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RTDS-Based Design and Simulation of Distributed P-Q Power Resources in Smart Grid

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Author
Taylor, Zachariah David

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RTDS-Based Design and Simulation of Distributed P-Q Power Resources in Smart Grid

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in

Electrical Engineering

by

Zachariah David Taylor

August 2014

Thesis Committee:
  Dr. Hamed Mohsenian-Rad, Chairperson
  Dr. Ertem Tuncel
  Dr. Qi Zhu
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The Thesis of Zachariah David Taylor is approved:

Committee Chairperson

University of California, Riverside
ABSTRACT OF THE THESIS

RTDS-Based Design and Simulation of Distributed P-Q Power Resources in Smart Grid
by
Zachariah David Taylor
Master of Science, Graduate Program in Electrical Engineering
University of California, Riverside, August 2014
Dr. Hamed Mohsenian-Rad, Chairperson

In this Thesis, we propose to utilize a battery system together with its power electronics interfaces and bidirectional charger as a distributed P-Q resource in power distribution networks. First, we present an optimization-based approach to operate such distributed P-Q resources based on the characteristics of the battery and charger system as well as the features and needs of the power distribution network. Then, we use the RTDS Simulator, which is an industry-standard simulation tool of power systems, to develop two RTDS-based design approaches. The first design is based on an ideal four-quadrant distributed P-Q power resource. The second design is based on a detailed four-quadrant distributed P-Q power resource that is developed using power electronics components. The hardware and power electronics circuitry as well as the control units are explained for the second design.

After that, given the two-RTDS designs, we conducted extensive RTDS simulations to assess the performance of the designed distributed P-Q Power Resource in an IEEE 13 bus test system. We observed that the proposed design can noticeably improve the operational performance of the power distribution grid in at least four key aspects: reducing power loss, active power peak load shaving at substation, reactive power peak load shaving at
substation, and voltage regulation. We examine these performance measures across three design cases: Case 1: There is no P-Q Power Resource available on the power distribution network. Case 2: The installed P-Q Power Resource only supports active power, i.e., it only utilizes its battery component. Case 3: The installed P-Q Power Resource supports both active and reactive power, i.e., it utilizes both its battery component and its power electronics charger component. In the end, we present insightful interpretations on the simulation results and suggest some future works.
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Chapter 1

Introduction
The portion of electrical energy in the overall energy production and consumption in the United States is expected to increase from 40% to 80% in the coming decades [1]. According to the Department of Energy, the future distribution grid will be an autonomous energy delivery network enabled with power electronics [2]. It is anticipated that over 80% of energy usage in new residential and commercial buildings are processed through power electronics converters. Given the recent paradigm shift in load profiles, away from conventional (e.g., heating, lighting, etc.) loads and toward emerging electronics loads, flexible power electronic interfacing has become indispensable. Moreover, accelerated electrification of transportation systems as well as the increased grid penetration of renewable Power Resources calls upon better utilization of power electronics-based components that are available in these new systems.

1.1. Power Electronics Interfaces

The switching power converters are conventionally classified based on their functionality and the types of sources and loads they connect. A generic anatomy of a power electronics device is shown in Figure 1.1. It consists of sources, semi-conductor devices (e.g., MOSFET and diodes), lossless passive elements (inductors and capacitor), and loads. The energy flow is managed through switching devices that operate in cut-off or saturated regions of their I-V curve, minimizing their power loss for high frequency applications. The switching control process is called modulation, and most commonly is done using Pulse Width Modulation (PWM). PWM is usually a simple pulse resulted from a comparison between a reference waveform and a sawtooth or a triangular carrier
waveform. One can consider the switching action as an impedance matching mechanism to deliver the maximum power from source to load.

Figure 1.1. A generic, single-port power electronics converter. In this chapter, the source is typically a distribution grid.

Passive components, e.g., inductor and capacitors, act as energy storage and/or filter elements, storing energy in one subinterval, and delivering it to the load in the next subinterval of a switching interval. The four main classes of power electronics devices are DC-DC (converters), DC-AC (inverters), AC-DC (rectifiers), and AC-AC converters (cyclo-converters), as shown in Figure 1.2. The power electronics converters are categorized according to operating regime (switched-mode, resonant), galvanic isolation (isolated, non-isolated), switching action (hard and soft switching), and operating mode (continuous, discontinuous).
DC loads include electronics, lighting (LED or incandescent), DC motors/actuators, and household appliances, electric vehicle chargers. AC loads include most motor-based loads (e.g., elevator), or adjustable ac drives (e.g., air conditioning). One can consider the combined set of power electronics converter and its served load as a controllable electronics load. In such cases, the source nature determines the type of power electronics load. For example, although motor drives are AC, since they are usually supplied by DC-sourced inverters, they can be considered as DC loads. Similarly, static DC loads supplied by AC-DC rectifiers are considered AC electronics loads since the input port of the combined rectifier and DC loads accepts AC signals. In modern topologies, the definition of converter type and source/load is not static and depends on the direction of power flow. For example, consider an AC outlet interfaced to a 3.3 volt battery. The outlet, converter,
and battery are respectively the source, buck rectifier, and load when the battery is being charged, and they are respectively the load, boost inverter, and sources when the power is supplied back to the AC outlet.

Most power electronics conversion happens at two stages. For AC-fed DC loads, there usually exist a rectifier stage (with power factor correction and electromagnetic interference filtering) followed by a signal conditioning stages. The PV systems are interfaced with two-stage DC-DC boost converter followed by a 3-phase inverter. The micro-wind turbines are connected to grid by cascading rectifier stages with an inverter stage. Energy storage elements and PHEVs utilize bidirectional inverters for charging as well as AC interfacing. Fuel cells are interfaced with series-resonant H-bridge or push-pull dc-dc converters, cascaded by a DC/AC inverter. Alternative designs include DC/AC inverters cascaded with AC/AC cyclo-converters. The power electronics converters are usually either used as front load converter, in which case they are tasked with output voltage regulation and power delivery, or a power processing units, where they are tasked with maintaining the DC bus voltage and supplying the front load converters. The power processing units can act as a power buffer that can locally stabilize the dc grid and provide fast stabilization to avoid the collapse of power systems [3].

1.2. Flexibility of Power Electronics Interfaces
A salient feature of power electronics systems is their controllability, by adjusting the duty cycles of active semi-conductor switches. These solid-state switches can be employed from a range of existing options, from MOSFETs to, GTOs and IGBTs based on the desired
switching frequency and blocking power level. Demand response programs require controllable power sources/sinks. In both AC and DC distribution networks, the power drawn/delivered can be regulated by adjusting the effective input impedance of the combined converter-plus-load unit.

However, the switching nature of power electronics converters defines a hybrid dynamic system which contains continuous state variables (inductor current and capacitor voltage) and a discrete control variable (the switching function resulting from the PWM process). The effective continuous input impedance can be obtained via averaging—an approximation that neglects the switching artifacts and, instead, focuses on the essential dynamic characteristics of the underlying converter. An averaged model can approximate the dynamics of the original converter up to a third of its switching frequency. Given the temporal disparity between switching frequency of power electronics converters (100 KHz- MHz) and the time-horizon of demand response programs, this time-scale separation is well justified. The average model of power stages shown in Figure 1.1 translates the output impedance into effective input impedance seen by the input port. Therefore, one can consider the effective input impedance of power converter as variable impedance, controllable by the duty cycle of the active switches.

For other types of switches, for example GTOs or Thyristors which are beyond the scope of this thesis, the firing angle of the switch plays a role similar to the duty cycle of the FET-derived switches. Power electronics interfaces with uncontrollable switches, for example
the 3-phase diode-rectifier systems shown in Figure 1.2(c), can be portrayed as a constant impedance (power sink) in the demand response paradigm.

1.3. P-Q Power Resources

Distribution systems are hereditarily an extension of the AC transmission system. They carry electricity from the transmission system, through a step-down substation, and deliver it to consumers. Each load in an AC distribution grid is typically modeled in terms of its apparent power consumption, which is a complex-valued quantity:

\[ S = P + j Q. \]  \hspace{1cm} (1.1)

The real part \( P \), called active power, is the power that is consumed by the load to create heat, light, motion, machine output, etc. The imaginary part \( Q \), called reactive power, is the power that is alternately stored and released in the inductive (more common) or capacitive (less common) components of loads. In case of inductive components, reactive power is used to create the electromagnetic field that is needed to run motor devices.

The ratio between real power and apparent power for each load is called its power factor:

\[ \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}. \]  \hspace{1cm} (1.2)

Note that, power factor is always between zero and one. Since \( P > 0 \) and \( Q > 0 \) for most loads, power factor can indicate how efficiently the current is converted to real work to be consumed at the load. A power factor closer to one means more efficient power conversion.
at the load. Therefore, there is typically a power factor correction phase required at some loads to bring the power factor near unity, e.g., see [4][5][6].

An extension of power factor correction is P-Q control [7][8][9]. In this approach, the power electronics components and on-site Power Resources such as batteries, are used to control $P$ and $Q$ based on the operational needs of the power distribution grid.

When it comes to exploiting flexibilities in power electronics interfaces in AC distribution grid a core idea is to conduct P-Q control, as shown in Figure 1.3. First, consider a simple flexible load in Figure 1.3(a), which is the building block in demand response programs [10][11][12][13][14][15]. Here, the idea is to control active power consumption within its flexible range. However, it is possible to use the controllable features of power electronics interfaces to also support reactive power. In that case, the combination of the load and its power electronics interface can be seen as a distributed P-Q Power Resource, as shown in Figure 1.3(b).

Next, consider a more resourceful scenario, where the load can potentially also act as a source of active power, as shown Figure 1.3(c). A good example is the case of discharging the battery of a plug-in electric vehicle (PEV) during a vehicle-to-grid (V2G) operation mode [17][18][19][20][21][22][23][24]. Again, one can utilize the controllable features of power electronics interfaces to also support reactive power. In that case, the combination
of the load and its power electronics interface can be seen as a four-quadrant distributed P-Q Power Resource, as shown in Figure 1.3(d).

![Diagram of load and storage units](image)

Figure 1.3. Extending the controllability of loads and storage units across both active and reactive power domains: (a) A typical flexible load. (b) A flexible load that is capable of supporting reactive power. (c) A typical flexible storage unit. (d) A flexible storage unit that is capable of supporting reactive power.

1.4. Issues at Distribution Networks

Distributed P-Q power resources can be utilized towards the following design objectives:

- **Substation Congestion Control**: Peak-load shaving at the power distribution level can help preventing congestion at power distribution substations; thus, increasing their lifetime and preventing faults related to substation overloading [25][26].
• **Reducing Power Distribution Loss:** The operation of distributed P-Q resources can be optimized also to reduce both active and reactive power loss on distribution lines. Depending on the price of electricity, the savings can be significant [27].

• **Voltage Control:** The voltage control capabilities that are offered by distributed P-Q resources can replace some of the existing expensive voltage control equipment such as static VAR compensators or static synchronous compensators [28][29].

• **Integrating Renewable Power Resources:** Renewable generation has introduced new challenges to power distribution networks [30][31]. Distributed P-Q control resources can help alleviating the intermittency of renewable generation.

1.5. **RTDS Simulator**

The RTDS® Simulator (see Figure 1.4) is the world’s benchmark for performing real time simulations of power systems and infrastructure. The primary users of RTDS simulators are the public and private power companies and utilities that are responsible for generation, transmission, or distribution of electricity. Since the worst-case power system conditions are rare but dangerous and costly to induce in real-world, the RTDS® Simulator is used to provide utilities with a controlled and safe environment to conduct various testing and prognostic analysis. In this regard, some of the key applications of the RTDS® Simulator for utilities and power companies include: Protection System Testing, Control System
Testing, Contingency and Risk Analysis, Expansion Planning, Training, and Maintenance. Southern California Edison (SCE) and Pacific Gas and Electric (PG&E) are among the major utilities that use the RTDS® Simulator [32].

![RTDS® Power System Simulator](www.rtds.com)

Figure 1.4. The RTDS® Power System Simulator (www.rtds.com).

The Smart Grid Research Lab at the University of California at Riverside is equipped with an RTDS® Simulator, which we used as the key simulation tool for this project.

1.6. Organization of the Thesis

The purpose of this thesis is to optimize the operation of a four-quadrant distributed P-Q resource to improve the efficiency and performance of power distribution networks. The rest of this thesis is organized as follows. First, we provide a literature review in Chapter 2. Then, our proposed optimization-based approach to P-Q control is presented in Chapter 3, in terms of both problem formulation and solution method. The details on RTDS simulation setup are explained in Chapter 4, where we present two different designs. The
first design is based on an ideal four-quadrant distributed P-Q power resource. The second design is based on a detailed four-quadrant distributed P-Q power resource that is developed using power electronics components. The hardware and power electronics circuitry as well as the control units are explained for the second design. A set of extensive simulation results is presented and discussed in Chapter 5. The results cover both stand-alone and grid-connected simulations of distributed P-Q resources. A summary of conclusions and some future research directions are presented in Chapter 5.
Chapter 2

Literature Review
2.1. Active Power Support

Non-generation active power compensation is usually achieved in the literature under two different contexts: demand response and energy storage. Next, we discuss each approach.

When it comes to demand response programs, active power is supported by reducing the load. In general, demand response programs are designed to control the demand side resources in response to changes in the grid’s operating conditions, see [10][11] for some interesting surveys. Currently, the focus in most DR programs is to lower consumption or to balance the load across time so as to reduce the demand at peak hours. This can be done via either direct load control (DLC) or smart pricing. In DLC programs, the utility company can remotely control energy consumption for certain high-load household appliances such as air-conditioners and water heaters [12][13][14][15][33][34][35][36][37][38][39][40][41][42][43][44][45]. In contrast, in smart pricing, users are encouraged to individually and voluntarily manage their loads [46][47][48][49][50][51][52][53][54]. This is done, for example, by setting the prices to be higher at peak hours. Some of the existing pricing models include time-of-use pricing, peak-pricing, coincidental peak pricing, inclining block rates, and real-time pricing [55].

The literature on energy storage systems is diverse. For example, in [56][57][58][59], the focus is on optimizing the operation an energy storage systems when they are combined and co-located with a wind farms. In contrast, in [60], the authors consider a scenario where a group of investor-owned independently-operated storage units, which are not co-located
with any other Power Resource, seek to offer energy and reserve in the wholesale electricity market. While the studies in [56][57][58][59][60] seek to benefit from energy storage systems on transmission networks, there are also studies that address the placement and operation of energy storage systems on distribution networks. For example, in [61], the authors assess the benefit of energy storage systems to supply active power when there is fault in the substation. In [62], the impact of energy storage costs on the economic performance in a distribution substation is investigated. In [63], the use of flywheel energy storage technology in distribution network is examined. Finally, in [64], Energy storage for power flow management and voltage control on a typical 11 KV distribution network in the United Kingdom is discussed.

2.2. Reactive Power Support

Recall from Chapter 1 that reactive power is the power that is alternately stored and released in the inductive or capacitive components of loads. In practice, most non-resistive consumer loads is inductive, therefore, reactive power is used to create the electromagnetic field that is needed to run motor devices. Reactive power compensation is usually done at the distribution level so as to avoid unnecessary power loss on transmission networks. This is typically done by means of shunt capacitors, switchable capacitors, or static VAr compensator (SVCs). For example, the placement and sizing of fixed shunt capacitors is discussed in [65][66][67][68][69]. Tacking uncertainty in the amount of needed reactive power support is addressed in [70] using switchable capacitors. The efficient operation of switchable capacitor with minimum control movement and minimum power loss is
addressed in [71] and [72], respectively. Reactive power support and voltage control using SVC devices are also discussed in [73][74][75][76], e.g., in presence of intermittent generator.

There are also some studies that have emerged only recently and aim to support reactive power using Power Resources other than shunt capacitors, switchable capacitors, or SVCs. For example, in [77] and [78], the authors proposed reactive power support at photovoltaic (PV) units. The use of PEV charger inverters to conduct reactive power compensation was first discussed in [79]. In [80], Cvetkovic et al. showed the possibility of using PEVs for frequency and voltage regulation. A similar idea was also examined in [81], [82] by taking into account the PEVs’ charging deadlines.

2.3. P-Q Control

The idea of P-Q control has been examined, e.g., in [7][8][9][79]. In [79], Kisacikoglu chiefly examines 4 quadrant operation of single phase EV chargers. He presents 3 four-quadrant bidirectional smart chargers and examines the safe area for reactive power support in each one. There are also papers, e.g., see [94][95] that examine the relationship between reactive power compensation and the circuit hardware used. It is discovered that reactive power can be supported without changing the vehicles battery’s SoC, but that for a fixed DC battery voltage and a certain allowable battery voltage ripple the DC capacitance requirement increases with increasing reactive power support to the grid. Active power can be supported by charging and discharging the battery.
In [83], Arancibia et al propose an electric vehicle battery charger. This charger allows not just vehicle to grid (V2G) power but also full four-quadrant operation while connected to either a one or three phase power system. This control requires measurements of voltage and current at only the terminals and was verified using a simulation and demonstrated in a smart grid laboratory [83].

2.4. Use of RTDS Simulator

While the primary users of the RTDS Simulator are the power companies and utilities, RTDS has also been used in recent years in various research projects. For example, in [84][85], data that is collected from phasor measurement units (PMUs) is fed into an RTDS Simulator in real-time to simulate the operation of power grid more accurately. In [86][87], the authors presented models to simulate PV panels in RTDS. The simulation of thermal and type of storage units is discussed in [88] and [89][90], respectively. In [91], the authors simulated a synchronous generator in RTDS. Finally, in [92][92], static synchronous compensators are simulated using RTDS.
Chapter 3

Design Optimization
3.1. Overview

Recall from Section 1.3 that a distributed P-Q resource can inject or consume active and reactive power. The question that we seek to answer in this Chapter is as follows: what is the best choice of set points for active and reactive power injection (or consumption) at each operation time so that a distributed P-Q resource can contribute to improving the performance of a power distribution system, with respect to the performance issues that are listed in Section 1.4? We answer this question in an optimization-based framework.

3.2. Power Flow Equations

Consider a balanced three phase radial power distribution system [96] with \( N \) as the set of buses. Our design here is about long-term P-Q support. That is, we update \( P \) and \( Q \) set points for the distributed P-Q power resource of interest every several minutes (e.g., every 15 minutes) and accordingly we use steady-state power flow equations. At each time slot \( t \), the standard power flow equations at distribution level are

\[
P_{ij}[t] = \sum_{k \in N_i} P_{jk}[t] + r_{ij} l_{ij}[t]^2 + P_j[t],
\]

(3.1)

\[
Q_{ij}[t] = \sum_{k \in N_i} Q_{jk}[t] + x_{ij} l_{ij}[t]^2 + Q_j[t],
\]

(3.2)

\[
V_i[t]^2 - V_j[t]^2 = 2(r_{ij} P_{ij}[t] + x_{ij} Q_{ij}[t]) - (r_j^2 + x_j^2) l_{ij}[t]^2,
\]

(3.3)

\[
l_{ij}[t]^2 = \frac{P_{ij}[t]^2 + Q_{ij}[t]^2}{V_i[t]^2}.
\]

(3.4)
The notations are shown in Figure 3.1. Here, $P_{ij}[t]$ and $Q_{ij}[t]$ denote the active and reactive power flow on line $(i,j)$, where $i$ is the parent node. More specifically, they indicate the power that leaves parent bus $i$ towards child bus $j$. Similarly, $I_{ij}[t]$ denotes the current that leaves parent bus $i$ towards child bus $j$. For each line $(i,j)$, the resistance and reactance are denoted by $r_{ij}$ and $x_{ij}$. For each bus $i$, the voltage is denoted by $V_i[t]$. Also, at each bus $i$, the active and reactive power load is denoted by $P_i[t]$ and $Q_i[t]$, respectively. If instead of load we have power injection at bus $i$, then $P_i[t]$ and $Q_i[t]$ will take negative values. Finally, for each parent bus $i$, the set of children buses is denoted by $N_i$. If a bus $i$ does not have any children, then $N_i$ is an empty set.

![Figure 3.1. The notations in power flow equations (3.1)-(3.4).](image)

Besides (3.1)-(3.4), we usually require the following voltage constraints at each bus $i$:

$$V^{\text{min}} \leq V_i[t]^2 \leq V^{\text{max}}, \quad (3.5)$$

where $V^{\text{min}}$ and $V^{\text{max}}$ are design parameters. They are defined with respect to the reference voltage and the reference bus, i.e., the bus that is connected to the sub-station.

Next, assume that we install a battery at one of the buses, which we refer to as bus $B$. The system setup at bus $B$ is shown in Figure 3.2, where we have introduced a *virtual bus* at
the coupling point $c$. Let us define $I_c[t]$ as the current that goes through the coupling transformer and coupling inductor. The direction of this current is defined from bus $B$ to the virtual bus at the coupling point. The following equations must hold:

$$ I_c[t]^2 = \frac{P_B[t]^2 + Q_B[t]^2}{V_B[t]^2} \tag{3.6} $$

$$ V_B[t]^2 - V_c[t]^2 = 2x_c Q_B[t] - x_c^2 I_c[t]^2 \tag{3.7} $$

where $x_c = \omega L_c$ and notation $L_c$ denotes the combined induction at the coupling transformer and the coupling inductor of the battery charger. The above two equations link the battery current $I_c[t]$ and voltage $V_c[t]$ to the power flow equations in (3.1)-(3.4).

Figure 3.2. The notations at bus $B$ which is the bus where the battery is installed.

3.3. Battery Operational Equations

In this subsection, we obtain the operational constraints for the battery and charger.

First, let $P_B^{max}$ denote the maximum charge/discharge rate that the charger and battery can support. Therefore, it is required that we always have
\[-P_B^{\text{max}} \leq P_B[t] \leq P_B^{\text{max}}. \] (3.8)

Since, in practice, our focus is particularly on supporting reactive power, we must have

\[Q_B[t] \leq 0. \] (3.9)

Next, let \(S^{\text{max}}\) denote the maximum apparent power limit of the inverter. We must have

\[P_B^2 + (Q_B - x_c I_c[t])^2 \leq S^{\text{max}}. \] (3.10)

Note that, \(Q_B - x_c I_c[t]^2\) denotes the total reactive power that the DC-line capacitor \(C_{dc}\) should support. Therefore, it is required to have

\[Q_B - x_c I_c[t]^2 \geq -C_{dc} \omega (V_c^{\text{max}})^2. \] (3.11)

Furthermore, we must limit \(V_c[t]\) within an acceptable range which is decided based on the parameters of the batteries being used. Therefore, we must have

\[V_c^{\text{min}} \leq V_c[t]^2 \leq V_c^{\text{max}}. \] (3.12)

For example, for Winston Chung batteries, \(V_c^{\text{min}}\) and \(V_c^{\text{max}}\) are 0.9032 and 1.2903 times the nominal voltage of the batteries [97].

Finally, we need to make sure that we do not attempt to charge an already full battery or to discharge an already empty battery. Let \(\phi_B[t]\) denote the charge level of the battery at time slot \(t\). Also let \(\phi_B^{\text{min}}\) and \(\phi_B^{\text{max}}\) denote the minimum and maximum allowed charge level of the battery. We need to satisfy the following constraints:

\[\phi_B^{\text{min}} \leq \phi_B[t] \leq \phi_B^{\text{max}}. \] (3.13)
where \( \varphi_B[0] \) denotes the initial charge level of the battery. We can keep track of the charge level of the battery by using the following equality constraints:

\[
\varphi_B[t] = \varphi_B[t-1] + P_B[t] \Delta T,
\]

where \( \Delta T \) denotes the length of each time slot, e.g., \( \Delta T = 15 \) minutes.

### 3.4. Problem Formulation

We are now ready to formulate the optimization problem. We are particularly interested in minimizing the total power loss across the distribution lines. This choice also naturally helps to do peak load shaving at the substation level. Let \( T \) denotes the number of time slots during the day. For example, if we update \( P_B[t] \) and \( Q_B[t] \) every \( \Delta T = 15 \) minutes, then \( T = 24 \times 4 = 96 \) for a daily operation. We can formulate the problem as

\[
\text{minimize} \sum_{t=1}^{T} \sum_{i \in N} \sum_{j \in N_i} r_{ij} I_{ij}[t]^2
\]

\[
\text{subject to} \quad \text{Eqs. (3.1) – (3.14)},
\]

where the variables are \( P_i[t], Q_i[t], P_{ij}[t], Q_{ij}[t], I_{ij}[t], I_c[t], V_i[t], V_c[t], P_B[t], Q_B[t] \).

Note that, for each distribution line \((i,j)\) and at each time \( t \), the term \( r_{ij} I_{ij}[t]^2 \) denotes the power loss. Accordingly, the objective function in (3.15) is the summation of the power loss across all distribution lines and across all time slots during the day.

### 3.5. Optimal Solution

The optimization problem in (3.15) is not convex. The non-convexity comes from various constraints. In particular, the equalities in (3.3), (3.4), (3.6), and (3.7) are all nonlinear.
Also, the inequality in (3.10) is a polynomial of degree four. To tackle the non-convexity in (3.15), we first conduct some change of variables, partly similar to those in [78]:

\[
\alpha_{ij}[t] = I_{ij}[t]^2
\]  
(3.16)

\[
\beta_i[t] = V_i[t]^2
\]  
(3.17)

Accordingly, we can rewrite the objective function in problem (3.15) as

\[
\sum_{t=1}^{T} \sum_{i \in N} \sum_{j \in N_i} r_{ij} \alpha_{ij}[t]
\]  
(3.18)

and the constraints as

\[
P_{ij}[t] = \sum_{k \in N_i} P_{jk}[t] + r_{ij} \alpha_{ij}[t] + P_i[t],
\]  
(3.19)

\[
Q_{ij}[t] = \sum_{k \in N_i} Q_{jk}[t] + x_{ij} \alpha_{ij}[t] + Q_j[t]
\]  
(3.20)

\[
\beta_i[t] - \beta_j[t] = 2(r_{ij}P_{ij}[t] + x_{ij}Q_{ij}[t]) - (r_{ij}^2 + x_{ij}^2)\alpha_{ij}[t]
\]  
(3.21)

\[
P_{ij}[t]^2 + Q_{ij}[t]^2 = \alpha_{ij}[t]\beta_i[t]
\]  
(3.22)

\[
V_{\min} \leq \beta_i[t] \leq V_{\max}
\]  
(3.23)

\[
P_B[t]^2 + Q_B[t]^2 = \alpha_c[t]\beta_c[t]
\]  
(3.24)

\[
\beta_B[t] - \beta_c[t] = 2x_cQ_B[t] - x_c^2\alpha_c[t]
\]  
(3.25)

\[-P_B^{\max} \leq P_B[t] \leq P_B^{\max}
\]  
(3.26)

\[Q_B[t] \leq 0
\]  
(3.27)

\[
P_B^2 + (Q_B - x_c\alpha_c[t])^2 \leq S_{\max}
\]  
(3.28)

\[
Q_B - x_c\alpha_c[t] \geq -C_{dc}\omega(V_c^{\max})^2
\]  
(3.29)

\[
V_c^{\min} \leq \beta_c[t] \leq V_c^{\max}
\]  
(3.30)

\[
\varphi_B^{\min} \leq \varphi_B[t] \leq \varphi_B^{\max}
\]  
(3.31)

\[
\varphi_B[t] = \varphi_B[t-1] + P_B[t] \Delta T
\]  
(3.32)
The objective function in (3.18) and the constraints in (3.19)-(3.21), (3.23), (3.25)-(3.27), (3.29)-(3.32) are all linear. Constraint (3.28) is nonlinear, but convex.

Constraints (3.22) and (3.24) are still non-convex. Let us replace them with

\[
P_{ij}[t]^2 + Q_{ij}[t]^2 \leq \alpha_{ij}[t] \beta_i[t]
\] (3.33)

and

\[
P_B[t]^2 + Q_B[t]^2 \leq \alpha_c[t] \beta_c[t],
\] (3.34)

respectively. The above inequality constraints are convex because they are rotated quadratic cone constraints [98][99]. Therefore, the following problem is convex:

\[
\text{minimize} \sum_{t=1}^{T} \sum_{i \in N} \sum_{j \in N_i} r_{ij} \alpha_{ij}[t]
\] subject to \ Eqs. (3.19) – (3.21), (3.23), (3.25) – (3.34).

Accordingly, optimization problem (3.15) can be solved using standard convex programming techniques, such as the Interior Point Method [99]. For the results in this thesis, we used MATLAB optimization package CVX [100] to solve problem (3.35).

Since problem (3.35) is a convex relaxation of problem (3.15), in general, its solution could be suboptimal for the original optimization problem in (3.15). However, the solution is exact as long as constraints (3.33) and (3.34) hold as equality at optimality. Interestingly, we observed that this condition always holds in all cases that we simulated.
Given the optimal solutions of problem (3.35), we take $P_B[t]$ and $Q_B[t]$ at all time slots $t = 1, \ldots, T$ and use them as set points for the distributed P-Q power resources.
Chapter 4

RTDS Implementation
4.1 Overview
In this chapter, we develop two four-quadrant power resource models in RTDS. The first design (Design I) is based on combining an ideal two-quadrant load and an ideal source. The second design (Design II) is based on actual power electronics and battery units.

4.2 Design I
4.2.1 RSCAD Model
The block diagram of Design I is shown in Figure 4.1.
In its RTDS implementation, Design I includes a power source, a breaker, and a controllable load, as shown in Figure 4.2. These components are used in tandem to create four-quadrant operations. For example, to operate in quadrant one (drawing real power and reactive power), the model would turn the power supply off, and use the controllable load to draw real and reactive power. To operate in quadrant two (supplying real power, and drawing reactive power) the model would turn the power supply on to supply active power, and then use the controllable load to draw reactive power. Using these two components in tandem allowed for arbitrary four-quadrant power at the terminals.

Figure 4.2 RSCAD Model of 4 Quadrant P-Q Power Resource (Design I)
4.2.2 Design I Control

The RTDS system in Figure 4.2 is controlled in real time using RTDS control modules. The source is connected and disconnected using a breaker. If the model is required to source power, then the breaker is closed to connect the source. The actual amount of power drawn from this source is controlled by varying the voltage magnitude of the source. The magnitude is controlled by a simple Proportional Integral (PI) controller created in RTDS. The breaker control and the PI controller can be seen in Figure 4.3-4.4.

Figure 4.3 Source Breaker Control
The load part of the model (responsible for real power draw and both positive and negative reactive power) is far simpler to control. Such simple model takes a P and Q input and internally adjusts its impedance to match the desired amount of power draw.

4.2.3 Design I Operating Range

Since we are using the RSCAD load model, which is the software side of the RTDS systems, the active power load and reactive power are unlimited. But since the power injection is limited by the voltage difference between the source voltage and the distribution grid voltage there is a limit to the amount of P we can inject into the grid. This limit is defined by the range of outputs we allow the PI controller to have.

\[
P_{\text{max}} = \frac{V_{\text{grid}}(V_{\text{max}} - V_{\text{grid}})}{R}
\]  

(4.1)

Where \(V_{\text{max}}\) is the voltage of the source, \(V_{\text{grid}}\) is the voltage at the connection point to the grid, and \(R\) is the source resistance. In this case we have limited it to roughly -1.5MW (with some variation due to the fluctuations in \(V_{\text{grid}}\)).
4.3 Design II

4.3.1 RSCAD Model

Design II is an actual hardware model of a four-quadrant battery load with power electronics and battery components. The batteries, control, and four-quadrant charger are all modelled inside RSCAD. The RTDS Lithium Ion battery model is used to model the energy storage. The following parameters are used in the setup of the battery:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity of Each Cell</td>
<td>.85Ah</td>
</tr>
<tr>
<td>Series Cells</td>
<td>1500</td>
</tr>
<tr>
<td>Parallel Cells</td>
<td>250</td>
</tr>
</tbody>
</table>

These parameters produce roughly 1MWh of available energy storage. Also, the charger that we designed in RTDS has the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage DC</td>
<td>~5 kV</td>
</tr>
<tr>
<td>DC Cap</td>
<td>5 mF</td>
</tr>
<tr>
<td>Coupling Inductance</td>
<td>3 mH</td>
</tr>
</tbody>
</table>

The RTDS battery model can be seen in Figure 4.5.
The circuit diagram of Design II’s charger is given in Figure 4.6. The 3-phase AC input is shown on the left, and the DC side is on the right (this is where the battery is connected).
4.3.2 Design II Control

The Design II control is much more complex than Design I. It is split into 4 main sections.

The generalized control diagram for the system can be seen below.

![Design II Control Block Diagram](image)

4.3.2.1. DQ Transform

Instantaneous DQ transform is based on the theory of instantaneous power. It converts abc three phase AC voltage or current to d-q rotating orthogonal coordinate system. In this coordinate system power and reactive power are directly related to two DC values (d and q). [105] These values can then be controlled using classic control systems before returning to the abc three phase reference frame.
Figure 4.8. DQ Transform in RSCAD

Figure 4.9. Transformation of P and Q set point to DQ reference frame
Figure 4.10. RSCAD implementation of PQ control in the dq reference frame
4.3.2.2. Inverse DQ Transform

The inverse DQ transform is simply the way to return from the non-rotating dq reference frame back to the rotating ABC reference frame. Once again, RSCAD has a premade block that can perform this transform. The RSCAD implementation of the inverse dq transform can be seen in the figure below. A normalization stage is also shown (on the right). Once we are back in the ABC reference frame we can move onto the final PWM control stage.

Figure 4.11. Design II Block Diagram

4.3.2.3. Space-vector Pulse Width Modulation

The last stage of the control takes 3 ABC voltages as inputs and outputs the duty cycles needed to run the charger bridge. In order to make full use of the battery voltage, as well as have a good harmonic profile, the charger’s bridge is driven by Space Vector PWM (SVPWM). In SWPWM, we define two states for each leg. (1 if the upper switch is closed, and 0 otherwise). Since the charger/inverter has 3 legs this means there are eight combinations for the entire inverter (000, 001, 010, ... , 111) and six of them produce non
zero voltage on the output. (111 and 000 produce zero voltage) These six combinations are mapped to \( \text{Vi} \) \((i=1,\ldots,6)\) vectors in alpha-beta space [101], as seen Figure 4.12.

![Figure 4.12. Vectors, Sectors, and Waves of SVPWM [101]](image)

The vectors can be seen as the arrows, and the sectors are shown as the triangular area between the vectors. Given a reference vector \( V \) (the grid voltage) with a sampling period \( T_s \) in some sector we can express it by using \( V_i \) and \( V_{i+1} \) as follows:

\[
\overline{V}T_i + \overline{V}T_{i+1} = \overline{V}T_s, i = 1, 2, \ldots, 6
\]  \hspace{1cm} (4.2)

where \( T_i \) is the operating time spent in that state. We can then solve for \( T_i \) and convert the time spent in each state to a duty cycle for the bridge switches [101]. In the [101] an algorithm that significantly reduces the computational burden is introduced. This algorithm is used in the RTDS implementation of SVPWM.
Figure 4.13. ABC to Alpha-Beta Transformation and Sector Identification
Figure 4.14. On/Off time calculator across the six sectors in Figure 4.12.
Figure 4.15. Reference Timing Information Generation
Figure 4.16. Over-modulation Prevention Control Blocks
4.3.3. Design II Operating Range

In a grid disconnected situation this design (with the above parameters) can produce -3 to 3 MVA of reactive power and -3 to 3 MW active power before it begins to fail. However, in a real hardware situation these set points could cause serious damage to the battery and power electronics.

4.4. Communication and Distributed Simulation

Once the 4 quadrant models were designed a communication scheme was developed to allow for the automatic sending of set points, and the automatic recording of data. This system allowed us to run MATLAB code to get the optimized P and Q set points for the 4 quadrant load, send those set points to the real time power system simulation, and view the results. The communication was all done over TCP/IP using the MATLAB JTCP library [102]. The block diagram of this system can be seen below. In the command case, MATLAB sends commands to RSCAD Runtime, which then interfaces with the actual simulation in real time. In the data logging state MATLAB requests a piece of data from RSCAD Runtime, which then requests it from the simulation. The simulation responds
with the data which RSCAD Runtime then passes back to MATLAB where it is finally logged. This process can generally be completed in less than a tenth of a second.

![Diagram of Real Time communication](image)

**Figure 4.18. Real Time communication Block Diagram**

Any program/system capable of TCP/IP communication could theoretically take the place of the first block above. The setup above was also done in C, which was slightly faster but for our purposes was more difficult to use. For this reason we simply used the MATLAB to RTDS method. For more details the C code can be seen in the appendix. This same procedure can also be done using Simulink. The method for implementing RTDS control and data logging in Simulink can also be found in the appendix.
Chapter 5

Simulation Results
5.1. Overview

In this Chapter, we present comprehensive simulation results using RTDS. Following the common approach in power engineering, the results in this Chapter are presented in *per unit* (pu) system. In per-unit system, the quantities are expressed as fractions of a defined base unit quantity. In other words, the quantities are normalized. The base unit quantities are particularly defined for power and voltage. In this Chapter, we define

\[ S_{\text{base}} = 1 + 1j \, VA \]  
\[ V_{\text{base}} = 4.16 \, kV \]

For example, when we indicate that active power injection at a bus is 1 pu, it means that the actual active power injection is 1 MW. Or when we indicate that reactive power draw at a bus is 0.5 pu, it means that the actual reactive power draw is 0.5 MVAR. Finally, when we indicate that the voltage magnitude at a bus is 0.9 pu, it means that the actual voltage magnitude is 3.744 kV. Per-unit system simplifies the presentation of results.

The rest of this Chapter is divided into three parts. First, we present simulation results for a stand-alone distributed P-Q power resource. The focus is to show how the distributed P-Q power resource can follow arbitrary set points for active and reactive power. Both RTDS Design I and RTDS Design II are examined. Second, we present simulation results for a grid-connected distributed P-Q power resource. The results in this part are much more comprehensive because we investigate a variety of performance metrics. Finally, we present a summary of the key observations based on our conducted simulation results.
In all simulations, the charging capacity of the battery is $\varphi_{B}^{max} = 2$ pu, while $\varphi_{B}^{min} = 0$. The maximum charge and discharge rate of battery is $P_{B}^{max} = 1$ pu. The maximum charger apparent power capacity is $S^{max} = 1$ pu. The rest of the system parameters are as follows:

$V_{c}^{min} = 0.9032$, $V_{c}^{max} = 1.2903$, $x_{c} = 3mH$, $C_{dc} = 5mF$, $V^{min} = 0.8$, $V^{max} = 1.2$, $\Delta T = 0.25 = 15$ minutes, $\omega = 2\pi \times 60 = 120\pi$.

5.2. Stand-Alone Simulation

First, consider the case where the distributed P-Q power resource of interest is connected to an absorbing test bus. The focus in this section is to show how the distributed P-Q power resource can follow arbitrary set points for active and reactive power.

5.2.1. RTDS Design I

The active and reactive power traces for RTDS Design I and for different set points are shown in Figures 5.1 to 5.4. We can see successful set point tracking in all four cases.
Figure 5.1. Reactive power set point tracking for Design I, where $P_B = 0$ and $Q_B = 1$.

Figure 5.2. Reactive power set point tracking for Design I, where $P_B = 0$ and $Q_B = -1$. 
Figure 5.3. Active power set point tracking for Design I, where $P_B = 1$ and $Q_B = 0$.

Figure 5.4. Active power set point tracking for Design I, where $P_B = -1$ and $Q_B = 0$. 
5.2.2 RTDS Design II

The active and reactive power traces for RTDS Design II and for different set points are shown in Figures 5.1 to 5.4. Again, we can see successful set point tracking in all cases.

Figure 5.5. Reactive power set point tracking for Design II, where $P_B = 0$ and $Q_B = 1$.

Figure 5.6. Reactive power set point tracking for Design II, where $P_B = 0$ and $Q_B = -1$. 

50
Figure 5.7. Active power set point tracking for Design II, where $P_B = 1$ and $Q_B = 0$.

Figure 5.8. Active power set point tracking for Design II, where $P_B = -1$ and $Q_B = 0$.
5.3. Grid-Connected Simulation

In this section, we present simulation results for a grid-connected distributed P-Q power resource. First, we present the topology and parameters for the grid.

5.3.1. Setup

The power distributed grid that we simulated is a modified version of the IEEE 13 bus test system, see Figures 5.9(a) and 5.9(b). The modifications that we made are as follows. First, we balanced the loads and lines across the three phases. Second, the circuit breaker between bus 671 and bus 692 is closed. Therefore, buses 692 and 675 are consolidated as one bus. Shunt capacitors are removed to create room for offering reactive power compensation by the distributed P-Q resource. The transformer between buses 633 and 634 is removed. Instead, we placed a transformer at the point of contact for the battery and its charger. The rest of the parameters, including the admittance for each line, are the same as in the IEEE 13 bus test system, see [103].
Figure 5.9. The power distribution network that is simulated in this Chapter: (a) the IEEE 13 bus test system [103]. (b) The modified 12 bus system.

We placed the battery system (i.e., the distributed P-Q resource) at bus 9. We also placed a 1.2 MW grid-connected solar panel at bus 8. The power output of the PV panel depends on solar irradiance. Accordingly, we simulate two different cases. First, the case of a cloudy day, where the PV power output is as in Figure 5.10 [104]. Second, the case of a sunny day, where the PV power output is as in Figure 5.11 [104].
Figure 5.10. The daily output of the solar panel during a cloudy day.

Figure 5.11. The daily output of the solar panel during a sunny day.
Finally, the traces of the background active and reactive power load at each bus are assumed to be as in Figures 5.12 and 5.13, respectively.

Figure 5.12. The daily trends for background active power load at various buses.

Figure 5.13. The daily trends for background active power load at various buses.
5.3.2. RTDS Design I

Given the simulation setup that we explained in Section 5.3.1, we are now ready to present different simulation results. In this section, the distributed P-Q power resource is modeled using the RTDS Design I. The simulation results when the distributed P-Q power resource is modeled using the RTDS Design II are presented later in Section 5.3.3.

5.3.2.1. Cloudy Day

First, suppose operation in a cloudy day, where the output of the solar panel at bus 8 is as in Figure 5.10. We examine three different design cases under this scenario:

- Case 1: The battery system at bus 9 is disconnected from the distribution grid.

- Case 2: The battery system at bus 9 is connected to the distribution. However, it is used in its traditional way to only support active power.

- Case 3: The battery system at bus 9 is connected to the distribution. It is used in a more efficient way to support both active and reactive power.

Note that the available resources are the same under Case 2 and Case 3. However, such resources are better utilized under Case 3 by also benefiting from the available flexible power electronics components at the bidirectional charger of the battery system.
5.3.2.1.1. Case 1: No Battery

Consider the case where the battery system at bus 9 is disconnected from the grid. This case serves as a benchmark to assess the performance of our proposed design for distributed P-Q power resources. The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.14 and 5.15, respectively. The peak active power load on the substation is 3.218 pu. The peak reactive power load on the substation is 2.358 pu.

Next, consider the voltage profiles at different buses as shown in Figure 5.16. Note that the voltage at the substation (i.e., reference bus) is always regulated at 1 pu. We can see voltage drop at all other buses. The voltage drop is particularly noticeable at buses that are further away from the substation, namely buses 6 to 12.

Finally, consider the amount of power loss across the distribution lines that are shown in Figure 5.17. We can see that power loss is more during peak hours. In total, i.e., across all buses and across all 24 hours, the daily power loss in this case is 2.6337 pu.
Figure 5.14. The daily active power draw from the substation in Case 1 in a cloudy day.

Figure 5.15. The daily reactive power draw from the substation in Case 1 in a cloudy day.
Figure 5.16. The daily voltage profiles at all buses in Case 1 in a cloudy day.

Figure 5.17. The daily power loss at distribution lines in Case 1 in a cloudy day.
5.3.2.1.2. Case 2: Battery with P Control

Consider the case where the battery system at bus 9 is connected to the grid. However, it is used in its traditional way to only support active power. The daily power injection and draw of the battery in this case is shown in Figure 5.18. Positive values indicate power draw while negative values indicate power injection by the battery system.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.19 and 5.20, respectively. The peak active power load at the substation is 2.607 pu. The peak reactive power load at the substation is 2.217 pu.

Next, consider the voltage profiles at different buses as shown in Figure 5.21. We can see some improvements in voltage profile across most buses, compared to Case 1.

Finally, consider the amount of power loss across the distribution lines that are shown in Figure 5.22. We can see that power loss is reduced compared to Case 1. In total, i.e., across all buses and across all 24 hours, the daily power loss in this case is 2.5861 pu.
Figure 5.18. The daily power injection / draw of the battery in Case 2 in a cloudy day.

Figure 5.19. The daily active power draw from the substation in Case 2 in a cloudy day.
Figure 5.20. The daily reactive power draw from the substation in Case 2 in a cloudy day.

Figure 5.21. The daily voltage profiles at all buses in Case 2 in a cloudy day.
Figure 5.22. The daily power loss at distribution lines in Case 2 in a cloudy day.

5.3.2.1.3. Case 3: Battery with P and Q Control

Finally, consider the case where the battery system at bus 9 is connected to the grid and it is used to support both active and reactive power. The daily active and reactive power injection and draw of the battery in this case is shown in Figures 5.23 and 5.24, respectively. Negative values indicate power injection by the battery system.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.25 and 5.26, respectively. The peak active power load at the substation is 2.772 pu. The peak reactive power load at the substation is 1.854 pu.
Next, consider the voltage profiles at different buses as shown in Figure 5.27. We can see some further improvements in voltage profile, compared to Cases 1 and 2.

Finally, consider the amount of power loss across the distribution lines that are shown in Figure 5.28. We can see that power loss is significantly reduced compared to Cases 1 and 2. In total, i.e., across all buses and all 24 hours, the daily power loss in this case is 1.9691 pu.

Figure 5.23. The daily active power injection / draw of battery in Case 3 in cloudy day.
Figure 5.24. The daily reactive power injection / draw of battery in Case 3 in cloudy day.

Figure 5.25. The daily power loss at distribution lines in Case 3 in a cloudy day.
Figure 5.26. The daily active power draw from the substation in Case 3 in a cloudy day.

Figure 5.27. The daily voltage profiles at all buses in Case 3 in a cloudy day.
5.3.2.2. Sunny Day

Next, suppose operation in a sunny day, where the output of the solar panel at bus 8 is as in Figure 5.11. We examine the same three different design cases as in Section 5.3.2.1.

5.3.2.2.1. Case 1: No Battery

Consider the case where the battery system at bus 9 is disconnected from the grid. The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.29 and 5.30, respectively. The peak active power load on the substation is 3.218 pu. The peak reactive power load on the substation is 2.358 pu.
Next, consider the voltage profiles at different buses as shown in Figure 5.31. Again, we can see voltage drop at all other buses. The voltage drop is particularly noticeable at buses that are further away from the substation, namely buses 6 to 12.

Finally, consider the amount of power loss across the distribution lines that are shown in Figure 5.32. We can see that power loss is more during peak hours. In total, i.e., across all buses and across all 24 hours, the daily power loss in this case is 2.5062 pu.

Figure 5.29. The daily active power draw from the substation in Case 1 in a sunny day.
Figure 5.30. The daily reactive power draw from the substation in Case 1 in a sunny day.

Figure 5.31. The daily voltage profiles at all buses in Case 1 in a sunny day.
5.3.2.2.2. Case 2: Battery with P Control

Consider the case where the battery system at bus 9 is connected to the grid. However, it is used in its traditional way to only support active power. The daily power injection and draw of the battery in this case is shown in Figure 5.33. Positive values indicate power draw while negative values indicate power injection by the battery system.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.34 and 5.35, respectively. The peak active power load at the substation is 2.53 pu. The peak reactive power load at the substation is 1.155 pu.
Next, consider the voltage profiles at different buses as shown in Figure 5.36. We can see some improvements in voltage profile across most buses, compared to Case 1.

Finally, consider the amount of power loss across the distribution lines that are shown in Figure 5.37. We can see that power loss is reduced compared to Case 1. In total, i.e., across all buses and across all 24 hours, the daily power loss in this case is 2.4455 pu.

![Graph showing battery active power draw over time](image)

Figure 5.33. The daily power injection / draw of the battery in Case 2 in a sunny day.
Figure 5.34. The daily active power draw from the substation in Case 2 in a sunny day.

Figure 5.35. The daily reactive power draw from the substation in Case 2 in a sunny day.
Figure 5.36. The daily voltage profiles at all buses in Case 2 in a sunny day.

Figure 5.37. The daily power loss at distribution lines in Case 2 in a sunny day.
5.3.2.2.3. Case 3: Battery with P and Q Control

Finally, consider the case where the battery system at bus 9 is connected to the grid and it is used to support both active and reactive power. The daily active and reactive power injection and draw of the battery in this case is shown in Figures 5.38 and 5.39, respectively. Negative values indicate power injection by the battery system.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.40 and 5.41, respectively. The peak active power load at the substation is 2.699 pu. The peak reactive power load at the substation is 1.789 pu.

Next, consider the voltage profiles at different buses as shown in Figure 5.42. We can see some further improvements in voltage profile, compared to Cases 1 and 2.

Finally, consider the amount of power loss across the distribution lines that are shown in Figure 5.43. We can see that power loss is significantly reduced compared to Cases 1 and 2. In total, i.e., across all buses and all 24 hours, the daily power loss in this case is 1.8987 pu.
Figure 5.38. The daily active power injection / draw of battery in Case 3 in sunny day.

Figure 5.39. The daily reactive power injection / draw of battery in Case 3 in sunny day.
Figure 5.40. The daily active power draw from the substation in Case 3 in a sunny day.

Figure 5.41. The daily active power draw from the substation in Case 3 in a sunny day.
Figure 5.42. The daily voltage profiles at all buses in Case 3 in a sunny day.

Figure 5.43. The daily power loss at distribution lines in Case 3 in a sunny day.
5.3.3. RTDS Design II

In this section, the distributed P-Q power resource is modeled using the RTDS Design II. Note that, Design II is more realistic and includes the charger power electronics and battery components. Nevertheless, the results are more or less similar to Design I.

5.3.3.1. Cloudy Day

First, suppose operation in a cloudy day, where the output of the solar panel at bus 8 is as in Figure 5.10. We examine three different design cases as defined in Section 5.3.2.1.

5.3.3.1.1. Case 1: No Battery

The amounts of active and reactive power draws from the substation in this case are shown in Figures 5.44 and 5.45, respectively. The peak active power load at substation is 3.218 pu. The peak reactive power load at substation is 2.358 pu. The voltage profiles at different buses are shown in Figure 5.46. The power loss across the distribution lines are shown in Figure 5.47. The results are similar to those in Figures 5.14 - 5.17.
Figure 5.44. The daily active power draw from the substation in Case 1 in a cloudy day.

Figure 5.45. The daily reactive power draw from the substation in Case 1 in a cloudy day.
Figure 5.46. The daily voltage profiles at all buses in Case 1 in a cloudy day.

Figure 5.47. The daily power loss at distribution lines in Case 1 in a cloudy day.
5.3.3.1.2. Case 2: Battery with P Control

The daily power injection and draw of the battery in this case is shown in Figure 5.48.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.49 and 5.50, respectively. The peak active power load at the substation is 2.607 pu. The peak reactive power load at the substation is 2.217 pu.

The voltage profiles at different buses are shown in Figure 5.51.

Finally, the trace for power loss across the distribution lines is shown in Figure 5.52.

Figure 5.48. The daily power injection / draw of the battery in Case 2 in a cloudy day.
Figure 5.49. The daily active power draw from the substation in Case 2 in a cloudy day.

Figure 5.50. The daily reactive power draw from the substation in Case 2 in a cloudy day.
Figure 5.51. The daily voltage profiles at all buses in Case 2 in a cloudy day.

Figure 5.52. The daily power loss at distribution lines in Case 2 in a cloudy day.
5.3.3.1.3. Case 3: Battery with P and Q Control

The daily active and reactive power injection and draw of the battery in this case is shown in Figure 5.53 and 5.54, respectively.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.55 and 5.56, respectively. The peak active power load at the substation is 2.787 pu. The peak reactive power load at the substation is 1.829 pu.

The voltage profiles at different buses are shown in Figure 5.57.

Finally, the trace for power loss across the distribution lines is shown in Figure 5.58.

Figure 5.53. The daily active power injection / draw of battery in Case 3 in cloudy day.
Figure 5.54. The daily reactive power injection/draw of battery in Case 3 in cloudy day.

Figure 5.55. The daily active power draw from the substation in Case 3 in a cloudy day.
Figure 5.56. The daily active power draw from the substation in Case 3 in a cloudy day.

Figure 5.57. The daily voltage profiles at all buses in Case 3 in a cloudy day.
It is interesting to notice the differences between the voltage profiles in Figure 5.57 for the case of RTDS Design II and Figure 5.27 for the case of RTDS Design I. We can see that the voltage profiles in Figure 5.57 have more ripples, which results from the switching operations of the power electronics components in the charger. Those ripples are not observed in the idea case of RTDS Design I.

5.3.3.2. Sunny Day

Next, suppose operation in a sunny day, where the output of the solar panel at bus 8 is as in Figure 5.11. We examine the same three different design cases as in Section 5.3.2.1.
5.3.3.2.1. Case 1: No Battery

The amounts of active and reactive power draws from the substation in this case are shown in Figures 5.59 and 5.60, respectively. The peak active power load at substation is 3.216 pu. The peak reactive power load at substation is 2.327 pu. The voltage profiles at different buses are shown in Figure 5.61. The power loss across the distribution lines are shown in Figure 5.62. The results are similar to those in Figures 5.29 - 5.32.

Figure 5.59. The daily active power draw from the substation in Case 1 in a sunny day.
Figure 5.60. The daily reactive power draw from the substation in Case 1 in a sunny day.

Figure 5.61. The daily voltage profiles at all buses in Case 1 in a sunny day.
5.3.3.2.2. Case 2: Battery with P Control

The daily power injection and draw of the battery in this case is shown in Figure 5.63.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.64 and 5.65, respectively. The peak active power load at the substation is 2.565 pu. The peak reactive power load at the substation is 2.143 pu.

The voltage profiles at different buses are shown in Figure 5.66.

Finally, the trace for power loss across the distribution lines is shown in Figure 5.67.
Figure 5.63. The daily power injection / draw of the battery in Case 2 in a sunny day.

Figure 5.64. The daily active power draw from the substation in Case 2 in a sunny day.
Figure 5. The daily reactive power draw from the substation in Case 2 in a sunny day.

Figure 6. The daily voltage profiles at all buses in Case 2 in a sunny day.

Figure 5.65. The daily reactive power draw from the substation in Case 2 in a sunny day.

Figure 5.66. The daily voltage profiles at all buses in Case 2 in a sunny day.
5.3.3.2.3. Case 3: Battery with P and Q Control

The daily active and reactive power injection and draw of the battery in this case is shown in Figure 5.68 and 5.69, respectively.

The amount of active and reactive power draws from the distribution grid substation in this case are shown in Figures 5.70 and 5.71, respectively. The peak active power load at the substation is 2.7 pu. The peak reactive power load at the substation is 1.77 pu.

The voltage profiles at different buses are shown in Figure 5.71.

Finally, the trace for power loss across the distribution lines is shown in Figure 5.72.
Figure 5.68. The daily active power injection / draw of battery in Case 3 in sunny day.

Figure 5.69. The daily reactive power injection / draw of battery in Case 3 in sunny day.
Figure 5.70. The daily active power draw from the substation in Case 3 in a sunny day.

Figure 5.71. The daily active power draw from the substation in Case 3 in a sunny day.
Figure 5.72. The daily voltage profiles at all buses in Case 3 in a sunny day.

Figure 5.73. The daily power loss at distribution lines in Case 3 in a sunny day.
Again, it is interesting to notice the differences between the voltage profiles in Figure 5.73 for the case of RTDS Design II and Figure 5.42 for the case of RTDS Design I. We can see that the voltage profiles in Figure 5.73 have more ripples, which results from the switching operations of the power electronics components in the charger. Those ripples are not observed in the idea case of RTDS Design I.

5.4. Summary

The summary of simulation results for a cloudy day is shown in Figure 5.74.

We can make the following important observations:

- In general, the results are similar for RTDS Designs I and II. This confirms the proper implementation of the power electronics and battery in Design II.

- From Figure 5.74(a), the P-Q power resource can significantly lower the power loss in the distribution grid. This is especially the case when it supports both active and reactive power, where the power loss reduces by 30%. Recall from Chapter 3 that lowering the power loss is the primary objective in our design.

- From Figure 5.74(b) and (c), the proposed design can also provide peak load shaving at the substation, both for active and reactive power.
From Figure 5.74(d), the proposed design, especially when both active and reactive powers are supported, can also help in regulating the voltage across the distribution grid. The average voltage drop in this figure is calculated as follows:

\[
\frac{1}{T} \sum_{t=1}^{T} \left( \frac{1}{N} \sum_{i=1}^{N} |1 - V_{i}[t]| \right),
\]

where \(T\) and \(N\) denote the number of time slots and buses, respectively.

Figure 5.74. The summary of the results for a cloudy day

The summary of simulation results for a sunny day is shown in Figure 5.75.
Figure 5.75. The summary of the results for a sunny day

We can see that the results are generally quite similar to the case of a cloudy day.
Chapter 6

Conclusions and Future Work
6.1. Conclusions

In this Thesis, we presented the idea of utilizing a battery system together with its power electronics interfaces and bidirectional charger as a distributed P-Q resource in power distribution networks. First, we presented an optimization-based approach to operate such distributed P-Q resources based on the characteristics of the battery and charger system as well as those of the power distribution network. Second, we used the RTDS Simulator platform, which is a leading simulation tool in the power industry, to develop two design approaches. The first design is based on an ideal four-quadrant distributed P-Q power resource. The second design is based on a detailed four-quadrant distributed P-Q power resource that is developed using power electronics components. The hardware and power electronics circuitry as well as the control units are explained for the second design. Third, given the two-RTDS designs, we conducted extensive RTDS simulations to assess the performance of the designed distributed P-Q Power Resource in an IEEE 13 bus test system. We observed that the proposed design can noticeably improve the operational performance of the power distribution grid in at least four key aspects:

- Reducing Power Loss
- Active Power Peak Load Shaving at Substation
- Reactive Power Peak Load Shaving at Substation
- Voltage Regulation
We examined the above four performance measures across three design cases: Case 1: There is no P-Q Power Resource available on the power distribution network. Case 2: The installed P-Q Power Resource only supports active power, i.e., it only utilizes its battery component. Case 3: The installed P-Q Power Resource supports both active and reactive power, i.e., it utilizes both its battery component and its power electronics charger component. We observed that utilizing the battery alone is very efficient in shaving the active power peak load at the substation. However, if we also utilize the power electronics charger component though a joint optimization effort, we also achieve efficient performance with respect to the other three performance measures.

Given the fact that almost all battery systems are essentially accompanied with a charger and power electronics interface before they can be connected to a typical AC power distribution network, the aforementioned performance improvements suggest that it is beneficial to look at battery systems not just as a source of active power, but rather a distributed P-Q Power Resource that can offer a variety of operational advantages.
6.2. Future Work

The study in this thesis can be extended in several directions:

- Here, we have presented the results based on a representative cloudy day and a representative sunny day. If sufficient solar irradiance data is available, it is interesting to extend the analysis to an entire year, e.g., for the city of Riverside.

- While the optimization-based aspect of this study focused on operating an already installed distributed P-Q Power Resource, it is interesting to extend the problem formulation to also include right sizing and right locating of the battery system.

- A promising aspect of this study is the use of industry-standard RTDS Simulator. Interestingly, RTDS can support hardware-in-loop (HIL) simulation. Therefore, it is possible to also extend our study to test an actual lithium-ion battery and four-quadrant charger hardware system as an actual distributed P-Q Power Resource.
References


[32] www.rtds.com


[100] cvxr.com/cvx/


[102] mathworks.com/matlabcentral/fileexchange/24524-tcp-ip-communications-in-matlab/content/jtcp.zip

