DC Optimal Dispatch Modeling of a Distribution Level Power Grid with Static and Vehicle-to-Grid (V2G) Energy Storage

Aaron I. Rabinowitz

Introduction

Modern developed economies are supported by electricity and transportation sectors which are interdependent and combine to account for substantial portions of the modern world's economic output, energy consumption, and environmental externalities. In the present both sectors rely overwhelmingly on hydrocarbon energy inputs. However, presently both sectors are being fundamentally effected by the simultaneous market share growth of Electric Vehicles (EVs) and renewable power sources. Much of the growth in renewable power generation has come in the form of solar capture which has seen a massive expansion in recent years due to decreasing capital costs. A fundamental shortcoming of solar capture is that power generation is proportional to solar intensity and, thus, production is negligible at night and marginal on cloudy days. Because solar power is unreliable and temporally restricted, it cannot be the only source of power for a grid and must be paired with dispatchable power generation assets such as thermal power plants and, optionally, energy storage assets such as chemical batteries, pump-hydroelectric generation or other mechanical and thermal energy storage systems.

EVs represent a further coupling of transportation and electricity. As more EVs take to the road in the coming years the power grid will have to both generate enough energy to power them and build the infrastructure to transfer that energy to them. In theory, EVs can also provide a utility to the grid in the form of energy storage and charge management. Grid-Aware Charge Management (GACM) involves an optimized unidirectional link between an EV and the grid where the EV responds to a dynamic pricing signal produced by the grid in order to optimize when it charges and at what power. GACM helps the grid by spreading charge requirements out spatially and temporally in order to minimize the difference between power generation peaks and troughs and operates on the same economic principles as smart home devices. Vehicle-to-Structure (V2S) energy storage involves a bidirectional connection between vehicles and the structures where they plug in which allows the structures to both manage vehicle charging and to discharge vehicles in order to power structure loads to minimize overall grid-borne energy costs for the structure. Finally, Vehicle-to-Grid (V2G) energy storage involves a bidirectional interaction between the grid and EVs facilitated by structures wherein EV batteries are used to store and release energy as dictated by the grid.

Because the power consumption due to EVs and the power generation due to solar capture are expected to grow rapidly in the coming years, there is, in theory, an obvious economic case to use these technologies in a synergistic manner. GACM, V2S, and V2G all allow the grid to make greater use of solar generation and be less reliant on thermal generation. However, many technological and infrastructural barriers stand in the way of making this a reality. Principally, the technological issues arise from a dated distribution and sub-distribution grids which make bidirectional power transfer efficiencies difficult and uncertain and from the design of all but the most recent EV which are not designed to discharge through their charging ports. Between these and other technological issues the potential benefits of GACM and V2S are limited and V2G is effectively impossible in most cases. In order to enable and maximize all three technologies, significant capital will need to be invested in upgrades to the power grid and EV fleet, all of which will be, eventually, borne by consumers. Some, but not all, of this cost will be included in otherwise necessary investments to increase grid capacity and to replace old vehicles.

A looming question is to what degree are investments in GACM, V2S and V2G justified. In particular, it is worth asking whether or not these technologies are the best alternative for the purpose of maximizing the benefits of solar generation. While GACM and V2S serve to arbitrage dynamic grid prices thus producing grid-friendly load profiles, V2G proposes to transform EVs into grid-dispatchable energy storage assets. In the V2G role, EVs must compete with static batteries as dispatchable storage assets.

The following model concerns the operation of a distribution level grid run by an Independent System Operator (ISO). An ISO provides a marketplace wherein entities can bid to provide and purchase wholesale energy at various time slots in a day-ahead or real-time market. In a generic case, the ISO will set prices based on a calculated load profile with the goal of minimizing generation and transmission costs. Because loads and weather conditions can be reasonably accurately predicted for a day-ahead this system enables significant arbitrage which, in theory, benefits all. The most direct and obvious form of energy arbitrage is performed by energy storage entities who currently consist of the operators of static storage installations but may, in the future, include V2G aggregators. Arbitrage is a negative-sum game as some economic value must be extracted by the arbitragers in order to be sustained. Energy arbitrage must be sufficiently profitable to overcome the losses incurred in charging and discharging batteries and in transmitting energy. In a well structured market, only those arbitrage operations whose contributions to market efficiency outweigh their extraction can be sustained. The arbitrage operations with the highest potential are those with the loosest limits on and highest certainties concerning inventory and timing. Because EVs often disconnect from the grid, can plug in at multiple locations, and use significant portions of stored energy capacity to move, they represent less-than-ideal candidates for arbitrage when considered individually. However, when considered collectively as elements controlled by a single aggregator, these deficiencies are somewhat mitigated and possibly offset by the scale and scalability of storage inventory. The following is an exploration of whether, and under what circumstances, V2G is economically justified.

DC-OPF Model

The DC Optimal Power Flow (DC-OPF) model used in this study minimizes generation cost while meeting load requirements via the control of dispatchable assets. The objective of the model is

$$\min_{u \in U} \sum_{d \in D^b} \sum_{t \in T} j_t^{b,g,d} u_t^{b,g,d} \quad \forall b \in B \tag{1}$$

where $B = \{b^0, b^1, \ldots, b^n\}$ is the set of buses in the model, $U^b = \{u^{b,g,0}, u^{b,g,1}, \ldots, u^{b,g,n}, u^{b,t}\}$ is the set of controls for all dispatchable assets and and transmission at bus b which contains the set of optimal controls $U^{b,*}$, D^b is the set of dispatchable assets at bus b, J^b is the set of costs for acquiring energy from each of the dispatchable assets at bus b, and $T = \{t^0, t^1, \ldots, t^n\}$ is the set of simulation time-steps. The optimization is subject to the following constraints:

Conservation of energy:

$$\sum_{d \in D^b} \sum_{t \in T} u_t^{b,g,d} + \sum_{y \in Y^b} \sum_{t \in T} c_t^{b,y} + \sum_{s \in S^b} \sum_{t \in T} (u_t^{s,t} - u_t^{b,t}) = 0 \quad \forall b \in B \tag{2}$$

Where C is the set of problem constants including $c_t^{b,y}$ which is the value of a load at a but at t time-step, Y^b is the set of demand loads (non-dispatchable) at bus b and $u^{t,b}$ is the transmission power at bus b, and S^b is the set of buses which have links to bus b.

Transmission Constraints:

$$c_t^{t,s,b,l} \leq (u_t^{s,t} - u_t^{b,t}) \leq c_t^{t,s,b,u} \quad \forall s \in S^b \quad \forall b \in B \quad \forall t \in T \tag{3}$$

Where $c_t^{t,s,b,l}$ and $c_t^{t,s,b,u}$ are the lower and upper bounds on transmission between a source and target node at a time-step respectively. As implied by the constraints, the model is a bi-directional graph composed of buses which contain dispatchable and non-dispatchable loads. Dispatchable loads are time-varying controls to be optimized ($u_t^{b,g,\cdots}$) and the non-dispatchable assets are exogenous time-varying constants ($c_t^{b,\cdots}$). With this construction Location Marginal Prices (LMPs) at the buses is the shadow price (dual value) of the transmission control at each bus.

There are four types of objects which may belong to a bus:

1. Generation: Dispatchable asset which sends between 0 and a defined upper limit of energy units to the bus. Generation must be positive. Constraints include

$$0 \leq u_t^{b,gen,d} \leq c_t^{b,gen} \quad \forall gen \in D^{b,gen} \quad \forall b \in B \quad \forall t \in T \tag{4}$$

   where $c_t^{b,gen}$ is the generation limit for a generator at a bus at a time-step.

2. Dissipation: Dispatchable asset which removes between 0 and a defined upper limit of energy units to the bus. Dissipation must be negative and is used to allow for valid solutions in situations where non-dispatchable generation exceeds load. Constraints include

$$0 \leq u_t^{b,d,diss} \leq c_t^{b,diss} \quad \forall diss \in D^{b,diss} \quad \forall b \in B \quad \forall t \in T \tag{5}$$

   where $c_t^{b,diss}$ is the dissipation limit for a dissipation asset at a bus at a time-step.

3. Storage: Dispatchable asset which can either send energy units to or remove energy units from the bus. Storage objects track a time-varying State of Charge (SOC) and have constraints on starting and final SOC as well as upper and lower limits at all time steps. Storage SOC is the only problem state. Constraints include

$$c_t^{b,s,l} \leq u_t^{b,s,batt} \leq c_t^{b,s,u} \quad \forall batt \in D^{b,batt} \quad \forall b \in B \quad \forall t \in T \tag{6}$$

   where $c_t^{b,g}$ is the generation limit for a generator at a bus at a time-step.

4. Load: Exogenous variable containing time-varying vector of energy added to or removed from the bus. Positive loads are contributions from non-dispatchable generation assets such as solar generation. Negative loads represent power demand.

Constraints associated with objects include:
A simple 3 bus example is shown in Figure 1.

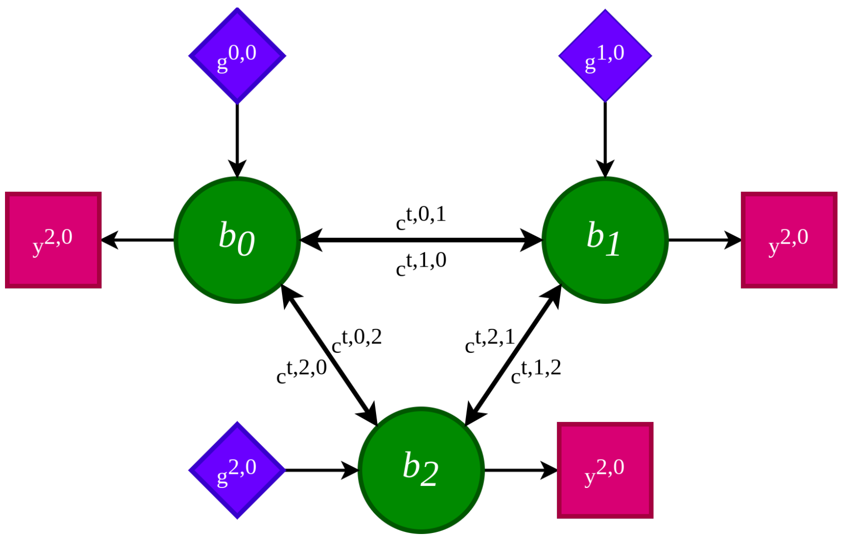

Figure 1: Simple 3 Bus Example

All three buses in the example have one generator (g), one load (y), and transmission connections to the other buses. All transmission connections are bidirectional and have flow limits. Two scenarios are shown in Figure **??**.