Hierarchical Control and Management of Virtual Microgrids for Vehicle Electrification

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Abstract: **In this paper, we investigate control and management of power distribution networks to meet the needs of vehicle electrification. We propose to divide a distribution network into several virtual microgrids (VMGs). Unlike microgrids studied before, virtual microgrids are flexible and cover the entire distribution network. Using VMGs, the control and management of a distribution network can be achieved in a hierarchical fashion. We propose to control the distribution network in two levels: a lower or VMG level and a higher or grid level. We introduce modeling frameworks for the two levels. At the VMG level, VMGs are modeled as stochastic hybrid machines. At the grid level, the distribution network is modeled as a finite state machine with variables. We illustrate the modeling and control approach for a typical distribution network.**
Keywords: **Smart Grids, vehicle electrification, microgrids, control, distribution networks, discrete event systems**

1. INTRODUCTION

Smart Grids have been widely hailed as the future infrastructure of electrical power generation and delivery. A Smart Grid is an intelligent and automated energy grid that enables multiple paths of information and power flow and integrates sensing, communication, and control. In addition to many other important features (e.g., resilience to unexpected faults), a Smart Grid must provide the following critical functions [1]: (1) accommodating a variety of renewable energy sources and new types of loads such as plug-in (hybrid) electric vehicles (PEVs); (2) optimizing system-wide operations; (3) enhancing system efficiency; and (4) improving power quality such as increased system reliability. Although the focus of the power industry has been given to the development of larger power stations, higher voltage transmission lines, and larger interconnected back-bone power systems, we argue that renovating distribution networks should be given the priority in implementing Smart Grids. This is because distribution networks are where most end users, PEVs, and clean distributed generation (DG) sources are connected and distribution networks currently have much less capability of sensing, control, and management compared with transmission networks.

Optimal control and management of distribution networks become especially important as vehicle electrification infrastructures are being developed and implemented. The benefit of vehicle electrification is overwhelming. One recent study from Carnegie Mellon University [2] assesses life cycle greenhouse gas emissions from PEVs including energy use and greenhouse gas emissions from battery production. They found that PEVs reduce greenhouse gas emissions significantly compared to conventional vehicles**.** The Electrification Roadmap [3] developed by the Electrification Coalition and the consulting firm PRTM call for a national goal of seeing EVs account for 75 percent of all light-duty miles driven by 2040. A high PEV penetration will have a significant impact on distribution networks. On one hand, it will increase the electricity demand. It is estimated that 10% PEV penetration can increase the peak demand of electricity by more than 30% (see Fig. 4). This may add a significant burden on distribution networks. On the other hand, as controllable loads, PEVs can be controlled to smooth electricity demands over peak and off-peak loads. It can also be controlled to better accommodate renewable (and often uncontrollable) generation sources such as wind and solar. The key to both is new frameworks for optimal control and management of distribution networks.

Although optimal power flow (OPF) control has been widely applied in power dispatch in transmission networks [4], it seldom reaches the distribution level. Different aspects of optimization of distribution networks have been investigated including optimal deployment of capacitor and VAR compensation devices, section-closers, and distributed generation sources. To date, however, the system wide optimum operation of a distribution network has never been carried out due to the lack of motivation and supporting infrastructure. For Smart Grid to provide the critical functions described above, energy management of distribution networks will have to rely on reliable bi-directional data communications, real-time information processing, and effective control to coordinate heterogeneous generation sources, loads, and imported power from the upper (transmission or sub-transmission) level of grids. It is now necessary and technically feasible to take a holistic approach to the optimal energy management of distribution networks because the development of advanced metering infrastructure (AMI) including the deployment of smart meters has laid the foundation for information acquisition and communication. Moreover, advances in new power electronic converters such

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as solid state transformers capable of regulating real and reactive power flows [5], the expanding use of intelligent appliance and other controllable loads [6], and the application of home and office automation networks [7], all make distribution network optimization possible.

The concept of microgrids (MGs) has been proposed for managing local generation sources and load demands and interfacing DG sources to the distribution networks [8]. A MG is considered to have its own communication and control capability and it can be treated as a single control unit to the power grid. MGs have been reviewed as a promising platform to integrate the intermittent renewable sources and electric drive vehicles to the grid [9]. Currently, the impacts of MGs on the optimum operation of existing distribution networks are limited since the current MGs do not cover the major parts of distribution networks.

We propose a virtual microgrid (VMG) scheme to optimally control and manage distribution networks. As shown in Fig. 1, a distribution network can be virtually partitioned into VMGs based on the physical feeder topologies, protection zones, or other partition and reconfiguration methods [10]. The VMG scheme will not require the physical change in the connections of customers in a distribution network. The virtual network partitions are for the purpose of communication, information processing, control, and energy management. Unlike MGs often operated as an attachment or extension to the distribution network, VMGs form the entire underlying layer of the distribution network. The whole distribution system will then have a hierarchical structure of at least two different levels/layers: the distribution grid level, the VMG level, and possibly sub-VMG levels. Without loss of generality, we consider two levels for a distribution network in this paper: the distribution grid level and the VMG level. We will call the distribution grid level as "grid level" unless otherwise specified.

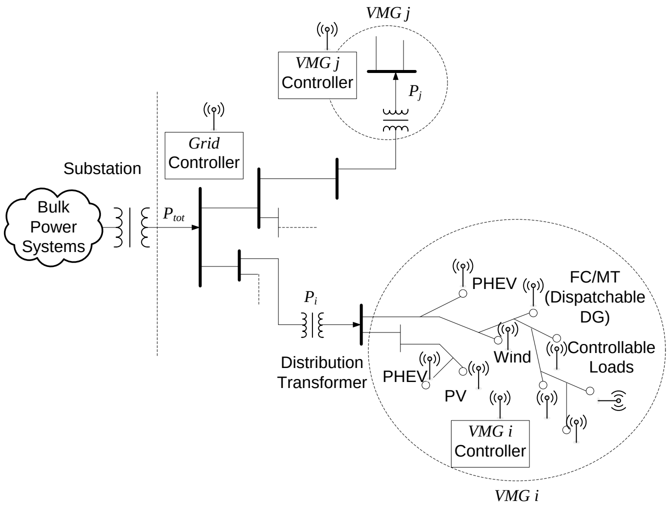

Fig. 1. A distribution network consisting of VMGs.

Our goal is to develop an optimal strategy to manage a power distribution system that can have heterogeneous distributed energy resources, PEVs, intelligent appliances, and other controllable or uncontrollable customer load demands. The energy management system will help the distribution network to (1) minimize the peak demand and load variations while allowing the maximum generation of renewable DG sources; (2) maximize the adoption of PEVs; (3) minimize the overall system power losses; (4) keep the system in the safe operation region, e.g., not overloading any feeder and the corresponding devices along the feeder and maintaining a good voltage profile throughout the distribution network; (5) increase the system reliability by isolating a fault area, allowing intended autonomous operation of VMGs, and restoring islanding and/or fault areas back to the grid; and (6) provide necessary information and grid support to the upper, bulk power system.

Our general approach is to carry out optimal control and energy management at two hierarchical levels: the grid level and the VMG level. At the grid level, the distribution grid controller makes optimal decisions and gives optimal commands to the VMGs in the system based on the command it may receive from the upper level power grid and the information collected from the VMGs. At the VMG level, each VMG controller manages the DG sources and load demands within its scope and reports its operating conditions and capability to the grid controller. In case a VMG controller cannot accomplish a certain task, it will also let the grid level controller know about its condition and constraint. The grid controller will then re-optimize the network (e.g., re-carry out the optimal load dispatch) based on the new constraints received.

We use two modeling frameworks in this paper to model distribution networks: stochastic hybrid machines (SHMs) and finite state machine with variables (FSMwVs). The reason for using these two models is that distribution networks and VMGs consist of both continuous variables such as voltages, currents, and wind speeds, as well as discrete events such as switch on, switch off, and occurrences of faults. They are typical hybrid systems with both continuous variables and discrete events. Many variables such as wind speeds, solar outputs, and electricity demands in the system are random or stochastic. SHMs are suitable models for such stochastic hybrid systems. FSMwVs can be viewed as an abstract model of SHMs, where the detailed dynamics of continuous variables are abstracted. Such an abstraction is necessary for control analysis and synthesis at a higher level. We will use SHMs at the VMG level and FSMwVs at the grid level.

Our approach will address the following challenges in developing control strategies for distribution networks: (1) The distribution network is a complex system containing heterogeneous generation sources and loads that have different operating characteristics and dynamics and require different control methods. For instance, the renewable generation sources are normally non-dispatchable while the output of fuel cells, Microturbine, or other dispatchable DG units can be controlled in a continuous range. (2) The controllable loads including PEVs can be turned ON/OFF or controlled in certain discrete steps while the conventional loads are normally uncontrollable. (3) The system contains both continuous and discrete event dynamics that need to be fully investigated before an optimal control can be developed. (4) The system possesses many uncertainties. The outputs of wind and solar DGs are determined by the wind speed and solar irradiation, which are stochastic variables. The number of PEVs connected to the system, and the power consumption of uncontrollable loads are all stochastic variables as well.

2. STOCHASTIC HYBRID MACHINES

At the VMG level, we propose a stochastic hybrid machine model for VMGs. SHM is an extension of hybrid machine model introduced in [11,12] to model hybrid systems. A stochastic hybrid machine is denoted by

$$SHM = (Q, \Sigma, D, G, \delta, (q_0, x_0), Q_m)$$

where Q is the set of discrete states; Q_m is the set of marked states; Σ is the set of discrete events; G is the set of guards; δ is the set of transitions; and D describes the continuous dynamics. D is often given by differential equations

$$\dot{x} = f_q(x, u, w)$$

where $x \in R^n$ are state variables; $u \in R^m$ are input variables; and $w \in R^p$ are random variables. The subscript q denotes the discrete state, because the continuous dynamics can change from one discrete state to another. q_0 is the initial discrete state; and x_0 is the initial condition of x. A transition in SHM is denoted by

$$(q, g \wedge \sigma, x = h(x), q') \in \delta \,,$$

where $g \in G$ is a Boolean condition on state variables, called guard. The transition is to be interpreted as follows. If at state q, the guard g is true and the event σ occurs, then the next state is q' and the values of variables x will be updated or re-initialized to $h(x)$. If g is absent in the transition, and then the transition takes place when σ occurs. Such a transition is called event transition. If σ is absent, then the transition takes place when g becomes true. Such a transition is called dynamic transition. If $x = h(x)$ is absent, then no variable is updated during the transition. It is known that any transitions can be decomposed into event transitions and dynamic transitions if needed [11].

Our approach to model VMGs using SHMs is as follows. First, we model each component in a VMG as a SHM, called elementary SHM. The overall VMG is then modeled as a composite stochastic hybrid machine (CSHM) using a parallel composition [11]:

$$CSHM = SHM_1 \parallel SHM_2 \parallel \ldots \parallel SHM_k \,.$$

To define CSHM, we assume that all transitions have been decomposed into event transitions and dynamic transitions and that a state variable can only belong to one of the SHMs. However, a state variable belonging to one SHM can be used in another SHM, that is, a guard in one SHM may depend on a variable belonging to another SHM. With these assumptions, CSHM is defined as

$$\begin{aligned} CSHM &= SHM_1 \parallel SHM_2 \parallel \ldots \parallel SHM_k \\ &= (Q_1, \Sigma_1, D_1, G_1, \delta_1, (q_{01}, x_{01}), Q_{m1}) \parallel \ldots \\ &\quad \parallel (Q_k, \Sigma_k, D_k, G_k, \delta_k, (q_{0k}, x_{0k}), Q_{mk}) \\ &= (Q_1 \times \ldots \times Q_k, \Sigma_1 \cup \ldots \cup \Sigma_k, D_1 \cup \ldots \cup D_k, G_1 \cup \ldots \cup G_k, \\ &\quad \delta_1 \times \ldots \times \delta_k, ((q_{01}, \ldots, q_{0k}), (x_{01}, \ldots, x_{0k})), Q_{m1} \times \ldots \times Q_{mk}) \\ &= (Q, \Sigma, D, G, \delta, (q_0, x_0), Q_m) \end{aligned}$$

where the definition of transition function $\delta = \delta_1 \times \ldots \times \delta_k$ is illustrated in Fig. 2 and 3. In the figures, l_i can be either an event ($l_i = \sigma_i$) or a guard ($l_i = g_i$). If $l_1 \neq l_2$, then the situation is illustrated in Fig. 2. For example, if the transition l_1 occurs at state (q_1, q_2), then the next state is (q_1', q_2). Variable x_1 is updated to $h_1(x_1)$ while x_2 is not updated. On the other hand, if $l_1 = l_2 = l$, then the situation is illustrated in Fig. 3. That is, if the transition l occurs at state (q_1, q_2), then the next state is (q_1', q_2'). Variables x_1 and x_2 are updated to $h_1(x_1)$ and $h_2(x_2)$ respectively.

To describe the behaviour of a SHM, we define a run of an SHM as a sequence

$$r = q_0 \xrightarrow{l_1, t_1} q_1 \xrightarrow{l_2, t_2} q_2 \xrightarrow{l_3, t_3} q_3 \ldots$$

where l_i is (the label of) the ith transition, t_i is the time of the ith transition, and q_i is the state after the ith transition. We denote the set of all possible runs of SHM as

$$R(SHM) = \{r : r \text{ is a run of SHM}\}.$$

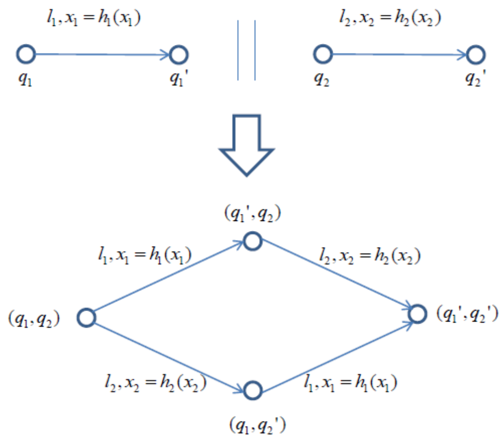

Fig. 2. Parallel composition when $l_1 \neq l_2$.

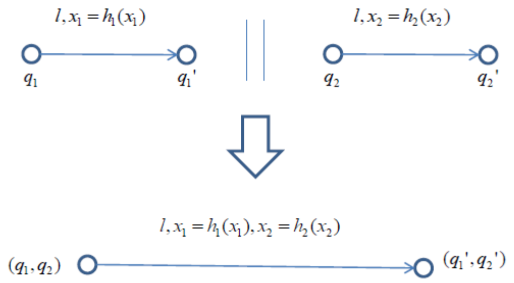

Fig. 3. Parallel composition when $l = l_1 = l_2$.

A trace of a run is the sequence of event transitions in the run

$$s = \sigma_1 \sigma_2 \sigma_3 \ldots .$$

That is, s is obtained from r by deleting the state and time information and dynamic transitions. The set of all traces of an SHM is a language denoted by

$$L(SHM) = \{s : s \text{ is a trace of SHM}\}.$$

This language is called the language generated by SHM. The language marked by SHM is defined as

$$L_m(SHM) = \{s \in L(SHM):$$
$$\text{the run of } s \text{ ends in a marked state } q \in Q_m\}$$

Since CSHM and SHM have the same structure, runs, traces, and languages for CSHM are defined similarly.

This hybrid system model has several advantages over traditional modeling methods: (1) It allows both discrete events and continuous variables; (2) it can handle both deterministic and stochastic variables; (3) it is a general model that can be used to model heterogeneous subsystems; (4) it is modular and robust by modeling each component separately, (5) it is flexible and amendable because components in the model can be added, removed, and replaced easily, and (6) it is scalable and can be used for large scale systems.

3. Finite State Machine with Variables

At the grid level, the grid controller does not need the detailed operation information from each VMG. Therefore, only abstracted and less detailed models of VMG need to be used at this level. We will use finite state machine with variables introduced in [13,14] for this purpose. A FSMwV can be viewed as an abstraction of SHM

$$FSMwV = (Q, \Sigma, V, G, \delta, (q_0, p_0), Q_m),$$

where Q, Q_m, and Σ are same as in SHM. We introduce variables into an FSMwV as follows: let $v \in V$ be a vector of variables, where *V* is some vector space. *V* can be either finite or infinite. A transition in FSMwV is defined as

$$(q, g \wedge \sigma, v = h(v), q') \in \delta.$$

It means that, if at state *q*, the guard *g* is true and the event σ occurs, then the next state is *q*' and the values of variables *v* will be updated or re-initialized to *h*(*v*). The transitions in a FSMwV can be classified as event transitions, dynamics transitions, and guarded event transitions as in SHM. To defined parallel composition of FSMwV, we assume that all transitions have been decomposed into event transitions and dynamic transitions and that a variable can only belong to one of the FSMwVs. As in SHM, a variable belonging to one FSMwV can be used in another FSMwV. The parallel composition is defined similarly to that of SHM.

$$CFSMwV = FSMwV_1 \| FSMwV_2 \| \ldots \| FSMwV_k$$

A run of an FSMwV is defined as

$$r = (q_0, v_0) \xrightarrow{l_1} (q_1, v_1) \xrightarrow{l_2} (q_2, v_2) \xrightarrow{l_3} (q_3, v_3) \ldots$$

The set of all possible runs of FSMwV is denoted by

$$R(FSMwV) = \{r : r \text{ is a run of FSMwV}\}.$$

A trace of a run is the sequence of event transitions in the run

$$s = \sigma_1 \sigma_2 \sigma_3 \ldots .$$

That is, *s* is obtained from *r* by deleting the state information and dynamic transitions. If an FSMwV is deterministic (which we assume throughout this paper), then a run is uniquely determined by its trace (this is not true for SHM). That is, we can reconstruct a run by looking at its trace and the FSMwV. The set of all traces of an FSMwV is a language denoted by

$$L(FSMwV) = \{s : s \text{ is a trace of FSMwV}\}.$$

This language is called the language generated by FSMwV. The language marked by FSMwV is defined as

$$L_m(FSMwV) = \{s \in L(FSMwV):$$
$$\text{the run of } s \text{ ends in a marked state } q \in Q_m\}$$

4. Hierarchical Control of Virtual Microgrids

In this section, we propose and illustrate a hierarchical control framework for distribution networks. The framework divides a distribution network into several VMGs that cover the entire distribution network. Each VMG is modeled by a SHM and controlled by a VMG controller. These SHM are abstracted as FSMwVs at the grid level and controlled by a grid controller.

The importance of control of distribution network can be illustrated by Figs. 4 and 5 . The base load curves in the figures show the power consumption in a typical summer day. We consider the impact of PEV on the distribution network, assuming 10% PEV penetration (i.e., 10% of the total demand in a day). Two cases are considered: (1) Without control, the charging can all start at 5:00 pm and finish in 4 hours. In this case, the load to the substation increased as illustrated in the upper curve in Fig. 4. It is clear that this cause additional peak load on the distribution network, which could be a serious issue on a hot summer day. (2) With control, the charging can be staggered between 10:00 PM and 6:00 AM. In this case, the additional load would have much less impact to the distribution network, as shown in the upper curve of Fig. 5.

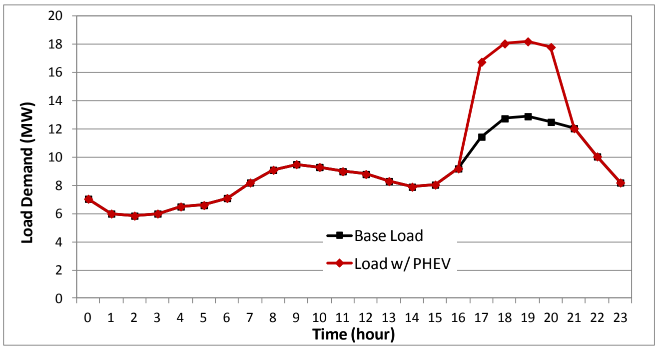

Fig. 4. Load on a distribution network with PHEV (no control).

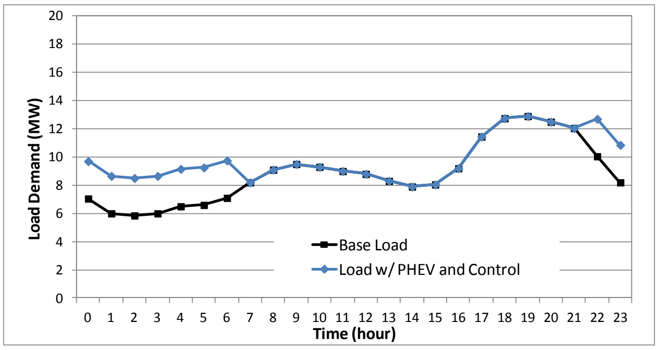

Fig. 5. Load on a distribution network with PHEV and control.

The control of a distribution network is achieved in a hierarchical fashion at two levels. At the lower level, each VMG is controlled by a VMG controller. We model a VMG as a CSHM which is the parallel composition of two SHMs shown in Fig. 6 and 7 respectively, that is,

$$CSHM = SHM_1 \| SHM_2 .$$

We consider a typical VMG which consists of some wind turbines and solar panels, a backup power generator, and a battery storage system. The event set of the CSHM is

$$\Sigma = \{w_{on}, w_{off}, s_{on}, s_{off}, b_{on}, b_{off}, e_{red}, e_{inc}, c_{red}, c_{inc}\},$$

where the events are w_{on}: turn wind generator on; w_{off}: turn wind generator off; s_{on}: turn solar generator on; s_{off}: turn solar generator off; b_{on}: turn backup generator on; b_{off}: turn backup generator off; e_{inc}: increase power for PEV charging; e_{red}: reduce power for PEV charging; c_{inc}: increase power of controllable load; c_{red}: reduce power of controllable load.

The power flow in the VMG is described by

$$P = P_w + P_s + P_b + P_G - P_u - P_c - P_e,$$

where P_w is the power generated by wind, P_s is the power generated by solar, P_b is the power generated by backup power generator, P_G is the power obtained from the grid, P_u is the power consumed by uncontrollable load, P_c is the power consumed by controllable load, and P_e is the power consumed by PEV.

Besides the powers, we use the following continuous variables in the stochastic hybrid machine.

(1) x_1: voltage in the VMG. We assume that the voltage varies around 110 V, depending on the balance of the power:

$$x_1 = 110 + \alpha(P),$$

where $\alpha(P)$ is a function of *P*. The node voltages in the system are certainly also a function of reactive power. Nevertheless, for the purpose of discussion, only real power is considered in this paper. In low voltage distribution networks with high *R*/*X* ratio, the voltage has a stronger relationship with real power (*P*) than reactive power. If *P*<0, then $\alpha(P)$<0, that is, if power supplied cannot meet power demanded, the voltage may drop. On the other hand, if *P*>0, then $\alpha(P)$>0. We also assume that as voltage drop, the demands will also drop. This serves as a mechanism to stabilize the voltage and balance the supply and demand. Formally,

$$P_u = P_{u,0} + \beta_u(x_1),$$

where $P_{u,0}$ is the nominal power of uncontrollable loads and $\beta_u(x_1)$ is a function of x_1. If x_1<110, then $\beta_u(x_1)$<0, that is, if the voltage drops, the power demand will also drop. On the other hand, if x_1>110, then $\beta_u(x_1)$>0. Similarly,

$$P_c = P_{c,0} + \beta_c(x_1) \text{ and } P_e = P_{e,0} + \beta_e(x_1).$$

(2) x_2: energy stored in the battery. If the battery is not fully charged (full) or completely discharged (empty), then x_2 is given by $\dot{x}_2 = P$.

(3) x_3: energy dumped. If the battery is full, then extra energy will be dumped. When the battery is full, x_3 is given by $\dot{x}_3 = P$. We would like to minimize x_3.

(4) x_4: energy generated by the backup generator. It is given by $\dot{x}_4 = P_b$. Since backup generator is usually less efficient, we would like to minimize x_4.

The VMG controller controls the VMG as follows. The desired state of the VMG is state 3 in Fig. 6, where both wind and solar generations are on. If the load P_u, P_c, P_e increases and the power P_G obtained from the grid exceeds the power allocated by the grid controller to this VMG, then the VMG controller will reduce the controllable load and hence move the SHM to state 4. In this state demand for controllable load is not met, that is, $P_c < P_{c,r}$, where $P_{c,r}$ is the demand for controllable load. If this is not enough, the VMG controller will reduce the power for PEV charging by unplugging PEV and hence move the SHM to state 5. On the other hand, if too much power is generated by wind turbines and solar panels, then the VMG controller will first turn off solar panels to move the SHM to state 2. If this is not enough, the VMG controller will turn off wind turbines and move the SHM to state 1. In the entire process, the battery serves as an energy storage device to buffer the random or unexpected changes in power flow. One objective of the control is to ensure the SHM never enters the undesired states 6 and 7, where the battery is full and empty, respectively.

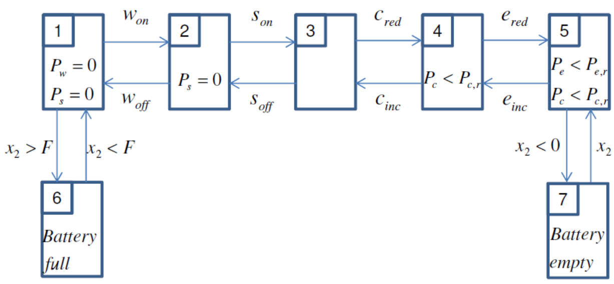

Fig. 6. SHM_1 for a VMG

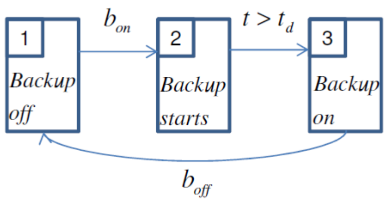

Fig. 7. SHM_2 for a VMG

The VMG controller also has control over the backup power generator. It can turn on and off the backup generator when necessary. Note that after the backup generator is turned on, it takes t_d seconds for it to start up and provide the backup power. Therefore, the VMG controller must anticipate the shortage of power ahead of time. For example the controller can turn on the backup generator when the state of charge of the battery reaches certain level. For more detailed discussion on control synthesis of hybrid systems, the reader is referred to [11].

At the higher level, each VMG is abstracted as a FSMwV:

$$CFSMwV_j = FSMwV_1 \parallel FSMwV_2,$$

where $FSMwV_1$ and $FSMwV_2$ are shown in Fig. 8 and 9 respectively. Assuming there are N VGMs in the distribution network, then

$$CFSMwV = CFSMwV_1 \parallel CFSMwV_2 \parallel ... \parallel CFSMwV_N,$$

The event set of the CFSMwV is given by

$$\Sigma = \{v^j_{red}, v^j_{inc} : j = 1,2,..., N\},$$

where the events are as follows. v^j_{inc} : increase power allocated to VMG_j, that is $v^j_{inc}, P^j_{alc} = P^j_{alc} + \Delta P^j_{alc}$; v^j_{red} : increase power allocated to VMG_j, that is $v^j_{inc}, P^j_{alc} = P^j_{alc} - \Delta P^j_{alc}$. $CFSMwV_j$ has the following variables. P^j_G : power consumed by the jth VMG, P^j_{req} : power requested by the jth VMG, P^j_{alc} : power allocated to the jth VMG, $P^j_{\min}$: minimal power requirement from the jth VMG, and $P^j_{\max}$: maximal power limit from the jth VMG.

A VMG controller must ensure that the power consumed by the VMG is within the limits set by the power allocated to the VMG, that is,

$$| P^j_G - P^j_{alc} | < e^j_1 .$$

This corresponds to state 0 in Fig. 8, which is the desired state. If the VMG controller cannot ensure this due to, say, failures, then $FSMwV_1$ will move to the undesired state 1.

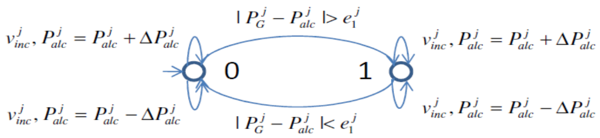

Fig. 8. FSMwV_1 for a VMG

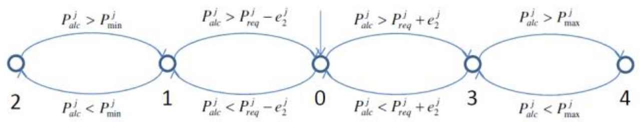

Fig. 9. FSMwV_2 for a VMG

To help the VMG controller achieve its goal, the grid controller will try to meet the power requested by the VMG controller as much as possible by increasing or decreasing the power allocated to the VMG controller, that is, we want:

$$| P^j_{req} - P^j_{alc} | < e^j_2$$

This corresponds to the desired state 0 in Fig. 9. If this is not possible, the grid controller will at least meet the minimal power requirement given by the VMG controller:

$$P^j_{alc} > P^j_{\min}$$

Otherwise, the CFSMwV will enter the illegal state 4. The power allocated shall also not exceed the maximal limit set by the VMG controller, that is,

$$P^j_{alc} < P^j_{\max}$$

Otherwise, the CFSMwV will enter the illegal state 1. The Grid controller will ensure none of the CFSMwVs will enter an illegal state. See [13] for a systematic synthesis of safety controllers for finite state machine with variables,

5. Conclusion

We investigated the problem of control and energy management of distribution networks with PEV for vehicle electrification. The main contributions of the paper are that it: (1) Proposed a virtual microgrid concept for control of distribution networks. (2) Proposed a hierarchical control scheme to control a distribution network, where controls are implemented at two levels: the VMG level and the grid level. (3) Used stochastic hybrid machines to model virtual microgrids. (4) Used finite state machine with variables to model the distribution network. (5) Illustrated the control scheme with a simplified distribution network.

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