Electric Power Systems Research 134 (2016) 80–87

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Decentralized Active Demand Response (DADR) system for improvement of frequency stability in distribution network

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ARTICLE INFO

Article history:
Received 25 May 2015
Received in revised form
29 December 2015
Accepted 13 January 2016
Available online 3 February 2016

Keywords:
System stability
Demand management
Decentralized system

ABSTRACT

The concepts of decentralized demand response systems are present in the state of the art literature, however, the material is limited to general ideas and possible system services. In this paper the original and application ready proposition of Decentralized Active Demand Response (DADR) system realization is presented in the form of a stochastic control algorithm. Such an approach to the system description enables simulation investigations of the DADR system as an element of dynamic stability improvement of an electrical energy distribution network. The results obtained from simulations have confirmed that the proposed DADR solution, because of its high dynamic response in dealing with disturbance phenomena, might be used as part of both primary and secondary Load Frequency Control in electrical power systems.

1. Introduction

The decentralization and decarbonization of power systems, induced by legal requirements aimed at enhancing competition on the energy market, require urgent development of novel technologies as well as elaboration of up to date mechanisms in control services to ensure stability of the power systems. This is especially important in the context of the dynamic growth of implementations of renewable energy sources with disturbed output power characteristics. Observed investments in the energy production sector are accompanied by development of Demand Side Response/Management (DSR/DSM) services [1–10], which would play the role of "hot" – operating or "cold" – intervention power reserves [11]. Demand control, based on the temporal reduction of load power or scheduling of a load operation, contributes to the flattening of the daily load profile of the power system which, in turn, leads to the improvement of energy efficiency. An application of these services enables reduction of the electricity prices, especially during peak load hours, avoiding contracting of expensive peak power.

In the presented paper the DSM/DSR idea of power system unload has been adopted for realization of primary and secondary control tasks. Realization of both tasks simultaneously requires an unload response time unattainable for DSM/DSR systems. The proposed Decentralized Active Demand Response (DADR) system offers the required high dynamic response, because the decision over the load disconnection is made almost immediately on the basis of the main frequency measurements taken at the load connection point, without the need for communication with other devices. In this context the DADR control technique can be considered as a part of Load Frequency Control (LFC) supporting existing Automatic Generation Control (AGC) systems in active disturbance rejection [12]. It can also be a part of emergency load shedding system preventing the electrical power system (EPS) from cascaded failure [13,14] or, due to deep dispersion and fast response, preventing the distribution system from wider intentional local blackouts in this case. The differences and similarities between DSM/DSR and DADR systems are more broadly described in the following sections.

Fig. 1 shows a simplified scheme for an electric grid consisting of the DADR controlled load.

The originality of the concept presented in the paper relies on the proposition of the particular DADR control algorithm, in contrast to general descriptions of such systems presented in state of the art subject matter literature [1,2,5,15–19], proposed algorithm is capable of operating without necessity of assumption regarding distributions of DADR controlled devices [20]. Detailed mathematical descriptions have enabled simulation investigations of the DADR system properties in primary control processes of power system dynamic states [11,4,21,22].

The stochastic DADR control algorithm presented in the paper constitutes the base for elaboration and pilot implementation

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http://dx.doi.org/10.1016/j.epsr.2016.01.007
0378-7796/

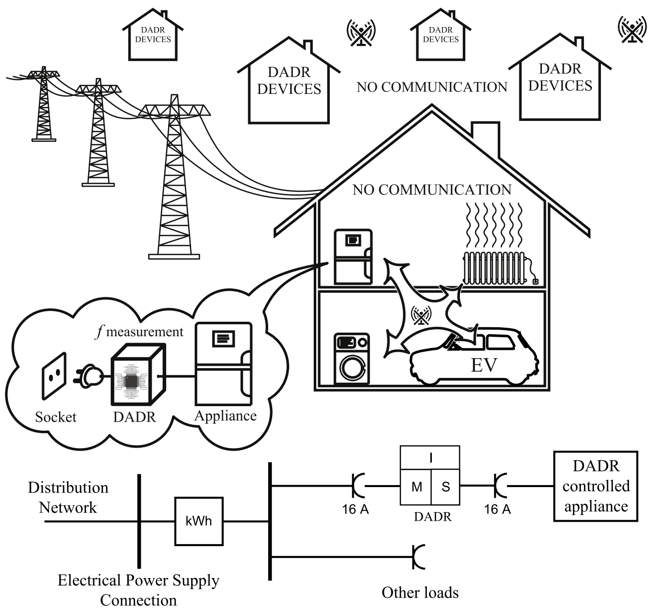

Fig. 1. Simplified scheme of installation equipped with DADR.

(1000 DADR devices) of the distributed demand control system enabling operation as part of the primary regulation [17]. Investigations as well as the practical verification of the DADR system services are supported within the framework of the national project – GEKON (Generator of Ecological Concepts). The main objective of the project is to investigate and develop the integrated solution for local, self balancing and self healing distribution area situated on Hel Peninsula in northern Poland.

2. Centralized DSR/DSM systems

In power systems with DSR/DSM functionality, power reductions are usually stimulated by market mechanisms, e.g., tariffs (fee reduction or executive command fees). Some significant drawbacks of these systems are the lack of guaranteed capacity of available control power for preventive actions (e.g., power system stability assurance) and a limited reaction time on the demand side. The delay in response time of the centralized system is caused by transmission of the information concerning demand for power reduction to the aggregation centers, their responses and finally the initiation of the power reduction. For this reason, such centralized systems are not suitable for primary control of the power system, where e.g., according to the regulations, typical for UCTE countries, the required reaction time should be shorter than 10 s [23]. While the main purpose of DSR/DSM systems is power system balancing, leading to energy efficiency improvement as well, nonetheless they are often treated as a part of the LFC systems, where unloading of the system generators could be realized by both reduction of the load power and connection of distributed generation capacities or energy storage [24,15,25]. The subject matter literature presents various methods of DSR/DSM service realization installed on the consumer side, including HAN (Home Area Network) arrangements [16], co-generation and HVAC (Heating Ventilation and Air Conditioning) systems and recently electric vehicle charging infrastructure providing V2G (Vehicle to Grid) services [26,21,27–30]. Unfortunately, in most cases the achieved periods for DSR/DSM service activation exceed the threshold value for primary control. However, taking into account the ability to provide the services for a period longer than 15 min these systems might realize secondary control using DSR/DSM systems.

3. Concept of Decentralized Active Demand Response (DADR) system

3.1. Technical and functional assumption of DADR system

The DADR is a distributed system without the communication between its individual elements. The basic idea of DADR is not new [31–34] but still there is no generally accepted DADR realization standard and many papers concerning this topic have been issued recently [13,35,5]. In the proposed system initiation of load reduction depends on the frequency fluctuations measured and analyzed at the point of the DADR installation. The DADR elements will be installed on the customer side, physically, and the individual DADR element will constitute an interface between the distribution network (electrical installation) and supplied devices, e.g., "cold" appliances, accumulation and storage heaters, HVAC, laundry dryers, EV chargers, etc. In this matter, especially thermostatically controlled loads, due to their population and thermal inertia, seem to be well suited for DADR control [36]. It is foreseeable that the aggregated regulative power of DADR controlled devices will strongly depend on the financial incentive schemes, introduced by distribution system operators or service aggregators such as Energy Saving COmpanies (ESCO).

Currently, the proposed DADR service can be realized as active intermediate sockets, while future proposed functionality of DADR elements would be implemented in control modules of Smart Appliances. The structure of individual DADR devices comprises three main blocks, presented in Fig. 1:

- measuring block *M*, responsible for frequency measurement according to primary regulation requirements (accuracy higher than 10 mHz, total measuring time between 0.1 s and 1 s) [23];
- decisive-executive block *S*, equipped with an element realizing power reduction and activating operation, when frequency fluctuation exceeds the threshold value characteristic for primary regulation, i.e., $f > 20$ mHz [23];
- inventory block *I*, serving for device activity registration in the frame of the DADR system, for the purpose of settlement and limitation of the given device activations.

Additional assumptions concerning DADR functionality:

- "soft" load/unload action, preventing degradation of network operation in respect of dynamic conditions of distribution, which might be caused by oscillations induced by a self-synchronization effect of DADR controlled loads [37], especially after the cessation of a disturbance and the simultaneous reconnection of a large number of working devices;
- an equal, fair share of individual DADR controlled loads in system services (legal requirement) obtained by unification of maximum permissible number of activations in specified unit of time;
- minimization of DADR application side effects, such as degradation in comfort of use of DADR controlled equipment and reduction of their lifetime, by intentional blocking of the DADR activation under circumstances specific for given type of load.

The developed system should assist existing primary regulation of generators and overfrequency control systems of micro-sources connected to the grid by grid-tied power electronic interfaces which meet the requirements of the recently issued standards [38].

3.2. Analytical model of a power system with DADR

The central feature of the proposed model, elaborated for the evaluation of an influence of DADR technology on frequency regulation, is the function describing the dependency between the