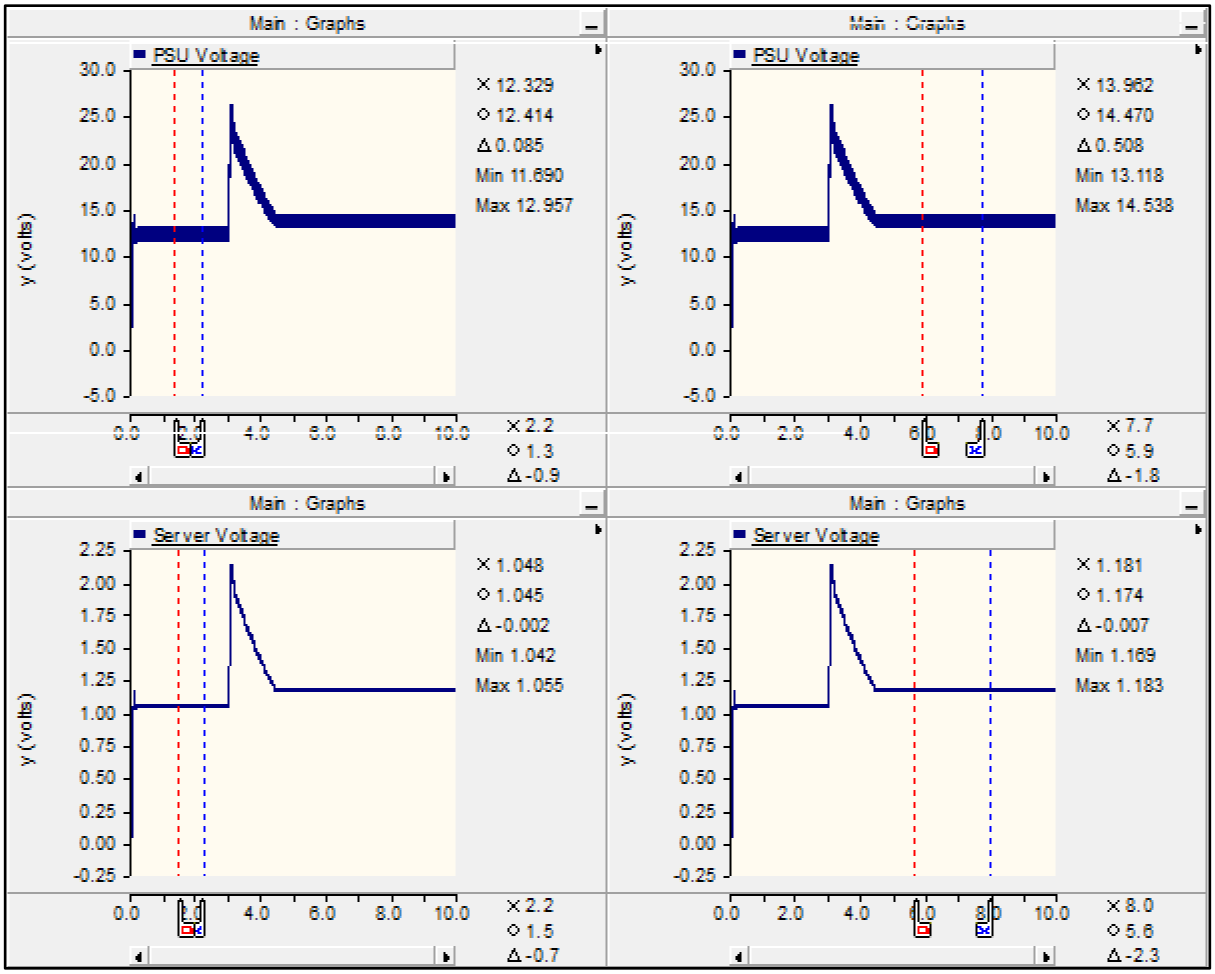

Figure 43: PSU and Server Processor Voltages

6.0 SUMMARY AND FUTURE WORK

This analysis shows that the voltage deviations in both distribution architectures exceeded their relative standards. In the AC case, the standard was exceeded in that the transient overvoltage persisted for a duration longer than that which is acceptable. In the DC case, the magnitude of the overvoltage greatly exceeded the acceptable range for DC power supplies.

Based on these results, it is anticipated that the AC case can be resolved by applying closed-loop regulation to the UPS inverter. By eliminating the steady-state error between the desired output voltage of 480 V, a PI controller can be used to return the output voltage to an acceptable level. Given a well-defined response time, the transient should be kept within the acceptable time frame, according to the ITIC standard.

In the case of the DC architecture, a means must be provided for lowering the magnitude of the voltage transient. Given that the transient originated outside of the datacenter facility, it is anticipated that the transient can be easily mitigated using a surge protector. However, the presence of this sever overvoltage in response to a common switching event raises questions concerning the nature and effect of other transients that may affect a DC distribution architecture.

Given a centralized DC architecture, it is possible for transients to originate within the datacenter facility, affecting the DC bus voltage. For instance, many institutions have advocated the DC bus architecture to allow for easier integration of onsite photovoltaic generation in datacenter facilities [32] [29] [37]. Figure 44 below shows a possible means of integrating solar power into a DC bus architecture.

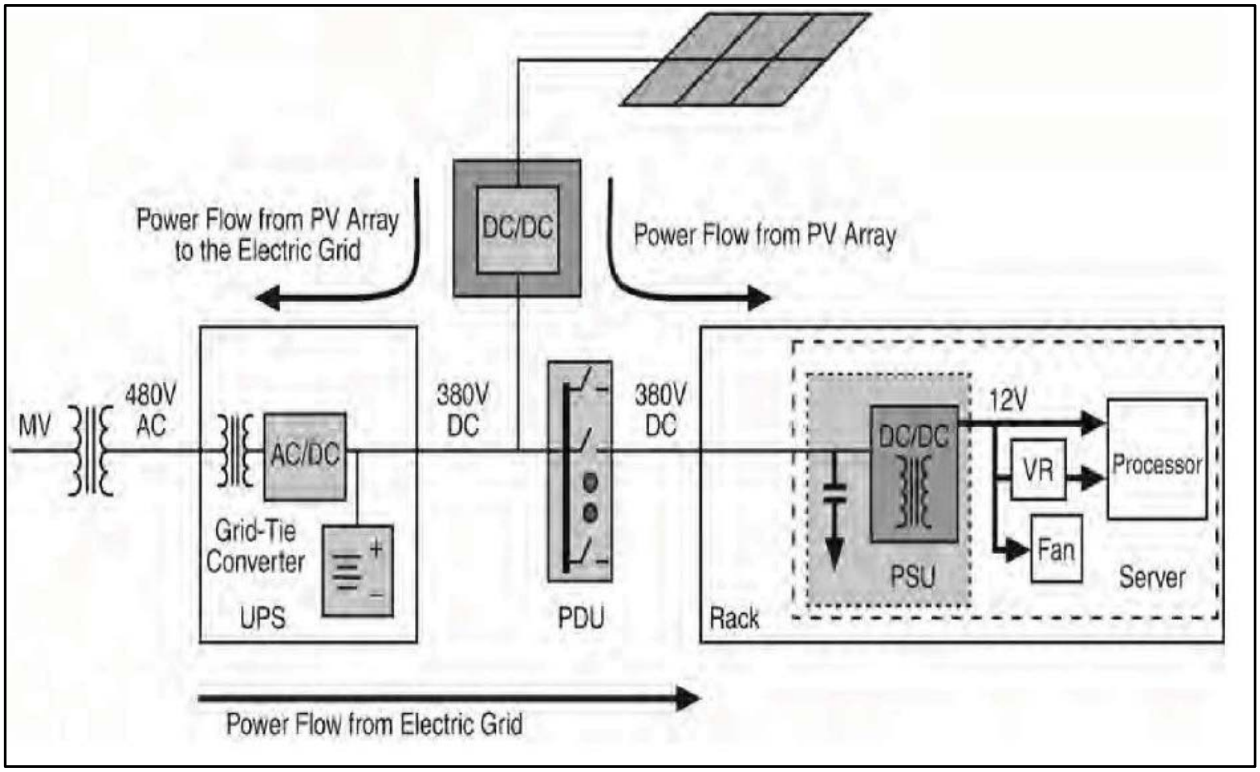

Figure 44: Solar Integration in DC Architecture [38]

The output voltage of a photovoltaic (PV) array is subject to in short periods of time, due to variations in operating temperature and available irradiation levels. For instance, PV array shading can happen due to cloud cover. In a matter of seconds, a PV array can make the transient from full sun, to full shade, and back to full sun again. During this time period, the output voltage of the array drops. As the output voltage changes, a transient can be generated due to the capacitance in the DC cable used to interconnect the PV array.

Alternatively, within the datacenter facility, a fault can occur, or a load can be quickly disconnected from the DC bus through a circuit breaker. Any sudden variation in operating conditions has the ability to affect the DC bus, superimposing an AC waveform on top of the DC voltage. The effects of transients originating within the datacenter facility are still unknown and need to be explored in future work.

This study demonstrates that attention must be given to the consideration of transients and their propagation through datacenter electrical distribution networks. However, this study has limitations. Most importantly, feed-forward control techniques were utilized in order to achieve steady-state operating conditions within the simulation. However, feedback control systems would have produced a more accurate portrayal of the duration of the voltage transients. Future work with regard to transient propagation in datacenter distribution architectures must address the effect of feedback control systems for regulating the power electronic switching. It is expected that the duration of the transient will be shortened if proper control systems can be designed.

Furthermore, this study dealt solely with transients that originating from without the facility. Given a DC bus architecture, it is possible for transients to originate within the facility, affecting the DC bus voltage. Transients originating from without the facility can be mitigated by using surge arrestors and similar devices. Transients originating within the facility must be more clearly researched and understood. More sophisticated strategies for protection and coordination must be developed in the future.

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