THE UTILIZATION OF POWER CONVERTERS IN CONSUMER PRODUCTS FOR DISTRIBUTED REACTIVE POWER SUPPORT

BY

CHRISTOPHER J. RECIO

THESIS

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Adviser:

Professor Thomas J. Overbye

ABSTRACT

The introduction of smart meters to residential customers opens the door to feedback which can be used to improve the nation's power grid. The motivation of this research lies in the use of emerging smart grid devices to supply reactive power as a means of distributed reactive power support. Such devices can include plug-in hybrid electric vehicles, solar panels, uninterruptible power supplies, computers, televisions, appliances, lighting, etc.

Power factor compensation closer to the load improves transmission line loading and efficiency. In addition to inverter-based devices to supply reactive power, loads that use active power factor correction are being explored. Traditionally, the goal of power factor correction at the device level has been to achieve as close to unity as possible, which implies that the current waveform is in phase with the voltage waveform with minimal distortion. An adjustable power factor correction scheme can be used to supply reactive power to correct for surrounding devices as well.

Example power systems, such as distribution feeders, are modeled to show the benefits of local injections of reactive power. Varying loading and supply voltage conditions are modeled. Algorithms are used to determine the validity of using distributed reactive power control with different assumptions of the cyber infrastructure, such as local control versus global control.

To my parents, for their love and support

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CCM	Continuous Conduction Mode
CRM	Critical Conduction Mode
DCM	Discontinuous Conduction Mode
DER	Distributed Energy Resources
DSM	Demand-Side Management
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission System
HEM	Home Energy Manager
HVAC	Heating, Ventilation, and Air-Conditioning
IHD	In-Home Display
MSC	Mechanically-Switched Capacitor
PHEV	Plug-in Hybrid Electric Vehicle
PFC	Power Factor Correction
PV	Photovoltaic
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
TCIPG	Trustworthy Cyber Infrastructure for the Power Grid

TSC	Thyristor-Switched Capacitor
UPS	Uninterruptible Power Supply
VAR	Volt-Ampere Reactive
VSI	Voltage Source Inverter

Chapter 1

INTRODUCTION

Reactive power has been studied since the inception of the power grid. In 1920, D.M. Jones wrote "Tied up with this relative timing of voltage and current waves (which make up one pair of the cause and effect twins of the electrical family) is much of the hope and grief of the distribution game" [1]. The game has changed in modern distribution systems but many of the objectives remain the same. Capacitor banks and synchronous compensators as a form of reactive power support are being supplemented or replaced with power electronics. Some of the power electronics devices commonly used in consumer homes today can provide the same function on a much smaller scale. In addition, the introduction of smart meters to residential customers opens the door to feedback which can be used to improve the nation's power grid. The motivation of this research lies in the use of emerging smart grid devices to supply reactive power as a means of distributed reactive power support. Such devices can include PHEV/EVs, solar panels, UPS systems, computers, TVs, appliances and lighting, among others.

Power factor compensation closer to the load improves transmission line loading and efficiency. In addition to inverter-based devices to supply reactive power, loads that use active power factor correction are being explored. Traditionally, the goal of power factor correction from a device level has been to achieve as close to unity as possible, which implies that the current waveform is in phase with the voltage waveform with minimal distortion. An adjustable power factor correction scheme can be used to supply reactive power to correct for surrounding devices as well.

PFC is common and often required in power converters above certain power levels. PFC controllers on the market today boast high power factors, typically around 0.99 at full load, and target unity. Previous work, such as [2], shows the benefits of Smart Grid devices to supply reactive power, but many converters have requirements to be above a specified power factor. For example, the ENERGY STAR Program Requirements for Computers (Version 5.0) [3] specifies a Power Factor ≥ 0.9 although there could be additional benefit to having a leading power factor below 0.9. This demonstrates the need for changes that would be necessary to promote reactive power support.

Having an adjustable PFC converter can provide the benefit of improving overall power factor in an area, rather than correcting a single device. For example, a household computer could actively adjust its power factor to compensate for a load such as the induction machines used in the HVAC system or other reactive loads. A common reference in the study of power systems is that two-thirds of the load is consumed by electric machines. While there is an increase in use of variable speed machines, there is a significant reactive load that requires compensation.

1.1 Background and Related Work

While the advantages of distributed voltage support have been shown for decades, the use of power electronics in the power systems industry is more modern, becoming prominent in the 21st century. Traditionally reactive power support was implemented by switching large banks of capacitors, such as in the mechanically-switched capacitor (MSC). The MSC has limitations as it requires human control to switch it on. A flexible alternating current transmission system (FACTS) generally uses power electronics to improve the dynamic response of the VAR support. The thyristor-switched capacitor (TSC) replaces the mechanical switch with back-to-back thyristors. The MSC and TSC are classified as static var compensators (SVC). The reactive power output of an SVC is proportional to the square of the voltage. SVCs have been used since the 1970s, but it was not until the late 1990s that power electronics started to gain traction for active switching applications. In 1997 the acronym FACTS was added to the IEEE dictionary and the first STATCOM was installed in 1999 [4]. A STATCOM is based on a voltage source converter and provides advantages over the TSC. In contrast to the SVC, the STATCOM has variable control of its reactive power output. Figure 1-1 shows examples of FACTS devices used for shunt compensation. The fundamentals of the STATCOM are similar to voltage-source inverters that are used in consumer products; however, the scale of a STATCOM is much larger and it is used on high-voltage transmission networks.

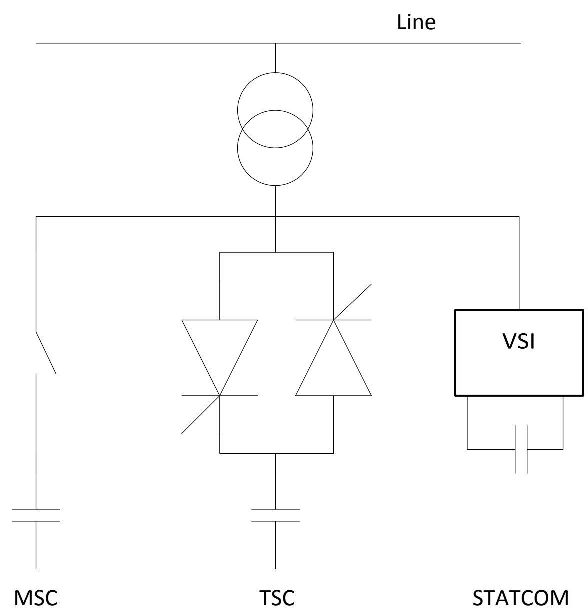

FIGURE 1-1: EXAMPLE OF DEVICES USED FOR SHUNT COMPENSATION

While the use of voltage-source converters for reactive power compensation is common in STATCOMs, it is not commonly used at a consumer level. Section 3.2 proposes a modification to the typical PFC topology used in consumer products today to intentionally target a non-unity

PF for reactive power compensation. While there is extensive research on non-unity PFC for reduced cost as in [5] and [6], little research has been conducted on its use for VAR support. These papers target a current in phase with the voltage but that would contain harmonics. The idea is a design that is “good enough” with a tradeoff of quality vs. cost. References [2] and [7] examine the use of electric vehicles for ancillary services, including VAR support.

References [8] - [10] present methods of the control required for distributed voltage support.

1.2 Chapter Summary and Thesis Organization

This chapter introduced the basic idea of reactive power support for a consumer product. The introduction of smart meters to residential customers opens the door to the potential for a distributed reactive power support on a level that has not be used before.

Chapter 2 presents examples to motivate the idea of reactive power based voltage regulation in a distribution network. The cost of reactive power is primarily the opportunity costs of the generator as the real power generation is reduced. Further benefits of distributed reactive power support, such as voltage control and stability, are harder to quantify.

Chapter 3 discusses hardware implementations for applications that could be used in consumer products. The most obvious candidate devices are products such as PV panels and PHEVs which have considerable capacity for reactive power support. Lower power devices which currently use active power factor correction are examined.

Chapter 4 presents different options for control. Initially, a single house or building is considered where the smart meter can communicate with an IHD or HEM which would act as the coordinator for reactive power support. The possibility of achieving unity power factor at the meter is examined. This opens the door to a distributed reactive voltage support where consumers could provide reactive power to help the power system in their area.

Finally, conclusions are presented in Chapter 5 as well as possibilities of future work.

Chapter 2

REACTIVE POWER SUPPORT

There has been an increasing mention of smart devices being utilized for active demand-side management. This covers a variety of strategies such as active response of home appliances, HVAC systems, hybrid electric vehicles, uninterrupted power supplies and PV panels. Their ability to communicate with the grid enables them to move beyond localized control schemes and respond to system-wide objectives through remote communication and algorithms. Many of these devices can be used to provide reactive power support, adding distributed energy resources (DER) to the grid. In addition to reducing peak demand, DSM can be used to provide an incentive for consumers to provide reactive power. The most effective solution for a load that is consuming reactive power is power factor correction or compensation at the source. The Smart Grid opens up opportunity for a level of distributed voltage support that has not been used in the past. This chapter discusses the benefits associated with distributed reactive power support.

Figure 2-1 shows possible constituents of a reactive support group [2]. As seen in the diagram, the plug-in HEV (PHEV) is a smart device which can be remotely controlled by a manager higher up in the hierarchy of the distribution/transmission network. These devices would be scattered over a large area and require substation level coordinated aggregate control to meet multiple objectives such as voltage set points, minimization in transmission line loading or minimization of network losses. At present, such devices are not common and remote control network algorithms are still a major research area. In theory such control schemes can be implemented with concurrent development of secure communication and smart device technology.

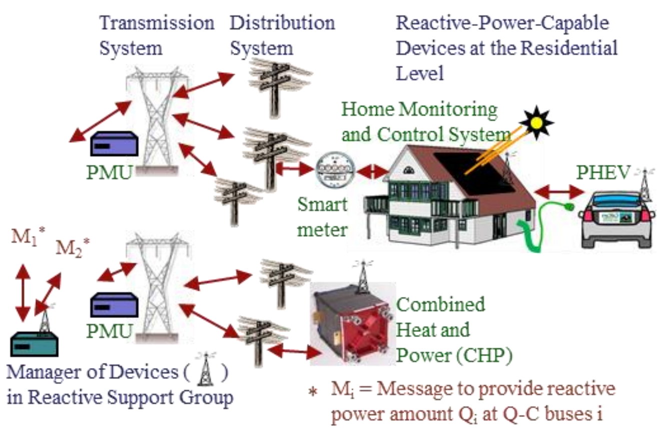

FIGURE 2-1: CONSTITUENTS OF A REACTIVE SUPPORT GROUP

Figure 2-2 shows a one-line diagram of a primary feeder supplying power to a load at the end of the feeder [11]. The load bus has a shunt of –j2.10 p.u. which can be switched in or out. The sending end voltage, VS, is maintained at 1.05 p.u. A summary of the calculations for the cases when the shunt is connected/disconnected is shown in Table 2-1.

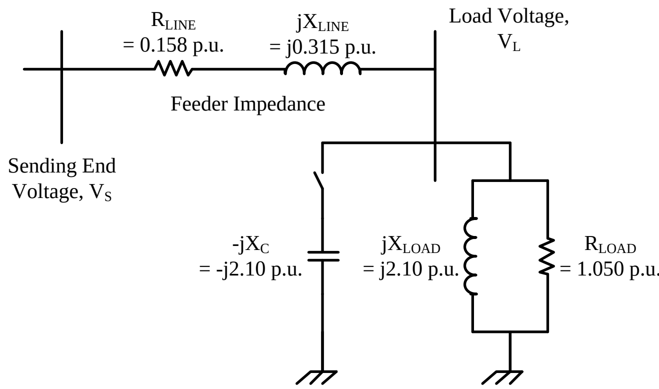

FIGURE 2-2: SHUNT CAPACITOR (SWITCHED OUT) AT THE END OF A PRIMARY FEEDER
($S_{BASE3\Phi}$ = 10 MVA & V_{BASELL} = 13.8 KV)

TABLE 2-1
SUMMARY OF CALCULATIONS

	Shunt Disconnected	Shunt Connected
Line Current, $\|I_{LINE}\|$ (p.u.)	0.8473	0.8414
Load Voltage, $\|V_L\|$ (p.u.)	0.7957	0.8833
Real Power Loss, P_{LOSS} (p.u.)	0.1131	0.1115

Since the transmission of reactive power over long distances (from power plants to loads) is not economically feasible, shunt capacitors are widely used in distribution systems. The example in Figure 2-2 shows the benefit of having reactive power injection closer to the load bus. When the shunt capacitor bank is connected, $|I_{LINE}|$ decreases, $|V_L|$ increases and $|P_{LOSS}|$ decreases. All of the above are desirable effects which can be achieved by power factor correction at the load bus instead of reactive power being supplied from the distribution substation.

Although the above example results in unity power factor at the load bus, similar effects can be achieved through real-time control of smart devices which help push the power factor closer to unity. Unlike the shunt capacitor bank, these smart devices will be able to inject reactive power in a more distributed way. This will be particularly helpful in residential distribution networks which are typically radial and are prone to under-voltage conditions.

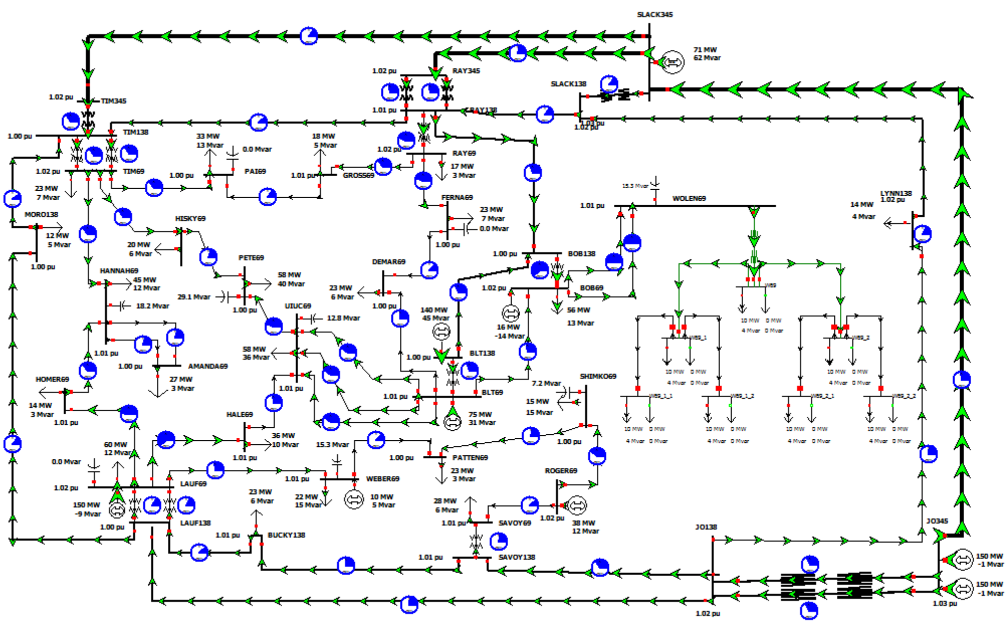

FIGURE 2-3: 44-BUS POWER SYSTEM

In order to demonstrate the feasibility of distributed smart devices to provide reactive power, the 37-bus system in [12] has been modified to a 44-bus system as illustrated in Figure 2-3 and simulated using PowerWorld. It has been adapted to include load buses in a radial configuration at the bus named WOLEN69. In essence, this reflects additional detail in the network topology as shown in Figure 2-4. Usually, such detail is ignored for large system studies. However, studying this extended network helps enforce the idea of distributed reactive voltage support.

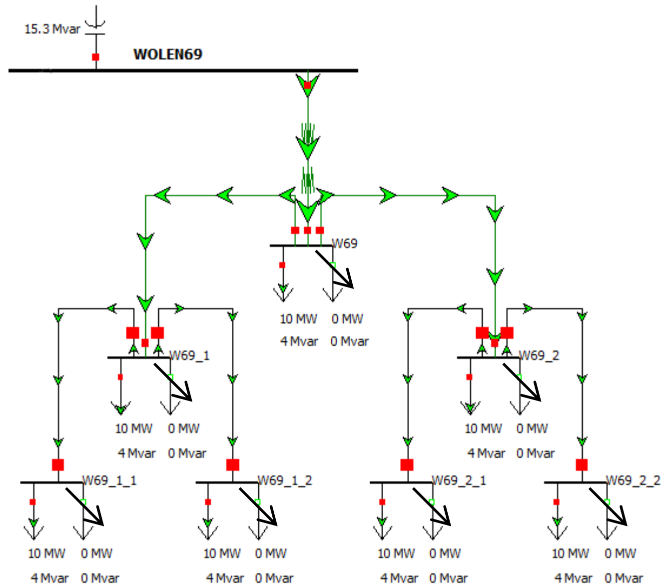

FIGURE 2-4: 13.8KV SUB-NETWORK OF WOLEN69
(SHUNT CAPACITOR IS CONNECTED AND SMART DEVICES ARE DISCONNECTED)

Distributed devices make it possible to inject reactive power more evenly along the radial load buses. These distributed injections ensure a better power factor at each load bus, ultimately resulting in a more even voltage profile throughout the radial network. Widespread presence of such smart devices would reduce the demand for reactive power, allowing generators to operate within the same ratings while increasing real power production. Such benefits make distributed reactive voltage support appealing.

Chapter 3

APPLICATIONS

With the coming of the Smart Grid to the average household comes opportunity to improve the nation's grid on many different levels. The impact of EV and PHEVs on the grid is an active area of research. Typically, a vehicle can be charged overnight when the demand for electricity is low. To improve the overall efficiency of transmission, the power factor at which the vehicle is charged can be controlled. Furthermore, it can be used to provide reactive voltage support when it is at full charge and even offers the option of real power support in the case of a critical need or to provide backup power during an outage. There is a multitude of other devices that can be used as well. Section 3.1 focuses on consumer products which use a voltage source inverter, such as EV/PHEVs, PV systems and UPS devices. Section 3.2 focuses on devices that use active power factor correction.

The advantages of injecting reactive power locally are clear from the discussion in Chapter 2. However, the benefits need to be weighed against the drawbacks. For example, in the case of a PHEV, the maximum charge current typically depends on the charging method available. The assumption for this research is based on a consumer grade system from [13], so Level 1 and 2 charging as shown in Table 3-1 are considered. By charging at a non-unity power factor, the charge time will be extended. Furthermore, the losses in the charging system will increase and the stress on the electrical components will be slightly higher. Ultimately the decision to choose should be left to the consumer based on the incentives.

TABLE 3-1
CHARGING LEVEL SPECIFICATIONS

	Voltage (V)	Phase	Peak Current (A)
AC Level 1	120	Single Phase	16
AC Level 2	240	Split Phase	32

Another point to consider is the availability of the devices since the peak-load occurs during the day. Solar panels and UPS systems are stationary, but PHEVs may be out on the road, at home or at work. It is reasonable to assume that the number of cars in an area has an effect on the load in that area. If charge stations are available, the car could have more impact than if it were connected at the home.

The modes of operation of interest (1, 2 and 3) are labeled in Figure 3-1; consuming reactive power is not being considered. Option 1 is the base scenario: charging at a unity power factor with no reactive power injection. Option 2 shows charging at a leading power factor. Both the current magnitude and current angle can be adjusted. A slow charge is recommended when time is not critical, such as overnight charging. Since the current magnitude is smaller, the stress on the batteries and system and conduction losses are reduced. Option 3 is used to solely inject reactive power while the loss in the system is to be compensated by the grid.

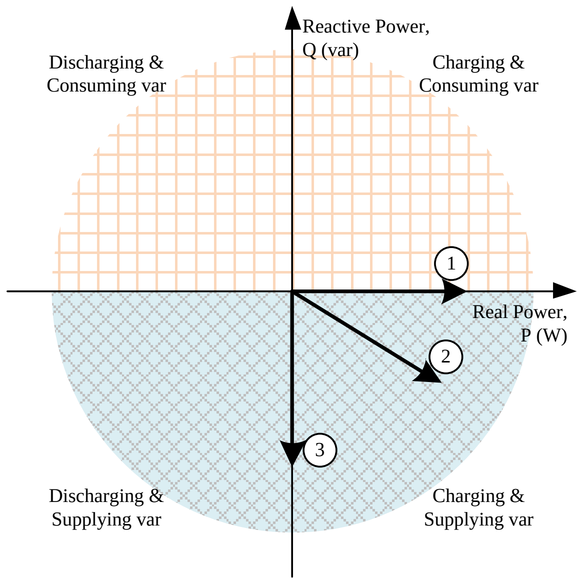

FIGURE 3-1: MODES OF OPERATION

Although the supply of real power is a possibility, it is assumed to be undesirable and such modes of operation will not be used [7], [14]. The objective is to supply reactive power strictly from the available capacitance without affecting battery life. As such, the chemistry of the cells is not critical, but proper battery management systems must be used to protect against improper use. The dc bus voltage is application specific; for this project it was selected to be 330V. As always, there is a tradeoff in using a higher voltage to achieve less conduction losses versus increased switching losses.

3.1 The Voltage Source Inverter

This section focuses on a voltage source converter which has a battery pack connected to the DC bus. The device is to be controlled purely for reactive power injection. This battery-inverter device as modeled in Figure 3-2 is representative of consumer products such as a UPS system or the drive inverter for a PHEV. The charger to a PHEV would likely use a scheme similar to that presented in Section 3.2.

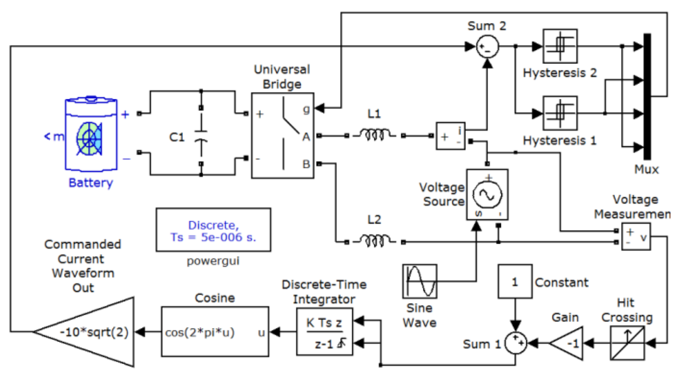

FIGURE 3-2: SIMULINK DIAGRAM FOR VOLTAGE SOURCE INVERTER WITH A BATTERY

Simulink was used for the simulations. The model for the battery type is Li-ion with parameters similar to those of approximately 100 series-connected batteries. Such batteries are being used in energy storage systems and HEVs [15]. The battery (330 V) is connected in parallel with a dc bus capacitor and to an H-bridge. The bridge is operated as an inverter and the output of the H-bridge is connected to a 120 V ac wall outlet.

The remaining blocks form a current-controlled hysteresis loop. This requires a voltage sensor to detect the wall outlet voltage phase and a current sensor to monitor the injected current. In the simulation, the commanded current is set to 10 A ac. The simulation shows that such a setup is able to track the voltage and inject a current which is approximately $\frac{\pi}{2}$ rad out of phase. This translates to an injection of reactive power except for the system's real power losses being compensated from the grid.

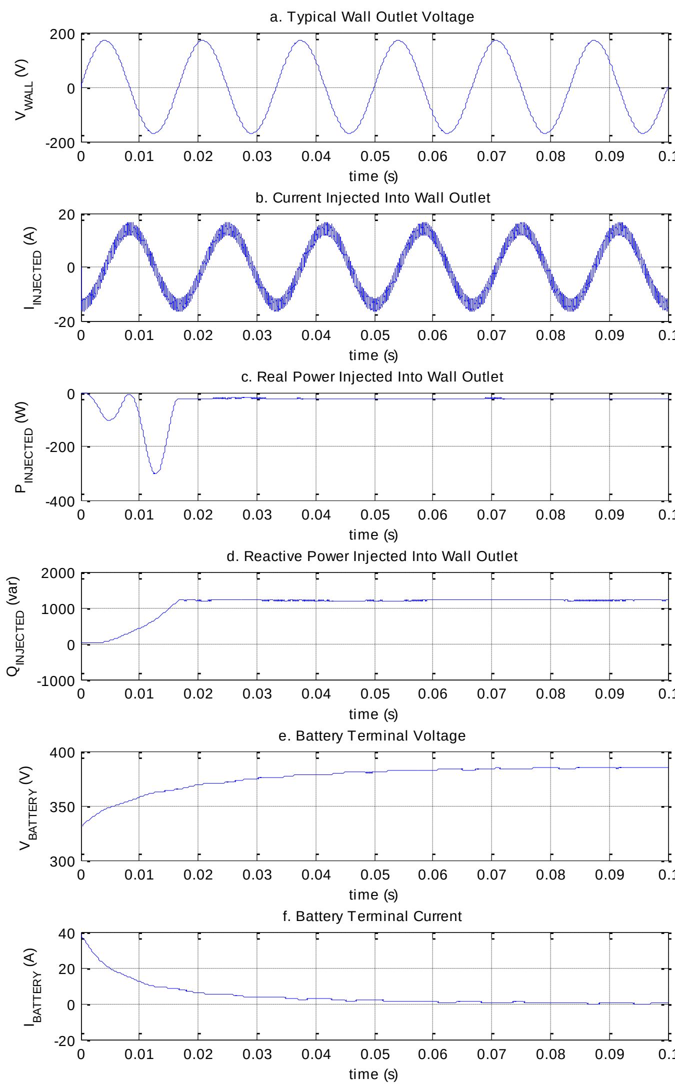

FIGURE 3-3: SIMULATION RESULTS

The simulation shows that this control scheme is able to detect the zero-crossing of the wall voltage, V_{WALL} (Figure 3-3a) and command an injected current which is $\frac{\pi}{2}$ rad lagging (equivalent to commanding a drawn current which is $\frac{\pi}{2}$ rad leading) with respect to V_{WALL}. The hysteresis loop is able to track the commanded current and ensure that the injected current, $I_{INJECTED}$, stays within limits of the hysteresis loop.

At t = 0 s (Figure 3-3), a command is issued to inject 10 A ac. The assumption is that the dc link capacitor, C_1, is fully charged before t = 0 s. Figure 3-3c shows that the battery-inverter device initially draws real power as the value of $P_{INJECTED}$ reaches approximately -300 W. After approximately one cycle, it reaches a steady-state value of -23 W, corresponding to system losses. Since the simulation model has bidirectional current flow capability, the battery remains fully charged throughout. The injected reactive power, $Q_{INJECTED}$, increases to its steady-state value of about 1.2 kVAR in the same duration.

Figure 3-3e and Figure 3-3f show the voltage, $V_{BATTERY}$, and current drawn, $I_{BATTERY}$, at the battery terminals. Studying these signals is necessary to understand what kind of voltage and current waveforms the battery will be exposed to. As shown in Figure 3-3e, the bidirectional nature of the simulation allows the battery to charge up to its maximum rating of about 384 V. In the simulation, this maximum bound is set in the parameters.

However, a battery management system would be required to ensure charge and other battery limits in a real hardware implementation.

The quick response of the battery-inverter device makes it an attractive candidate for responding to emergency conditions in the electric grid. It is representative of increasing types of upcoming devices. With a proper control framework, such devices can collectively provide voltage support rather than just burdening the grid.

3.2 Power Factor Correction

Traditionally, the goal of power factor correction (PFC) has been to achieve a clean current waveform in phase with the voltage waveform. Exploration of non-unity PFC methods has been primarily focused on reducing filter size to reduce cost. This section presents an adjustable PFC scheme to provide reactive power support that can be used to correct for surrounding devices.

Traditionally, most switched-mode power supplies and variable speed motor drives have used diode rectifiers (such as a bridge rectifier or a voltage doubler) on the front end to convert the AC mains to a high voltage DC bus. While many of these supplies have high efficiency, the power factor is typically poor. An SMPS without power factor correction typically has a power factor below 0.65 [16]. In power systems, power factor is considered to be the phase shift between the voltage and current waveforms. When considering the nature of power electronics, harmonic distortion is often of more concern. The bridge rectifier shown in Figure 3-4 conducts for short intervals and draws extreme currents. The peak current draw is approximated in Equation (3.1). To reduce the voltage ripple, the capacitor size is increased, which increases the peak current draw. Power factor is defined as the ratio of real power to apparent power. Since real power can only be transferred for the components of voltage and current that are at the same frequency, it is clear from the current waveform that the power factor is poor even though the phase shift is minimal.

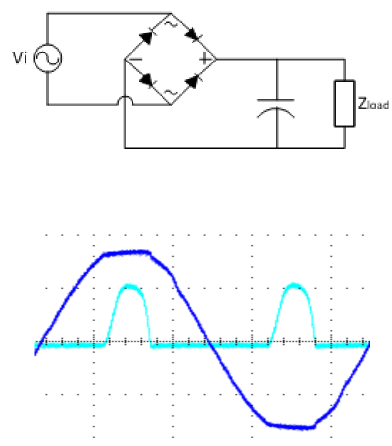

FIGURE 3-4: VOLTAGE AND CURRENT WAVEFORMS OF BRIDGE RECTIFIER

$$i = C\frac{dV}{dt} = \omega C V_0 \sin(\omega t_{on}) \quad (3.1)$$

The need for power factor correction has been established for non-linear loads. There are two types of PFC: active and passive. Active PFC controllers have become the norm as they offer more control over shaping the input current and require line filtering that is significantly less bulky/expensive.

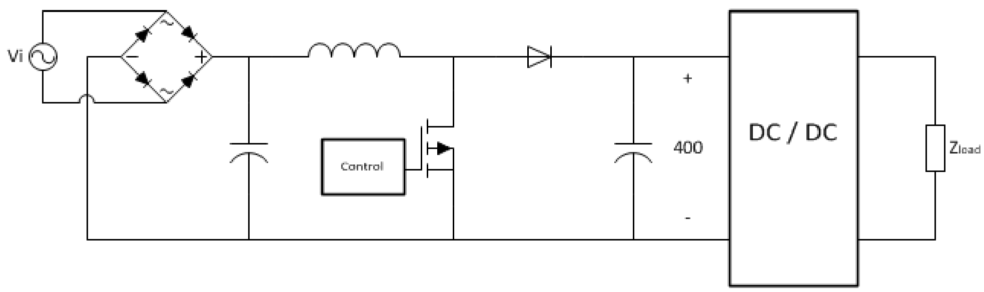

FIGURE 3-5: TWO-STAGE CONVERTER WITH PFC BOOST FRONT END

Typically, PFC is implemented as an additional stage, although it can be implemented in a single stage as in the DCM flyback converter in [16]. A two-stage converter is shown in Figure 3-5. The efficiency of such a system is the multiplication of the efficiencies of all stages; however, some of the loss of efficiency can be recouped as the secondary stage can be optimized for a known input voltage. For example, consider a system with a universal input (85 – 265V) and a PFC boost with a 400±5% V output. The secondary stage can now be designed for 380-420 V as opposed to 120–375 V.

In choosing a topology that is suitable for a controllable PFC, it is important to understand the current PFC techniques. The boost topology shown in Figure 3-6 is the most common as it is able to control the current at every part of the wave. There are two major control approaches: the current tracking approach and the voltage-follower approach.

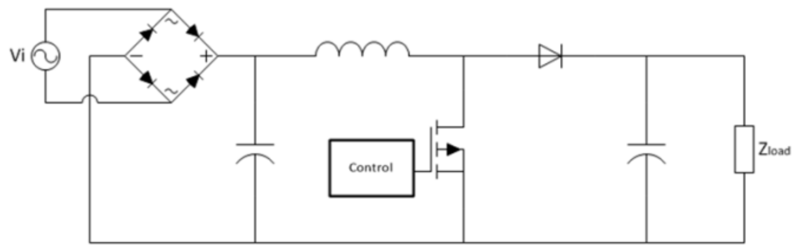

FIGURE 3-6: BOOST CONVERTER

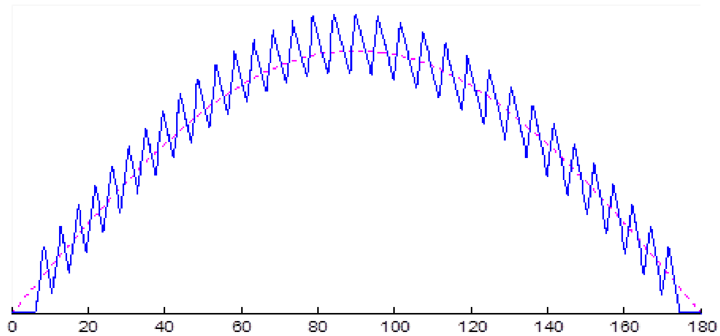

FIGURE 3-7: HYSTERESIS-BASED CURRENT TRACKING

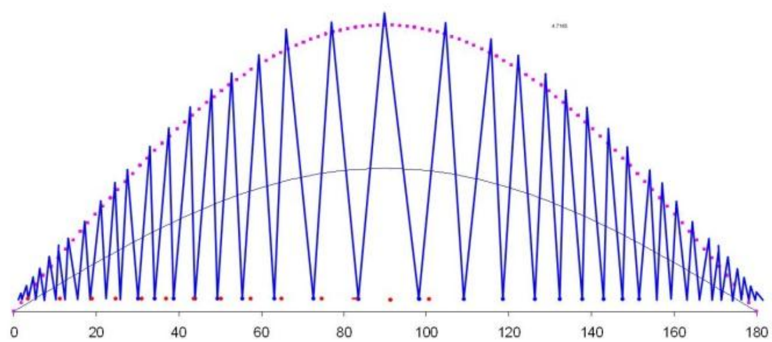

FIGURE 3-8: BOUNDARY MODE CONTROL

The hysteresis-based approach (Figure 3-7) is a current tracking technique that operates the converter in continuous conduction mode (CCM). The shape of the inductor current is controlled to follow that of the rectified input voltage waveform. The control uses an outer loop to control the current magnitude based on a PI control which measures the difference between the output value and its intended value. A hysteresis band is then used to control the switching based on the desired current waveform [17].

In contrast, if the inductor current is allowed to reach zero, the converter is said to operate in discontinuous conduction mode (DCM). Critical conduction mode (CRM) is when the converter is at the boundary between CCM and DCM. Operating in CRM continuously is called boundary mode control as shown in Figure 3-8. CRM allows the inductor to reach zero or near zero current, at which point it is switched to begin charging and the current in the inductor begins to ramp up. It can be seen that the current is proportional to the input voltage and with filtering it naturally provides power factor correction as the current follows the voltage. The voltage follower uses a simple control scheme – requiring a single voltage control loop. This is how many of the traditional boundary mode PFC controllers operate.

The boost topology in Figure 3-6 needs some modifications to be able to operate at a controllable PF. The topology in Figure 3-9 has a fully controllable bridge and is suitable for a non-unity controller. Figure 3-10 shows a hysteresis based control scheme similar to that of Figure 3-7, and its simulation is shown in Figure 3-11. Additional logic is required since the current in the inductor is bidirectional. Figure 3-12 shows a boundary mode control scheme similar to that of Figure 3-8, and its simulation is shown in

Figure 3-13. The inductor is grossly oversized to reduce the switching frequency for illustrative purposes.

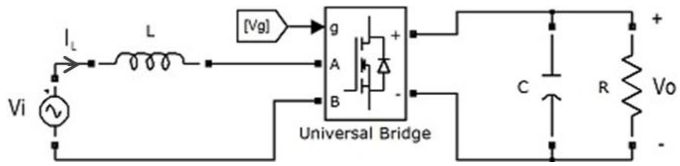

FIGURE 3-9: PROPOSED PFC CIRCUIT

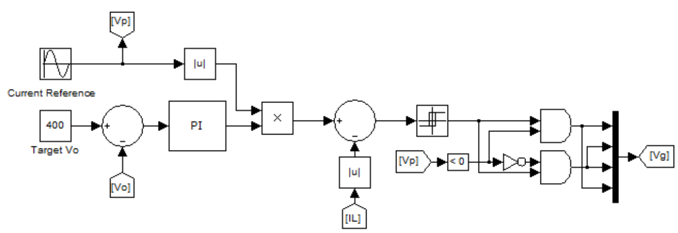

FIGURE 3-10: HYSTERESIS-BASED CURRENT CONTROL

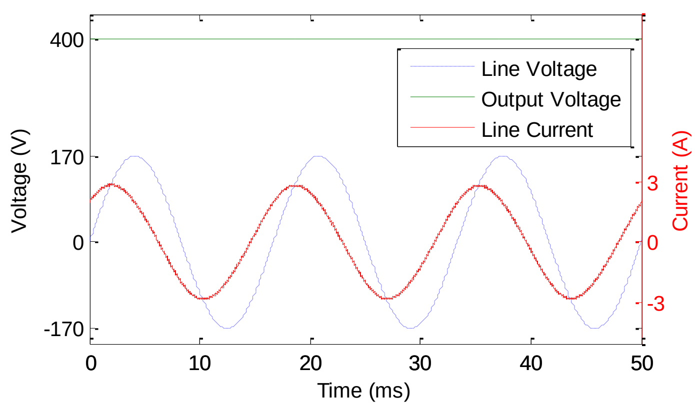

FIGURE 3-11: HYSTERESIS-BASED SIMULATION WITH 45° LEAD

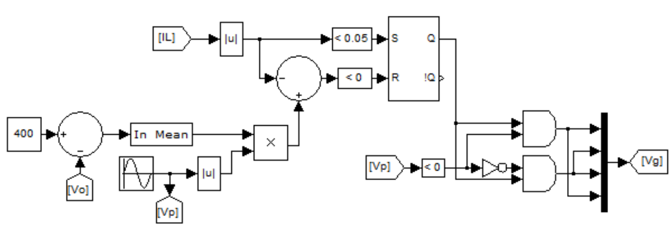

FIGURE 3-12: BOUNDARY MODE CONTROL

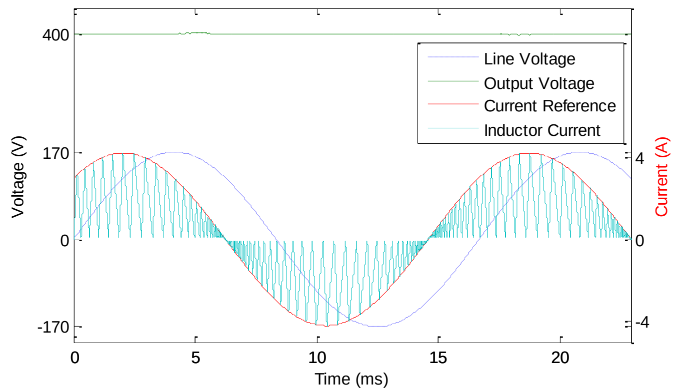

FIGURE 3-13: BOUNDARY MODE SIMULATION WITH 45° LOAD

This section has introduced a technique for a controllable power factor converter which shows promise for future use as a distributed source for reactive power compensation. The topology is similar to the circuit simulated in Figure 3-2 but has an additional degree of freedom as the DC bus is used to feed a second stage converter rather than being connected to a battery bank. Non-unity PFC can be achieved with a feasible topology for consumer-based devices. Additional filtering is required for the circuit proposed in Figure 3-9, as well as in the traditional boost PFC presented in Figure 3-6, depending on the mode of operation and performance requirements.

Chapter 4

CONTROL

If devices with active power factor correction are to correct for surrounding devices, a control system is required to coordinate the injections. One possible objective could be to target a unity PF from a house. More complex algorithms could be extended to optimize the power grid by having a demand response for reactive power. A lack of reactive power was one of the root causes of the 2003 blackout [8]. The additional reactive power resources proposed in this paper can be used for voltage control and to improve the resiliency of the power grid to voltage instability.

4.1 Controllable Power Factor House

Perhaps the most obvious approach would be to target unity power factor at a house level. The pie chart in Figure 4-1 shows the annual energy usage for a typical single family home including gas and electric [18]. The main electric loads were used to create a load table, Table 4-1, to model the house over a period of time and include the capability and availability of the loads. Some loads, such as TVs and desktop computers, would typically be on-line for reactive power support as opposed to laptop computers and lighting which are intermittent. If the reactive sources are idle and available, they can be operated at 90° phase lead and supply zero to full output. If the devices are consuming real power, the phase can be shifted to vary the reactive power while staying within the power ratings of the converter.

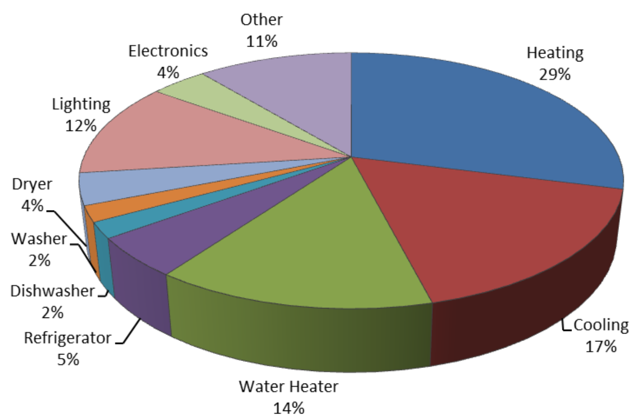

FIGURE 4-1: ENERGY USAGE FOR SINGLE FAMILY HOME

Figure 4-2 shows a smart meter that can communicate with an HEM or IHD that would act as the coordinator for reactive power. The coordinator would receive a target power factor from the meter and run a house control algorithm to control the reactive loads. This approach assumes two-way communications between the coordinator and the reactive power sources. When a device is powered on, it connects to the network. Each device has a unique identifier and communicates both its capability and current power usage. When a device is powered off, the HEM detects that it is no longer available and attempts to adjust accordingly.

TABLE 4-1
LOAD DATA

	S rated (VA)	Availability and power consumption at time									
		15:00		16:00		17:00		18:00		19:00	
Load 1	300	Y	50	Y	225	Y	250	Y	100	Y	100
Load 2	60	N	0	N	0	Y	60	Y	25	N	0
Load 3	1000	Y	100	Y	100	Y	100	Y	0	Y	100
Load 4	115	Y	0	Y	0	Y	500	Y	0	Y	0
Load 5	1000	N	0	N	0	N	0	N	0	N	0
Load 6		-	0	-	0	-	640+j320	-	0	-	0
Load 7		-	0	-	0	-	0	-	0	-	1200+j200
Load 8		-	100+j10	-	0	-	100+j10	-	0	-	100+j10
Load 9		-	0	-	0	-	0	-	2800+j10	-	0
Load 10		-	20+j10	-	20+j10	-	1000+j500	-	100+j50	-	100+j50
Total			270+j20		345+j10		2650+j830		3025+j150		1600+j260

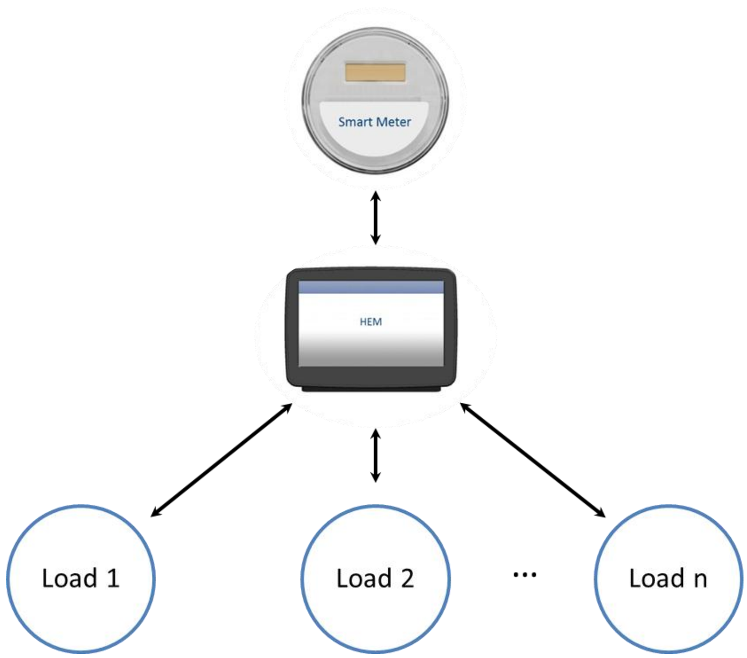

FIGURE 4-2: HOUSE CONTROL

A house control function was modeled in MATLAB as shown in the Appendix. The function uses a load profile with the data presented in Table 4-1. Since the coordinator knows the loads connected as well as their capability, it knows whether the target power factor can be achieved and assigns the VAR support. If the target cannot be achieved, it will get as close as possible and raise a flag to indicate that the sources are providing their maximum capability. This algorithm assigns the VAR support proportionally to the source's capability as long as the source is available. A more complex control scheme could be used to optimize the reactive power injections. For example, Figure 4-3 shows the efficiency curve for a representative PFC boost converter rated at 100W. The coordinator knows the active power of the device so a possible improvement could be to optimize for efficiency by not using devices that are in standby unless needed and targeting the optimal efficiency of the devices that are active. The coordinator could also favor devices that are more likely to be connected, such as a desktop computer or a UPS system.

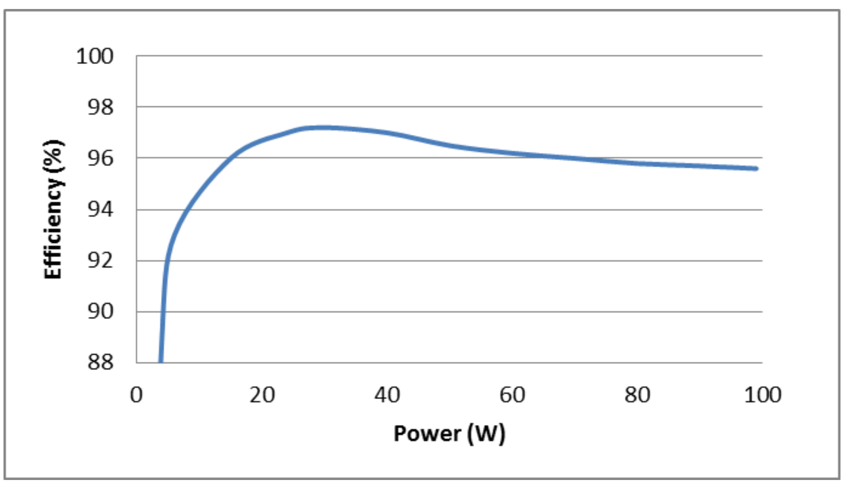

FIGURE 4-3: EFFICIENCY CURVE FOR PFC BOOST CONVERTER

TABLE 4-2
RESULTS FOR HOUSE CONTROL

Target	S (VA)	Power Factor
-	2650+j830	0.95
1.00	2650	1.00
0.95	2650-j871	0.95
0.91	2650-j1207	0.91
0.90	2650-j1259	0.903

The simple house model shows the potential for an abundance of reactive power resources under certain loading conditions. The utilization of these resources shows promise for reactive power support. The house is able to reach unity power factor at all times for the load profile simulated. The worst case is at the peak power usage which occurs at 5:00 PM for this case. Table 4-2 shows the simulation results for this time. Without control the house has a 0.95 lagging power factor. The target power factor is then changed to unity followed by leading until the maximum reactive power injection is reached showing that the house can provide enough reactive power to bring the power factor to 0.903 leading, delivering 1.26 kVAR. This shows that the household loads that consume the most energy can be compensated. High power loads that are used infrequently, such as vacuum cleaners and power tools, do not contribute very much to the average energy usage but use significant reactive power when on. Depending on the load and available reactive power resources, it is possible that the house cannot reach unity. Section 4.2 presents a scheme for a feeder level control with the objective of achieving a target power factor at the feeder. Houses with available reactive power resources can be used to correct for houses that are consuming reactive power.

Another possibility is for quick reactive power support for transient loads. The air conditioner load modeling studies in [19] show significant reactive power draw during compressor startup for approximately fifteen cycles with a significant voltage dip. An autonomous control could be used to supply reactive power during these short intervals.

4.2 Distributed Control

Having control over reactive power sources in the house opens the door to a distributed control scheme in which the power company can have some control over the power factor in an area. As discussed in Chapter 2, reactive power does not travel well as transmission lines are predominantly reactive causing large reactive power losses in the lines. Figure 4-4 shows the subtransmission circuits of a typical distribution system. Reactive power compensation closer to the load is more effective. This section presents a control scheme for a feeder to coordinate the power factor in an area - Figure 4-5 shows a typical power distribution feeder. The house control described in Section 4.1 assumes two-way communication and a home energy manager which acts as the coordinator. The coordinator knows which loads are connected and what their capabilities are. While a similar system is possible for a distributed control scheme, some limitations are assumed with regards to the communication between the feeder and the houses. It is assumed that the feeder does not know the capability of the loads to supply reactive power and therefore will attempt to achieve the target power factor within a specified tolerance. The feeder will operate in a continuous loop and at a time interval will send a command if the power factor is outside of the specified tolerance. While this control does not use the power flow equations, it does account for losses in the lines since the power is measured at the feeder.

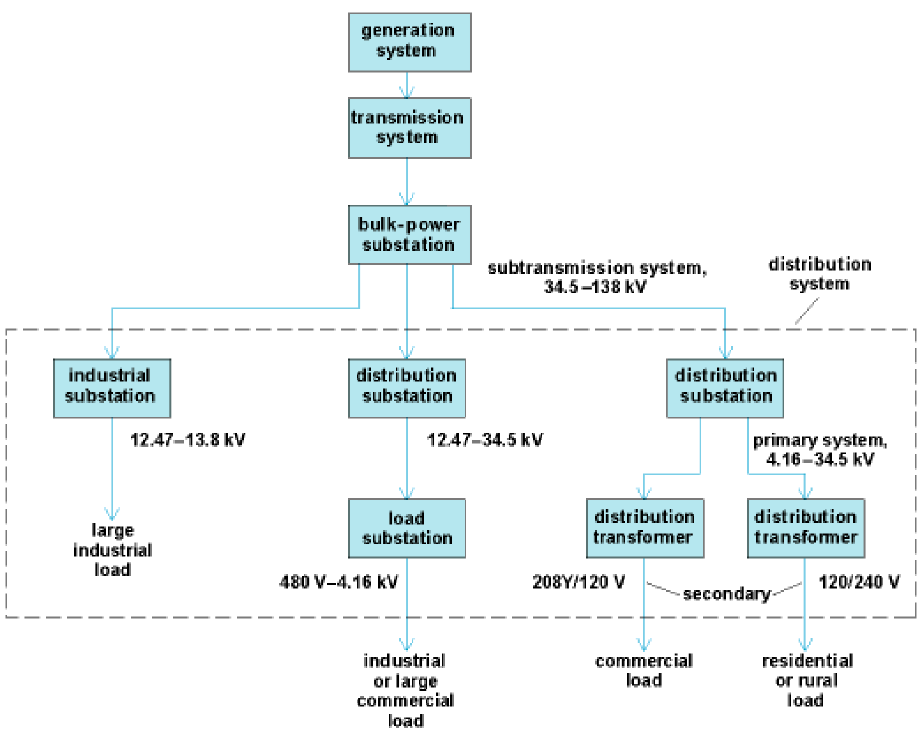

FIGURE 4-4: SUBTRANSMISSION CIRCUITS OF A TYPICAL DISTRIBUTION SYSTEM [20]

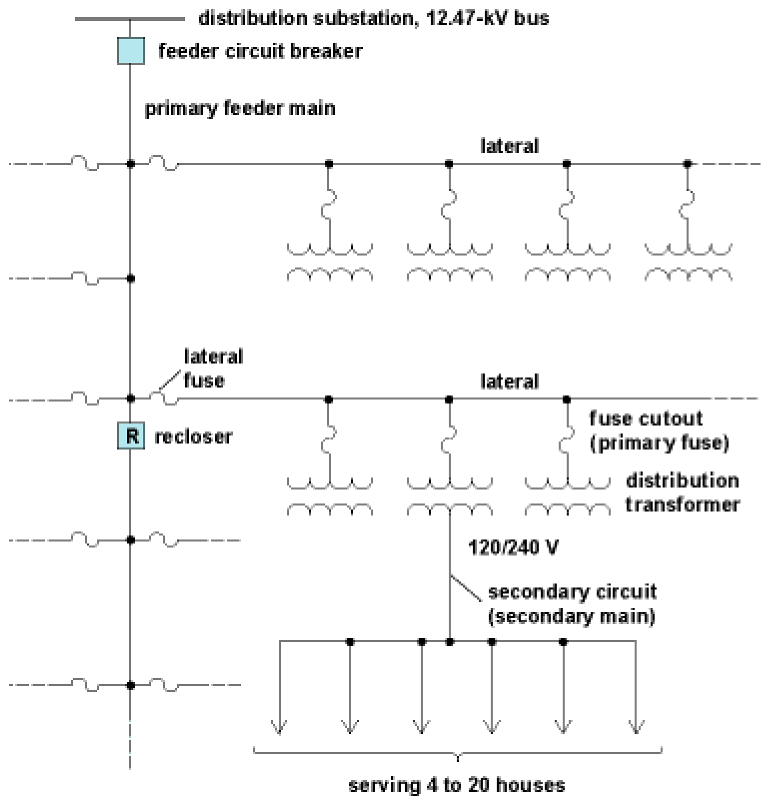

FIGURE 4-5: TYPICAL POWER DISTRIBUTION FEEDER [20]

A feeder control function was modeled in MATLAB as shown in the Appendix. The feeder uses a load file which contains the load profiles of all of the houses connected to it. The house load used in Section 4.1 was used to represent ten houses of which only five are controllable. With a specified tolerance of 1%, the feeder achieves a lagging power factor of 0.997 when the target is set to unity. The five controllable houses are at a leading power factor of 0.988 to compensate for the houses that are at a lagging power factor. When a leading power factor of 0.98 is requested, the feeder cannot reach the target. The feeder achieves a leading power factor of 0.997 and a flag is raised to indicate that the houses are supplying their maximum reactive power output with the controllable houses leading at 0.9.

Unlike capacitor banks, reactive power will only be provided in this scheme when needed. This is an important benefit – during off-peak periods there is often too much reactive power in the system. In addition to over-voltage conditions, excessive reactive power can cause instability in the system, inefficiencies in generation and even damage to generating units. Figure 4-6 shows the capability curve for a generator. The area within the armature current limit is the apparent power rating of the machine. Beyond that range the generator is limited by the field current limit when sourcing reactive power and the underexcitation limit when absorbing reactive power. Figure 4-7 shows a capability curve for a synchronous machine used in a generator set. Operating at a leading power factor is in the abnormal operating range. It is important to note that the ability of the generator to absorb reactive power is not specified by the power factor but by the reverse kVAR limit. Reference [22] shows a scenario where a leading power factor below 0.97 is in the damage area. This demonstrates that excess reactive power can present problems. Since power systems typically do not have effective methods of absorbing reactive power, the distributed control offers this benefit over traditional methods.

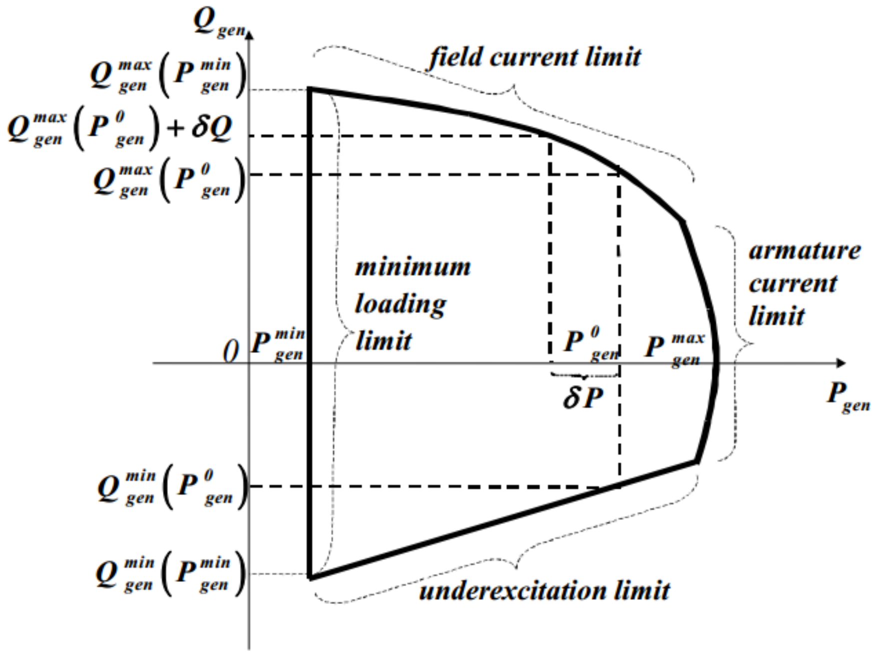

FIGURE 4-6: THE GENERATION CAPABILITY CURVE [21]

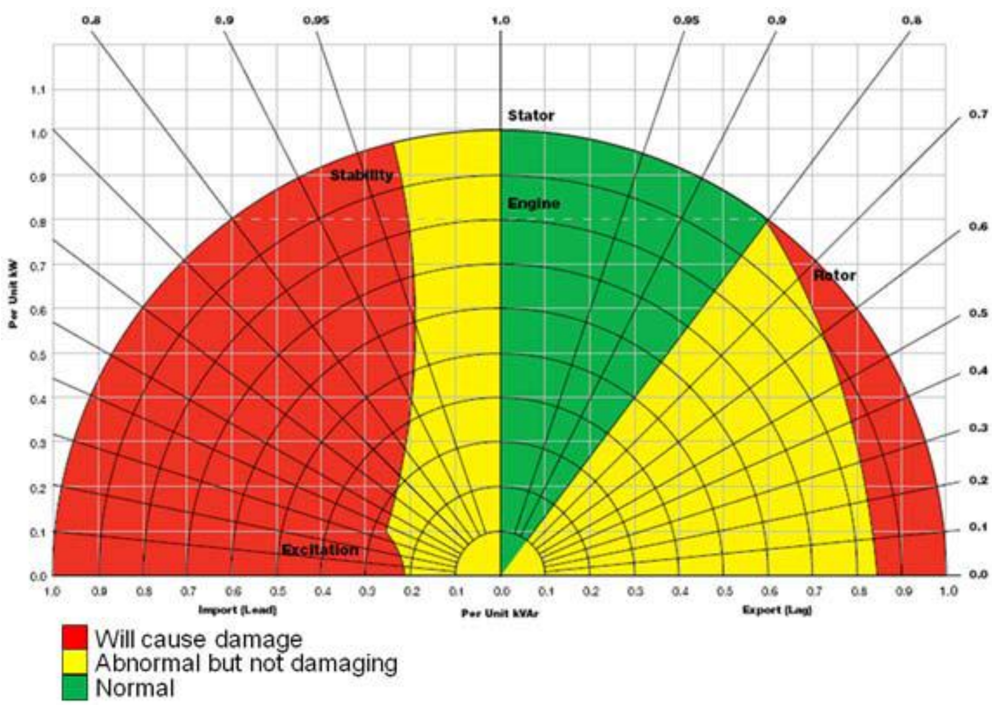

FIGURE 4-7: SYNCHRONOUS MACHINE CAPABILITY CURVE [22]

Chapter 5

CONCLUSION

This thesis has discussed the use of smart devices for distributed reactive voltage support. The sensing and processing required are within the capability of target systems which presents new possibilities to supply reactive power, during both active and standby modes. Although several control schemes can be remotely implemented, communication, security and consumer confidence still remain a challenge. Cost and robustness of such energy storage and auxiliary technologies would be a major driver in the consumer's willingness to opt in or out of such schemes. Distributed voltage support has the potential to transform the electric grid while improving voltage stability.

A technique for a controllable power factor controller has been presented which shows promise for future use as a distributed source for reactive power compensation. Non-unity PFC can be achieved with a feasible topology for consumer-based devices. The proposed scheme can supply benefits beyond traditional PFC methods, but there are challenges and obstacles to overcome. The cost structure for residential energy use does not promote power factor correction as consumers are only charged for real power consumption. Furthermore, regulation is in place for devices to target a unity power factor. The scenario of the unity power factor house shows promise and is relatively easy to implement. This could open up the capability for future distributed algorithms where houses could supply reactive power to compensate for houses which are consuming reactive power. The outcome shows the possibility of increasing the overall efficiency of transmission and distribution while improving voltage stability and reliability.

5.1 Future Work

The campus distribution system for the University of Illinois at Urbana-Champaign does not have reactive power support. As such, the local power factor is poor. As a continuation to this research, future work is planned on the control of distributed reactive resources which can be verified on the campus distribution system. As a parallel to the unity power factor house, a campus building, such as a student housing unit, can be used to apply the concept on a larger scale. Furthermore, a device as proposed in this thesis is planned to be deployed to test distributed algorithms. The ultimate goal is to determine the best approach for a control scheme – the least complexity required to drive the most beneficial results.

Appendix

MATLAB CODE

```
% House Control Function
% [S,PF,flag]=house(load_file,target_pf,time,reset)
%
% Inputs:
%  load file: house with loads that have adjustable VAR
support
%  pf_t: Target power factor (Negative for leading P.F.)
%        Set to unity if not specified or outside of range
%  time: time of day to reference column of load file table
%  reset(optional): An input of 1 sets all controllable loads
to unity
% Output:
%  Apparent power: P+jQ
%  Actual power factor
%  Flag: 0 if target PF achieved, 1 if not

function [S,actual_pf,flag] = house(load_file,varargin)

Load=load_file;

% set defaults for optional inputs
numvarargs = length(varargin);
optargs = {1 1 0};
optargs(1:numvarargs) = varargin;
[target_pf, j, reset] = optargs{:};
j=j+1;

% If target power factor out of range - set to unity
if(target_pf <=1 && target_pf>-1); pf_t=target_pf;
else pf_t=1; end

[m,n]=size(Load); % m = # of loads, n = columns of time
flag=0; % If flag is raised, target P.F. is unable to be
achieved


S=sum(Load(:,j));
Q_t=sign(pf_t)*real(S)*tan(acos(abs(pf_t)));     % Q at target
P.F.
```

```
% Calculate available VAR support
Q_a=0;    % Available VARS
Q_u=0;    % Q from uncontrollable loads
for i=1:m
    if(Load(i,1)>0)
        Load(i,j)=real(Load(i,j));
        Q_a=Q_a+sqrt(Load(i,1)^2-Load(i,j)^2);
    else
        Q_u=Q_u+imag(Load(i,j));
    end
end
Q_n=Q_u-Q_t;

% No available VAR support
if(Q_a==0);
    actual_pf=pf(S);
    if (actual_pf ~= pf_t); flag=1; end;
    return;
end

adjust=Q_n/Q_a;
if(sign(Q_n)>0 && Q_a<Q_n); flag=1; adjust=1;
elseif(sign(Q_n)<0 && Q_a<abs(Q_n)); flag=1; adjust=-1; end

% Assign VAR support
for i=1:m
    if(Load(i,1)>0)
        Load(i,j)=Load(i,j)-1i*adjust*(sqrt(Load(i,1)^2-
Load(i,j)^2));
    end
end

% Sets PF to all controllable loads to 1
if(reset==1)
    for i=1:m
        if(Load(i,1)>0)
            Load(i,j)=real(Load(i,j));
        end
    end
end

S=sum(Load(:,j));
actual_pf=pf(S);
end
```

```
% Chris Recio
% Feeder Control function
% [S,PF,tPF,flag]=house(load_file,target_pf,time,tol,reset)
%
% Inputs:
%  load file: file with variables of house loads
%  pf_t: Target power factor (Negative for leading P.F.)
%  time: time of day to reference column of house load file
table
%  tol: Tolerance
%  reset(optional): An input of 1 sets all controllable loads
to unity
% Output:
%  Apparent power: P+jQ
%  Actual power factor
%  tPF: The new target sent to the controllable houses
%  Flag: 0 if target PF achieved, 1 if not

function [S,actual_pf,pf_t,flag] = feeder(load_file, varargin)
%target_pf , time , tol, reset)

h=load(load_file);
n=fieldnames(h);

% set defaults for optional inputs
numvarargs = length(varargin);
optargs = {1 1 0.01 0};
optargs(1:numvarargs) = varargin;
[target_pf, j, tol, reset] = optargs{:};

S=0; flag=0;

% If target power factor out of range - set to unity
if(target_pf <=1 && target_pf>-1); pf_t=target_pf;
else pf_t=1; end

pf_t_o=pf_t; % Original target

% Sets PF to all controllable loads to 1
if(reset==1)
    for k = 1:length(n)
        [a,b,f]=house(h.(char(n(k))),pf_t,j,1);
        S=S+a;
        flag=flag+f; % flag resources that cannot supply more
VARs
    end
    actual_pf=pf(S); pf_t=actual_pf;
    if(flag==length(n)); flag=1; else flag=0; end
    return
end

% Find PF at current target
```

```
for k = 1:length(n)
    [a,b,f]=house(h.(char(n(k))),pf_t);
    S=S+a;
    flag=flag+f; % flag resources that cannot supply more VARs
end

actual_pf=pf(S);

if(abs(pf_diff(pf_t_o,pf(S)))<tol || flag==length(n))
    actual_pf=pf(S);
    if(flag==length(n)); flag=1; else flag=0; end
    return;
else
    while(abs(pf_diff(pf_t_o,pf(S)))>tol && flag~=length(n))
        diff=pf_diff(pf_t,pf(S));
        if (abs(diff)>.02); diff=sign(diff)*.02; end %
Prevents change of greater than 0.02 for new target
        pf_t=pf_add(pf_t,diff); % Set new target
        S=0; flag=0;

        for k = 1:length(n)
            [a,b,f]=house(h.(char(n(k))),pf_t);
            S=S+a;
            flag=flag+f;
        end
        actual_pf=pf(S);
    end

    if(flag==length(n)); flag=1; else flag=0; end
end
```

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