Safety Control of PHEVs in Distribution Networks Using Finite State Machines with Variables

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***Abstract*—Transportation electrification is viewed as one of the most viable ways of reducing CO2 emissions and gasoline dependency. However, how to manage the dramatically increasing Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs) for the safety of distribution networks is still a vital challenge. To mitigate the influence of PHEVs, we propose that a distribute network be modeled by a Finite State Machine with Variables (FSMwV) method and then controlled by a corresponding safety controller. The calculation results of four scenarios verify the effectiveness of managing PHEVs by the FSMwV method. To manage a distribution network within a wider area, a supervisory control approach is proposed to cooperate with smart distribution network technologies. Therefore, the distribution network could be effectively managed with the safety controller on the bottom layer and supervisory control on the upper layer.**

***Index Terms*—Discrete event systems, finite state machines, PHEV, supervisory control, smart distribution networks.**

I. Introduction

PLUG-IN hybrid electric vehicles (PHEVs) have been widely considered as a viable solution to increase fuel economy and to reduce emissions of vehicles so that a higher level of sustainability in energy development and transportation can be achieved. Major auto manufacturers around the world are making PHEVs and competing for the future market of PHEVs. Wide adoption of PHEVs will affect power grids, particularly at the distribution level, in a variety of aspects including system operation, maintenance and design [1-4]. One of the major concerns is that the peak charging power of PHEVs may overload the distribution feeders and the corresponding devices such as distribution transformers [1]. This will cause both short term problems (i.e., undesired power quality and compromised system stability and reliability) and long term issues such as reduced lifetime of distribution transformers if they are overloaded [1], [5].

To address the aforementioned issues, more research is required not only on interfacing PHEVs to power grids, but also on developing a new paradigm of delivering electric power. The concept of smart grids has been proposed as the future electrical power generation and delivery infrastructure. A Smart Grid is envisioned as an intelligent and automated energy grid, which allows multiple paths of information and power flow and combines techniques in sensing/measurement, communication and control. Smart grids also open new paths to investigating the interconnection of PEHVs to grids using alternative methods such as safety control theories of discrete event system (DES).

DES theories have been explored for applications in power systems [6-9]. DES supervisory control was applied and reported in [6] for line restoration. Hybrid automaton and Petri Nets have been used to model power systems for handling problems such as parameter uncertainty and parameter estimation [7]. DES was used in [9] to describe cascading events such as blackouts in power systems. A number of potential power system control problems were discussed in [9]. However, most of the results obtained so far in this area are still preliminary. The relevance and applications of DES to power systems remain not so clear [8]. As one of the largest and most important hybrid systems in the world, power systems deserve more research efforts to better capture both discrete and continuous dynamics and the interactions between them so that more effective control methodologies for power systems can be developed.

The Finite State Machines with Variables (FSMwV)[1] method is a novel one to mitigate the problem of state explosion, from which the DES theory suffers a lot [10-13]. The FSMwV method employs both finite state machines and sets of variables in modeling discrete event systems. In [10-13], the authors focus on control synthesis using FSMwV. They first extend the scope of the traditional DES control to include both event disablement and event enforcement. Then they propose an offline safety control synthesis procedure that takes the advantage of both event disablement and enforcement in order to prevent the controlled system from venturing into the

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[1] It was previously called Finite State Machines with Parameters (FSMwP).

prohibited state space.

In this paper, a distribution network is modeled by an FSMwV. We consider both conventional uncontrollable loads and controllable loads (such as plug-in hybrid electric vehicles) by using appropriate variables to avoid possible state explosion. A supervisor is then designed to ensure the network is fully utilized and never overloaded. Four scenarios are analyzed and compared to show the management of this supervisor.

The rest of the paper is organized as follows: The FSMwV theory and corresponding safety control are introduced in Section 2. Then the modeling of distribution network based on the FSMwV is described in Section 3. In Section 4, the safety control of power distribution network is considered and analyzed by exploiting four different scenarios. In Section 5, the management of PHEVs is extended to smart distribution feeder system. Finally, the paper is concluded in Section 6.

II. Finite State Machine with Variables

A. *FSMwV Theory*

To mitigate the problem of state explosion, the method FSMwV is proposed to employ both finite state machines and sets of variables in modeling DES [12]. This method can represent a broader class of discrete event systems with far smaller numbers of discrete states. The FSMwV theory is first proposed in [10].

First, assuming a finite state machine (FSM) is described by a 5-tuple [14].

$$FSM = (\Sigma, Q, \delta, q_0, Q_m),$$

where Σ is the (finite) event set, Q the (finite) state set, δ: $\Sigma \times Q \rightarrow Q$ the transition function, the q_0 initial state, and Q_m the marked (or final) states.

In [10-13], to introduce variables into an FSM, let $p \in P$ be a vector of variables, where P is some vector space. More often, P is over the set of natural numbers. The guards $g \in G$ are also considered as predicates on the variables p. The transition function δ can be defined as a function from $\Sigma \times Q \times G \times P$ to $Q \times P$ as illustrated in Figure 1. The transition shown 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 will be updated to $f(p)$. Such a transition is denoted by $(q, g \wedge \sigma / p := f(p), q') \in \delta$.

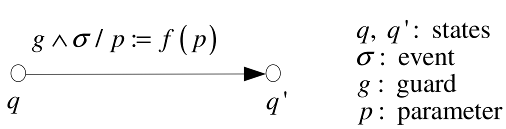

Fig. 1. A transition in FSMwV.

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 $p := f(p)$ is absent, then no variable is updated during the transition. In summary, a finite state machine with variables can be viewed as a 7-tuple

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

where p_0 is the initial value of variables at the initial state q_0.

Similar to FSMs, the parallel composition of several FSMwVs running in parallel is defined to form a composite finite state machine with variables (CFSMwV)

$$CFSMwV = FSMwV_1 \parallel FSMwV_2 \parallel \cdots \parallel FSMwV_n.$$

To define a CFSMwV, it is assumed that any variable can only be updated by at most one FSMwV. Variables that are not updated by any of the FSMwVs are updated by the un-modeled environment. In general, a variable updated by one FSMwV can be used in another FSMwV. That is, a guard in one FSMwV may depend on a variable updated by another FSMwV.

To describe the behaviour of an FSMwV, $(\Sigma, Q, \delta, P, G, (q_0, p_0), Q_m)$, the run of an FSMwV is defined as a sequence

$$r = (q_o, p_o) \xrightarrow{l_1} (q_1, p_1) \xrightarrow{l_2} (q_2, p_2) \xrightarrow{l_3} (q_3, p_3) \ldots,$$

where l_i is (the label of) the ith transition and (p_i, q_i) is the state and variable values after the ith transition. We denote the set of all possible runs of FSMwV as

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

In the DES theory, a legal specification $E \subseteq R(CFSMwV)$ is often used to specify the legal behaviour of the system modeled by a CFSMwV: if the legal behaviour is specified in terms of legal and illegal states, that is, a run r is legal if and only if it does not visit any illegal state, then the specification is called a static specification.

B. *Safety Control of the FSMwV*

Assuming that the system to be controlled is given by a CFSMwV:

$$CFSMwV = (\Sigma, Q, \delta, P, G, (q_0, p_0), Q_m),$$

and the safety requirement is given by a set of illegal states $Q_b \subseteq Q$. Note that the specifications in terms of illegal states are very general and cover a large class of practical situations.

The control objective is to make sure that the system never visits any illegal state in Q_b. There are two control mechanisms that can be used to achieve the control objective.

1) *Disablement*: Events in $\Sigma_c \subseteq \Sigma$ can be disabled by a controller. Events $\sigma \in \Sigma_c$ are called controllable events.
2) *Enforcement:* Events in $\Sigma_f \subseteq \Sigma$ can be enforced by a controller. Events $\sigma \in \Sigma_f$ are called enforceable events.

The behavior of the uncontrolled system is described by the set of runs generated by CFSMwV, R(CFSMwV). The legal behavior of the system is described by a subset of runs in R(CFSMwV) that does not visit illegal states:

$$E = \{r \in R(CFSMwV): r \text{ does not visit any}$$

illegal states in Q_b}.

We will treat all transitions, including event transitions and dynamic transitions, in a unified manner for simplification. To this end, we introduce an artificial uncontrollable event σ_u and extend the event set Σ to include σ_u.

To investigate the control in a generalized framework, we use generalized control patterns as follows [15]:

$$\Gamma=\{\gamma\subseteq \Sigma: \Sigma-\Sigma_c\subseteq \gamma \vee \gamma\subseteq \Sigma_f\}.$$

This set of control pattern allows two types of control: (1) Disabling some controllable events (that is, those in $\Sigma-\gamma$, if the first disjunction is satisfied); and (2) Enforcing some enforceable events (that is, those in γ, if the second disjunction is satisfied). This is a generalization from pure disablement of standard supervisory control.

The controller is defined as a mapping from the set of runs R(CFSMwV) to the set of control pattern Γ:

$$\psi: R(\text{CFSMwV})\rightarrow\Gamma.$$

The behavior of the controlled system, denoted by R(CFSMwV, ψ), is given as follows:

1) $\varepsilon \in R(\text{CFSMwV}, \psi)$, where ε denotes the empty trace (empty run);
2) Then inductively,

$$(\forall r=(q_o,p_o)\xrightarrow{l_1}(q_1,p_1)\ldots\xrightarrow{l_n}(q_n,p_n)\in R(\text{CFSMwV},\psi))(\forall l_{n+1}=g\wedge\sigma)$$
$$r\xrightarrow{l_{n+1}}(q_{n+1},p_{n+1})\in R(\text{CFSMwV},\psi)$$
$$\Leftrightarrow r\xrightarrow{l_{n+1}}(q_{n+1},p_{n+1})\in R(\text{CFSMwV})\wedge\sigma\in\psi(r).$$

Our goal is to synthesize a controller such that R(CFSMwV, ψ) = E if possible. It is shown in [11-13] that a necessary and sufficient condition for the existence of a controller is the controllability defined as follows**:** A set of possible runs $K \subseteq R$(CFSMwV) is controllable with respect to R(CFSMwV) and Γ if

$$(\forall r\in\bar{K})(\exists\gamma\in\Gamma)(\Sigma_{R(\text{CFSMwV})}(r)-\Sigma_K(r))=\Sigma_{R(\text{CFSMwV})}(r)-\gamma$$

where $\bar{K}$ denotes the prefix-closure of K, $\Sigma_{R(\text{CFSMwV})}(r)=\{\sigma\in\Sigma: r\xrightarrow{g\wedge\sigma}(q,p)\in R(\text{CFSMwV})\}$, and $\Sigma_K(r)=\{\sigma\in\Sigma: r\xrightarrow{g\wedge\sigma}(q,p)\in\bar{K}\}$.

From this and other results in [11-13], the least restrictive safety controller, that ensures the closed-loop system will never visit illegal states, could be derived. The strategy to synthesize the least restrictive safety controller is as follows: Initially, the system can be in any legal state of the system. However, the system may move to an illegal state via some transitions. If a transition is associated with a controllable event (i.e., transition $(q, g\wedge \sigma/p:=f(p), q')$ with $\sigma\in\Sigma_c$), then the transition can be disabled. On the other hand, if a transition is associated with an uncontrollable event, then we must prevent it from occurring by strengthening (or tightening) the conditions under which the system can stay in legal states. We call these conditions safety conditions. We use I_q to denote the safety condition for state q. The key to synthesizing the least restrictive safety controller is to update I_q iteratively. To do this formally, let us denote the number of iterations by k. Initially, we let safety condition $I_q(0)=T$ for all legal states $q\notin Q_b$ and $I_q(0)=F$ for all illegal states $q\in Q_b$. For a legal state $q\notin Q_b$, its safety condition $I_q(k)$ is updated as:

$$I_q(k+1)=I_q(k)\wedge(\neg(\bigvee_{(q,g\wedge\sigma/p:=f(p),q')\in\delta\wedge\sigma\notin\Sigma_c}(g\wedge\neg I_{q'}(k)|_{p:=f(p)}))$$
$$\vee(\bigvee_{(q,g\wedge\sigma/p:=f(p),q')\in\delta\wedge\sigma\in\Sigma_f}(g\wedge I_{q'}(k)|_{p:=f(p)}))).$$

This formula implies that the new safety condition will be true only if the old safety condition $I_q(k)$ is true and either there are no uncontrollable transitions leading to illegal states, $\neg(\bigvee_{(q,g\wedge\sigma/p:=f(p),q')\in\delta\wedge\sigma\notin\Sigma_c}(g\wedge\neg I_{q'}(k)|_{p:=f(p)}))$, or there are some enforceable transitions leading to legal states, $(\bigvee_{(q,g\wedge\sigma/p:=f(p),q')\in\delta\wedge\sigma\in\Sigma_f}(g\wedge I_{q'}(k)|_{p:=f(p)}))$.

Since Q is finite by definition, if P is finite, then the iteration will converge. When it converges, we have $I_q(k+1)= I_q(k)$. Denote $I^*_q=I_q(k+1)=I_q(k)$. Based on I^*_q, we can obtain the controller ψ:R(CFSMwV)$\rightarrow\Gamma$ as follows: Let $r\in R$(CFSMwV) be a run ending at (q, p). Then

$$\psi(r)=\begin{cases}\{\sigma\in\Sigma:(q,g\wedge\sigma/p:=f(p),q')\\ \in\delta\wedge\neg(g\wedge\neg I^*_{q'}|_{p:=f(p)})\}\cup(\Sigma-\Sigma_c)\\ \qquad \text{if } \neg(\bigvee_{(q,g\wedge\sigma/p:=f(p),q')\in\delta\wedge\sigma\notin\Sigma_c}(g\wedge\neg I^*_{q'}|_{p:=f(p)}))\\ \{\sigma\in\Sigma_f:(q,g\wedge\sigma/p:=f(p),q')\\ \in\delta\wedge(g\wedge I^*_{q'}|_{p:=f(p)})\}\\ \qquad \text{otherwise.}\end{cases}$$

Under this control, the closed-loop system will satisfies safety condition I^*_q for all legal state $q\notin Q_b$.

III. Distribution Network

In this section, we apply the above supervisory control to power grids that needs to accommodate more and more use of PHEVs. The FSMwV and supervisory control will be used to model a small distribution network and control the charging of PHEVs.

Let us consider a typical distribution network shown in Fig. 2. We assume that there are N nodes (or buses) in the distribution network and consider radial distribution networks in this paper. For each node i, all the conventional local loads are lumped together and denoted as $p_{i,i}$. All the power lines including transformers connected to *Node i* should not be overloaded. For example, for the local loads connected to *Node 2*, $p_{1,2}$, $p_{2,3}$ and $p_{2,2}$ all should be within their corresponding limits $p_{1,2,m}$, $p_{2,3,m}$ and $p_{2,2,m}$. We call $p_{1,2}$ the incoming power to *Node 2*, at the same time, $p_{2,3}$ and $p_{2,4}$ are called the outgoing powers. At each node, there is a power meter to measure the power of each line connected to the node.

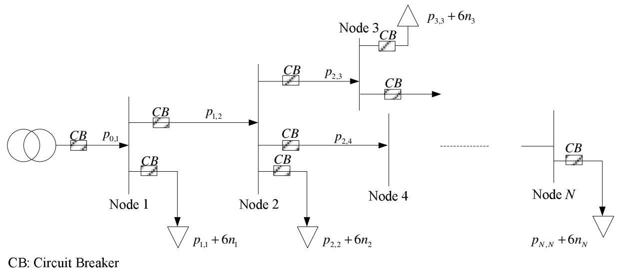

Fig. 2. A distribution network with N nodes.

The power loss of the distribution network is neglected. It is assumed that if the power of a power line is 10% over its limit, the circuit breaker (CB) will trip to protect the line and other devices. This constraint can be readily changed to any actual protection setting in a distribution network. For the purpose of simplification, only PHEVs are considered as controllable loads. The control target is to avoid the over loading type of tripping while satisfying all the load demands as much as possible. Therefore the only safety criterion considered now is the power limit of each node in the distribution network. Since the incoming powers and the outgoing powers are the summation of the local loads, the illegal condition can also be considered as the overload of every local load power line.

A PHEV load is assume to be $n_{i,i} \times m$, where $n_{i,i}$ is the number of PHEVs being charged at the node i and m is the power consumed by each PHEV at the unit of kilowatts (kW). Three scenarios were proposed in [2] to charge the PHEVs and one of them, $m=6kW$, is used in this paper. All local loads are calculated as conventional loads plus the PHEV load, that is, $p_{i,i}+6n_i$. For instance, the local loads at *Node 2* is $p_{2,2}+6n_2$. The control must ensure that all local loads connected to all nodes do not exceed their limits. For example, for the local loads connected to *Node 2*, $p_{2,2}+6n_2$ must be within its corresponding limit $p_{2,2,m}$.

Based on previous introduction, the FSMwV model for the distribution network is developed and analyzed in the next section.

IV. Model, Simulation and Analysis

In this section, four scenarios will be analyzed for the distribution network with and without PHEVs. Only conventional uncontrollable loads are considered in scenarios 1 and 2. On the other hand, the management of new PHEV loads is considered and compared in scenarios 3 and 4. The method described in Section II is used to calculate safety conditions I_q iteratively. $p_{i,i,m}$ is set as 100 kW. In scenarios 1 and 2, no PHEVs loads are considered in the distribution network, so that we could see the influence of the conventional load to the distribution network. The model is shown in Fig. 3.

The states set $Q_{i,i}$ contains three states representing load level: the marked state N is for $0 \le p_{i,i} < p_{i,i,m}$; O is for $p_{i,i,m} \le p_{i,i} < 1.1 p_{i,i,m}$; D denotes for the dangerous state and at D the circuit breaker will be tripped to protect the power line thereby moving the system to the illegal state J.

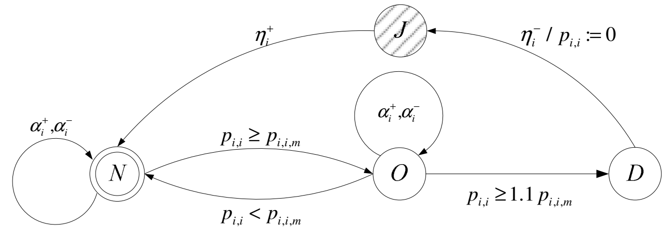

Fig. 3. Local load FSMwV model at node i for Scenarios 1 and 2.

Three dynamic transitions are defined correspondingly as: $N \rightarrow O$ when $p_{i,i} \ge p_{i,i,m}$; $O \rightarrow N$ when $p_{i,i} < p_{i,i,m}$; $O \rightarrow D$ when $p_{i,i} \ge 1.1 p_{i,i,m}$.

Four events in $\Sigma_{i,i}$ are defined as follows: α_i^+ is for "increase the conventional load"; α_i^- is for "decrease the conventional load"; the uncontrollable event η_i^- is for "trip the circuit switch" and η_i^+ is for "restore the power line". One variables, the conventional loads $p_{i,i}$ will be updated with the occurrence of corresponding events as: α_i^+ with $p_{i,i} := p_{i,i}+1kW$; α_i^- with $p_{i,i} := p_{i,i}-1kW$; η_i^- with $n_i := 0$ and $p_{i,i} := 0$.

A. Scenario 1

In this scenario, only the uncontrollable conventional loads are considered. In other words, it is assumed the increase of the conventional loads is uncontrollable and unenforceable, so that we could track the change of the loads by the FSMwV model. The results of the iteration process to calculate I_q at different states is given in Table I.

From Table I, it is shown that all the states status will be updated as illegal since the unlimited increase of the conventional loads. This table gives us the intuitively image of the change of the states status and the update process of the safety area I_q, even though the unlimited increase of the conventional loads is not practical.

TABLE I
Calculation of Iq at Four States for Scenario I

State / k	N	O	D	J
0	T	T	T	F
1	T	T	T∧ {¬(T∧¬F)} = F	F
2	T	T∧{¬[(T∧¬T)∨ (T∧¬T)∨ (p<100∧¬T)∨ (p⩾110∧¬F)]} = p<110	F	F
3	T∧ {¬[(T∧¬T)∨ (T∧¬T)∨ (p⩾100∧¬(p<110))]} = p<110	p<110∧ {¬[(T∧¬(p+1<110))∨ (T∧¬(p-1<110))∨ (p<100∧¬T)∨ (p⩾110∧¬F)]} = p<109	F	F
4	p < 109	p<108	F	F
…	…	…	…	…
112	p < 1 ***F***	p<0 ***F***	***F***	***F***

B. Scenario 2

In this scenario, it is assumed that the actual load $p_{i,i}$ will not exceed the 0.9 $p_{i,i,m}$=90 kW. This assumption is not unrealistic because we usually have some estimate of the maximum possible load. It means that the guard $p_{i,i} \leq 90\ kW$ is added to the event α_i^+. Then the results of the iteration process to calculate I_q at different states is given in Table II.

TABLE II
CALCULATION OF IQ AT FOUR STATES FOR SCENARIO II

State / k	N	O	D	J
0	T	T	T	F
1	T	T	T∧ {¬(T∧¬F)} = F	F
2	T	T∧{¬[(p≤90∧¬T)∨ (T∧¬T)∨ (p<100∧¬T)∨ (p≥110∧¬F)]} = p<110	F	F
3	T∧ {¬[(p≤90∧¬T)∨ (T∧¬T)∨ (p≥100∧¬(p<110))]} = p<110	p<110∧{¬[(p≤90∧ ¬(p+1<110))∨ (T∧¬(p-1<110))∨ (p<100∧¬T)∨ (p≥110∧¬F)]} = p<110 **I_O*= I_O(3)= I_O (2), stop!**	F	F
4	p <110 **I_N*= I_N(4)= I_N (3), stop!**		***F***	***F***

It is clear from Table II that the safety area of state O and state N both converge to 110. It means that the state O and state N will stay safe because of the existence of the guard of event α_i^+. Intuitively, the conventional uncontrollable load will not increase once $p \leq 110kW$.

The PHEVs loads are considered in the distribution network in scenarios 3 and 4. The model of the local load FSMwV$_{i,i}$ is shown in Fig. 4.

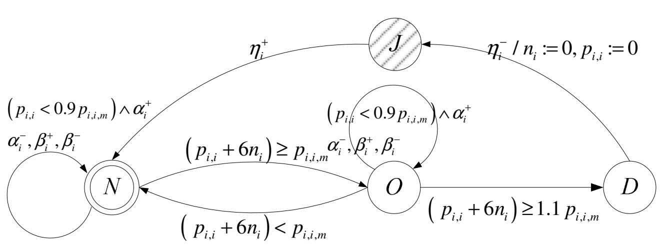

Fig. 4. Local load FSMwV model at node i for Scenarios 3 and 4.

The states set $Q_{i,i}$ contains three states representing load level: the marked state N is for $0 \leq (p_{i,i}+6n_i) < p_{i,i,m}$; O is for $p_{i,i,m} \leq (p_{i,i}+6n_i) < 1.1 p_{i,i,m}$; D denotes for the dangerous state and at D the circuit breaker will be tripped to protect the power line thereby moving the system to the illegal state J.

Three dynamic transitions are defined correspondingly as: $N \rightarrow O$ when $(p_{i,i}+6n_i) \geq p_{i,i,m}$; $O \rightarrow N$ when $(p_{i,i}+6n_i) < p_{i,i,m}$; $O \rightarrow D$ when $(p_{i,i}+6n_i) \geq 1.1 p_{i,i,m}$.

Six events in $\Sigma_{i,i}$ are defined as follows: α_i^+ is for "increase the conventional load"; α_i^- is for "decrease the conventional load"; β_i^+ is for "add one PHEV"; β_i^- is for "remove one PHEV"; η_i^- is for "trip the circuit switch" and η_i^+ is for "restore the power line". Two variables, the conventional loads $p_{i,i}$ and number of PHEVs being charged n_i, will be updated with the occurrence of corresponding events as: α_i^+ with $p_{i,i}$:= $p_{i,i}$+1kW; α_i^- with $p_{i,i}$:= $p_{i,i}$−1kW; β_i^+ with n_i:=n_i+1; β_i^- with n_i:=n_i-1; η_i^- with n_i:=0 and $p_{i,i}$:=0. We assume that charging PHEV can be controlled (disabled). Therefore, the controllable event set is $\Sigma_c=\{\beta_i^+\}$. We assume that the event in $\Sigma_f=\{\eta_i^+\}$ is enforceable.

As for the event β_i^-, we will consider two scenarios, one is uncontrollable and unenforceable (cannot unplug a PHEV) and the other is enforceable (can unplug a PHEV). We will discuss these two scenarios separately and compare their effects in the control.

Two assumptions for the FSMwV model of local loads are made as follows: (1) The occurrence of α_i^+ has a guard $p_{i,i}<p_{i,i,m}$ since the conventional local loads normally cannot exceed the limit; and (2) Initial limitation of the state O is set as: $(p_{i,i}+6n_i)<1.1p_{i,i,m}$.

C. Scenario 3

When the event β_i^- is considered as uncontrollable and unenforceable, the safety regions representing safety conditions I_q of states N and O are shown in Fig. 5 after 89 iterations. We do not show safety conditions I_T and I_D, because they are simple: I_T is always "False" and I_D is "False" after the first iteration since the transition from state D to state T is uncontrollable.

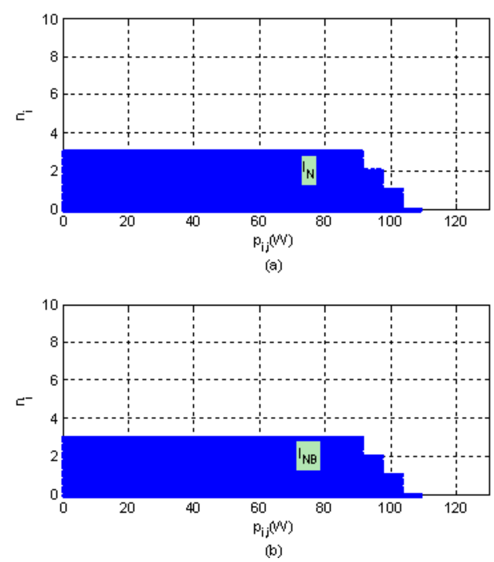

Fig. 5. Safety regions when β_i^- is uncontrollable for (a) State N, (b) State NB.

From Fig. 5, we can see that the safety regions of states N and O are both very small. Intuitively, this is because if the controller cannot unplug PHEVs, then it must be very conservative when it allows PHEVs to charge. The maximal number PHEVs can be charged is only 1. This is the case even if the conventional loads are very low. This means the capacity of the distribution network (and the generation capacity) is not fully utilized. This control is not suitable for the increasing use of PHEVs.

D. Scenario 4

When the event β_i^- is considered as enforceable, the safety regions representing safety conditions I_q of states N and O are shown in Fig. 6 after 32 iterations. The I_D is also "False" after the first iteration.

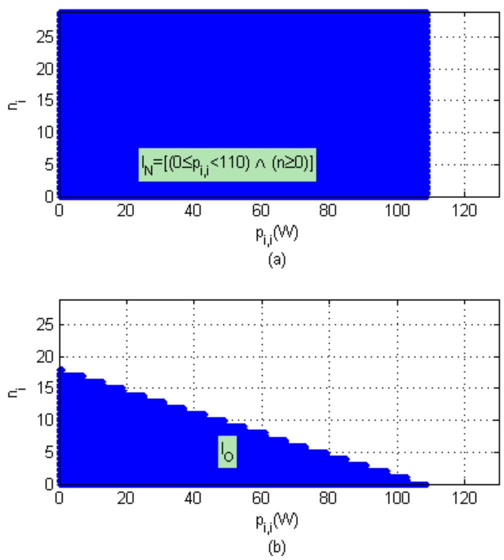

Fig. 6. Safety regions when β_i^- is enforceable for (a) State N, (b) State NB.

Fig. 6 shows that the safety regions of states N and O are much bigger than Scenario 3. This is because if PHEVs can be unplugged by the controller, then the control of charging of PHEVs becomes more flexible. The control strategy is based on two premises: to guarantee the safety of the system (to avoid entering the illegal states) and to give preference to uncontrollable conventional loads. This control not only ensures the safety of the distribution network, but also takes full advantage of its capacity. It allows as many PHEV to be charged as possible.

From the step by step analysis of the four scenarios, the change of the power grid is clearly shown and the management of the PHEVs at a node could be achieved by the FSMwV and corresponding safety control. Since the model of multi-nodes distribution network could be constructed by the composing operation as CFSMwV, the corresponding safety controller can be designed by the same method.

V. Supervisory Adaptive Control of Smart Distribution Networks

The research reported in [1] and [9] considered the management of PHEVs in traditional distribution networks As the smart grid technologies advance, it is necessary to study PHEV's interface to future smart distribution networks. We are facing great challenges in how to utilize the smart distribution network technologies (e.g., smart meters) to provide service to more PHEVs and how to reduce cost while developing a new paradigm of distribution networks with more reliable and flexible control strategies.

The development of advanced metering infrastructure (AMI) including smart meters has laid the cyber-physical base for information acquisition and communication in future smart distribution networks. Feeder Terminal Unit (FTU), distribution Transformer Terminal Unit (TTU) and Distribution Terminal Unit (DTU) are typical devices used in smart distribution networks, based on the IEC60870-5-104 communication protocol [16] which could work on Ethernet Passive Optical Network (EPON) communication system or 3G wireless communication system. Fig. 7 shows a simple example distribution grid with AMI infrastructure. As shown in the figure, zone H is a residential area and zone O is an office and business district. The circuit breakers CB_D, CB_O and CB_H are for the protection of the transformer, zone O and zone H, respectively. The protection settings of these circuit breakers are fixed since the design of the distribution grid. During the operation, they cannot be adjusted or adjusted frequently according to the change of the corresponding loads in a traditional way.

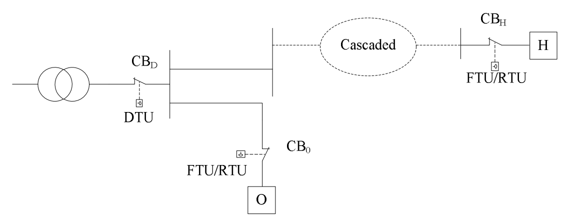

Fig. 7. Smart distribution network.

Since the PHEVs are moving around, they can cause load shifts among different zones in the network. For example, most of them may be parked in zone O at daytime and move to zone H at night. The load shifts in the network can cause the following issues:

For the movement of PHEVs， most of them are parked in the zone O in daytime and in the zone H at night, which cause two issues:

1) At the design stage. For a new distribution grid design, the settings and ratings of CB_H and CB_O should be set to handle possible charging peak demands of PHEVs. Based on the traditional peak demand design, the capacity of transformer and the setting of CB_D will be almost double what the actual need for PHEVs. As a result, the system investment will increase.
2) At the operation stage. For an existing distribution grid, with high penetration of PHEVs, a portion of the distribution grid may get overloaded for a period of time in a time due to PHEV load shift. This will cause some PHEVs not be charged or fully charged as needed. For the system shown in Fig. 7, both zones may see a need for upgrade if the total PHEV charging demand is over the limit of each them. However, the reality is that the chance for the two zones to have peak PHEV charging demands at the same time is almost zero.

The smart grid communication technologies make it possible for us to rethink the aforementioned problems. One way is to develop a supervisory control strategy to adaptively re-set the protection settings at different zones to accommodate the load changes. For example, for the system of Fig. 7, at day time, the load demand in the zone H may decrease while the load demand will increase in zone O. We can then lower the protection settings of CB_H increase that of CB_O. In the evening we can do in the opposite way to accommodate more PHEVs at zone H.

VI. Conclusion

In this paper, the implementation of FSMwV and the corresponding supervisory control was presented for the management of distribution networks with PHEVs. Based on the FSMwV theory, a distribution network with PHEVs was modeled and a safety control strategy was developed for the PHEV management. The calculation results of four scenarios showed the effectiveness of the proposed safety controller for PHEVs management in distribution networks. A supervisory control concept was proposed to adaptively change the protection settings to manage the entire distribute network by incorporating smart grid communication technologies. Future research will be extended to developing a two-layer control framework for distribution networks with PHEVs: safety control as the bottom layer and supervisory adaptive control as the upper layer.

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