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Multi-agent based distributed control of distributed energy storages using load data

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ABSTRACT

Peak power shaving is one of the important demand side management programs in the distribution systems. It can be achieved by shifting the demand and/or using the distributed energy storage systems (DESSs) which can be geographically located in the system equipped with the smart grid infrastructure for communication. In this paper, an agent-based distributed control (ABDC) scheme is proposed for real time peak power shaving using DESSs. In this control scheme, a distributed pinning consensus control scheme is developed to control and manage the power sharing among different batteries operated as agents while convergence in consensus is achieved. The medium voltage electricity consumption data of a practical distribution system is used to validate the effectiveness of proposed control scheme.

1. Introduction

In the future power systems, the deployment of smart grid technologies such as smart meters, automatic voltage regulators, etc., to improve the smart grid capabilities like grid optimization, self-healing, dynamic pricing, renewable energy integration, usage of storage devices will increase. Therefore, the electric utilities have to pay more attention in upgrading their information and communication technologies (ICT), termed as “soft grid”, which incorporates pervasive sensors, actuators, data networks, etc. Thus, there is a transformation of the modern power grid into a cyber-physical-system which requires extensive monitoring and control features. Also, advanced computational tools will be used for analysis of massive amount of data streams for efficient and reliable operational and planning decisions.

Data mining and pattern matching techniques are used to identify critical conditions in energy usage to develop controls for ensuring grid reliability. The major challenge in developing and implementing smart grid solutions is to create analytics on the distributed data generated in event processing for latency, scale and robustness problems. New scalable methods and tools are to be created for leveraging quality master data classes and analytics/application characteristics based on the historical smart grid data deluge. New control and operation schemes of smart grid need to be created for modernization of power usage coupled with the increased penetration of renewable energy sources (RESs) [1–5].

The applications of distributed energy storage systems (DESSs) can be useful for peak-load deductions at substations, wind and solar power smoothing, ancillary service provisions (such as frequency regulation, black start), improvement in distribution feeder reliability and low voltage (LV) load management [3]. To improve the life cycle of energy storage systems, an intelligent management scheme is designed in Ref. [6] for flexible sharing of power among different storage elements. A cooperative control scheme of the micro-sources and the energy storage system during islanded operation is implemented in Ref. [7]. The power outputs of a group of photovoltaics (PVs) in a distribution network are controlled using distributed control scheme such that all PVs are required to run at the same output ratio [8]. A distributed control strategy based on consensus algorithm is implemented to coordinate the energy storage units within the LV network for efficient voltage reduction [9]. The network loading is managed by using a consensus algorithm to share the required active power with the same ratio among different energy storage units [10]. A consensus based algorithm is proposed to solve economic dispatch problem in a distributed manner [11]. A consensus algorithm is introduced in Ref. [12], to determine the optimal incremental cost of charging rate for battery energy storages. A reputation-based secure distributed control methodology guarantees that all the

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well-behaving robots reach consensus in the presence of misbehaving robots [15].

In Ref. [16], authors discussed leader–follower distributed control scheme and proved that states of all agents converge to their leader provided that all agents are linked to the leader with neighbors as the system evolves. Leader-follower consensus problem for multiple agents with time-varying coupling delay and directed interconnection graphs is discussed in [17]. A neighbor-based rule for every agent to track a leader, whose states may not be measured, is developed. A convergence analysis in multi-agent system is carried out for time-invariant and time-varying topologies, in Ref. [18], of leader and followers' connections. A distributed control design for a leader–follower multi-agent system is considered in Ref. [19] under partial and noisy measurements, and time-varying directed network topology. Leader–follower consensus with some adaptive updating laws is proposed to estimate the information of unknown system matrices and the bounds of disturbance on-line [20]. A leader–follower consensus problem of multi-agent systems consisting of stationary leader and moving followers is discussed with static and switching topologies and communication time-delays in Ref. [21]. Leader–follower consensus control scheme is implemented in continuous-time single-integrator multi-agent system with multiplicative measurement noises while topologies are directed as fixed and switching [22]. Authors in Ref. [23] introduced a rescaling transformation and presented a new design freedom to stabilize the errors between the leader signals and follower signals.

In this paper, leader–follower distributed control scheme is explored and applied in a group of distributed energy storages for their equal utilization in a power distribution system. To achieve consensus in the leader–follower distributed control scheme, communication topology plays a major role. The communication topology has to be a spanning tree for this control scheme [14,15]. In real time operation, at different time intervals, the state of leader changes for getting the desired objective in the followers and hence leader's information state has also to be controlled. The work reported in Refs. [9] and [10] do not focus in getting spanning tree for communication topology. Also for real time operation, these do not ensure consensus among energy storages at a desirable equilibrium information state with and without communication failures, and with variable topologies. Also, these do not show any strategy for the cases of overcharging of batteries or discharging beyond batteries' depth of discharge (DOD). As the leader–follower control strategy is based on the equal participation of energy storages, an adaptive strategy is required to tackle the aforementioned cases. To the best of authors' knowledge, no literature which deal with communication with the nearest neighbors and minimum communication for leader–follower distributed control in power system, is available.

In this paper, a multi-agent based distributed control scheme is proposed for scattered DESSs for peak shaving in the distribution system. The proposed control scheme can work in real time to decide new charging or discharging strategies of various DESSs, for current time interval, while avoiding overcharging and discharging beyond DOD. A new scheme is introduced such that convergence in consensus among different battery agents with variable communication topologies is ensured. The other major contributions of this paper include

- A leader–follower pinning consensus control scheme for DESSs is designed for the system power mismatch.
- A communication protocol strategy among different DESSs is proposed to occur with minimum communication and communication with the nearest neighbors. Also, this strategy adapts itself on the failure of communication link between two battery agents.
- An approach is incorporated such that unfair participation of power among DESSs is allowed to avoid the DESS constraints violation.
- The proposed control scheme does not perform online estimation of state of charge (SOC) of a battery during charging and discharging cycles but works on its maximum and minimum allowed energy and its rated power.

The organization of the paper is as follows. In Section 2, preliminaries are discussed and problem formulation is outlined. In Section 3, an overview of ABDC is provided. In Section 4, distributed pinning control schemes are discussed. Section 5 discusses power and energy management of DESSs. Section 6 demonstrates the simulation of the case studies. Finally, Section 7 concludes the paper.

2. Preliminaries and problem formulation

2.1. Preliminaries

Let $V=\{1,...,n\}$ be a set of nodes and $E \subseteq V \times V$ be a set of edges of a weighted digraph (or directed graph) $G_n=\{V,E,A\}$. $\boldsymbol{A}=[a_{ij}]$ is the adjacency matrix with non-negative adjacency elements a_{ij} and $a_{ii}=0$ for $i=1,2,...,n$. The ed_{ij} is the directed edge, from node i to node j, of digraph G_n. The adjacency elements of an edge ed_{ji} is positive i.e., $a_{ij}>0$ if and only if $ed_{ji} \in E$. A digraph is undirected if $a_{ij}=a_{ji}$ for $\forall i,j \in \{1,2,\ldots,n\}$.

A group of agents represents the nodes in a digraph G_n and unidirectional information exchange links among agents correspond to edges of the graph. An interaction topology among the battery agents shows the communication pattern at some particular time and is designed by using the digraph G_n. In adjacency matrix $\boldsymbol{A}$, an element a_{ij} is greater than zero, if and only if, node i gets information from node j. A directed tree is defined as a directed graph in which every node except the root has exactly one parent. A directed (rooted) spanning tree of the digraph G_n is a subgraph such that this subgraph is a directed tree and consists of all the nodes of G_n. A spanning tree of G_n consists of n nodes and n-1 edges and a path exists from root node to every other node. Thus, root node can send information to every other node.

The $n \times n$ Laplacian matrix $\boldsymbol{L_n}=(l_{ij})$, associated with the adjacency matrix $\boldsymbol{A}$ of a digraph G is defined as given below:

$l_{ij} = -a_{ij}, i \neq j$ and $l_{ii} = \sum_{j=1, j\neq i}^{n} a_{ij}$

According to the definition of $\boldsymbol{L_n}$, it is ensured that in any row, $\sum_{j=1}^{n} l_{ij} = 0$ and it is an asymmetric matrix of a digraph. There is an aim to control all the nodes such that information states of all agents of a group converge into one single state [13,14].

2.2. Problem formulation

In the power distribution system, the DESSs are proposed for installation in order to achieve reliable peak shaving operation, in real time, at the distribution substation. As the demand changes, the DESSs come into action. During off peak hours, these can be charged and in peak hours, these can be discharged. Controlling and managing scattered DESSs with different ratings is a challenging task. Therefore, the objective is to design a leader-follower consensus distributed control scheme for controlling all DESSs to cater dynamic imbalance created due to change in demand in the distribution system.

The control objective is to achieve the fair participation by all DESSs to its maximum utilization level. A virtual agent, a centralized pinner, is introduced to guide all agents in the group toward the global objective asymptotically. The dynamics of this agent represents a dynamic high level control scheme to generate a