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# Multi-agent based distributed voltage regulation scheme with grid-tied inverters in active distribution networks

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ABSTRACT

Due to the increasing penetration of distributed generation, large voltage fluctuations are becoming a problem to the distribution network operators. In this paper, the voltage problem is mitigated using smart grid technologies. A multi-step distributed voltage control method is proposed that utilizes the coordination of reactive power control (RPC) and active power curtailment (APC) methods of inverters, while using node voltages, loading and photo voltaic distributed generation (PVDG) output power as the decision making entities. Multi-agent system (MAS) is utilized to keep the method fully distributed and autonomous, in order to improve the latency of response to voltage violations. The proposed scheme incorporates the least data for voltage control strategies. The effectiveness of the proposed technique is authenticated through numerical simulations on a typical Finnish medium voltage distribution system. The results show that the proposed MAS based coordinated RPC and APC of inverters will keep the voltage value of nodes within the statutory limit, with least curtailment possible.

## 1. Introduction

Nowadays, photo voltaic distributed generation (PVDG) is abundant in distribution systems and its penetration will increase in the near future. With the introduction of PVDGs and their inherent intermittent nature, voltage fluctuation problem is becoming common, due to the bidirectional flow of power in the distribution networks [1]. Traditionally, the centralized voltage control approach is opted for, which can be divided into two categories: rule based and optimization based algorithms. Mainly, on-load tap changer (OLTC), static VAR compensators (SVC's or STATCOM's) and real and reactive power control of PVDGs constitutes the controllable entities that are adopted in different combinations to eradicate the problem of voltage statutory band violation. Furthermore, these devices are designed to operate for the unidirectional flow of power, which is not the case in the modern distribution networks. The rule based algorithm is applied for OLTC tap operation for voltage violations in Refs. [2,3]. But the frequent tap changing is infeasible, so the algorithm was further improved by introducing the real and reactive power control of PVDGs [4]. The optimization based algorithms are discussed in Refs. [5–7]. Integer optimization, linear algorithm and Tabu-search algorithm are employed to yield the optimal solution to avoid voltage values outside of the permissible limits.

Voltage control architectures (VCAs) are also to be revised with the penetration of PVDGs in the distribution system. In previous studies, VCAs are divided into centralized, hybrid and distributed architectures. The control strategy optimization and peaking of the performance were achieved with centralized VCA in Refs. [8–10]. They not only make use of the data gathered from the whole distribution system but also take real time optimality into account. The main short comings include the single point failure problem, a large number of monitoring devices for up-to-date data, strong communication network and powerful control center. Moreover, the control schemes tend to become complicated with the network meshing, large data overhead and its computation. As for hybrid architectures in Refs. [11–13], the balanced approach is utilized, to benefit from pros of both centralized and distributed VCAs. Ref. [11] discusses the artificial neural network concept utilizing SVCs for local control, while OLTC provides supervisory control. Load forecasting is also used to make optimized utilization of substation and feeder capacitors [12]. PVDGs are operated as localized controllers under the direct command of the distribution management system in Ref. [13].

With the recent research on the smart grid technologies, autonomous distributed voltage control (DVC) algorithms can be proposed that are based on agents and have the ability to keep the voltage within the permissible band of ±10% of the nominal

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voltage, with minimal computational overhead and minimal data input from the network. DVC architectures benefit from the local data to make decisions without compromising the autonomy and reliability of the control system. Agents are the autonomous entities capable of making decisions and completing their tasks in a robust manner. Multiple agents working in cohesion to achieve the greater goal comprises multi-agent system (MAS). The agents' communication with each other makes the system proactive, robust and reactive to external stimuli. Ref. [14] makes use of the remote terminal units (RTUs) as agents at the DG vicinity. Maximum and minimum voltage of the feeder are estimated by using the readings of the RTUs and are updated by others upstream RTUs, while communicating with the controlling device. Moreover, the communication between RTUs is hierarchical (from last RTU of network to the voltage regulator vicinity). Flat architecture (communication between agents without any hierarchy) implementation will be more robust in handling the voltage fluctuations. Ref. [15] uses, iterative negotiations among distributed agents before corrective actions are applied on the distribution feeders. Moderator agent contacts all the control agents in the network for their sensitivity to the violated node and their set points. Based on the response from all the agents, decision about the reactive power support is made and implemented. This process continues till the voltage of the violated node is within the limits. Ref. [16] utilizes generator agents (GAs) and load agents (LAs) for voltage control during catastrophic disturbances. Firstly the LA with the voltage violation will contact the GA of the same region and update about the voltage value at the vicinity. Upon receiving the request, GA will ask for proposals from the other GAs of the network that contains their sensitivity and reactive power reserves. Later assign the most sensitive GA, the reactive power required for voltage regulation and the process continues till the voltage support is provided or the limits are reached. Both methods proposed in Refs. [15] and [16] will take more time for the optimal solution due to excessive communication between agents. Ref. [17], has introduced a token based approach, which visits each node of the network for voltage control. LAs are operated with decision making block and are able to remove violation by requesting reactive power support from the downstream control agents. This approach uses less communication between agents but the downstream control agents are providing maximum voltage support and the control agents closer to the primary substation have the least contribution in the control strategy.

This paper proposes a distributed voltage control method, utilizing the MAS architecture that makes the voltage control completely autonomous. This method aims to utilize minimum data of the system to make control decisions, with minimum latency. A token transversal method is used for communication. Token is represented by the tuple sequence as presented in Ref. [18]. A bi-stage token transversal method is proposed. First token collects the data of the network, about all the agents and their set points and stores it in Black-Board Memory (BBM), which is shared among all the agents to make decisions. It reduces the large number of iterations for collecting the data at the instant of voltage violation. Second token then removes the violation by allowing LAs to take the steps required for voltage regulation, utilizing flat architecture. The actor that is the main focus of this paper is PVDG, for which a distributed coordinated voltage control (DCVC) strategy between different reactive power control (RPC) methods and active power curtailment (APC) methods is proposed. RPC of the grid tied inverter (GTI) can optimally mitigate the voltage fluctuation problem while utilizing different droop characteristics. But once the voltage violates the critical limit and also the RPC capability of the inverter is exhausted, agent can opt for APC method. The proposed DCVC scheme is verified by simulations on a typical Finnish medium voltage distribution network and sensitivity analysis is conducted with variable PVDGs penetration and loading.

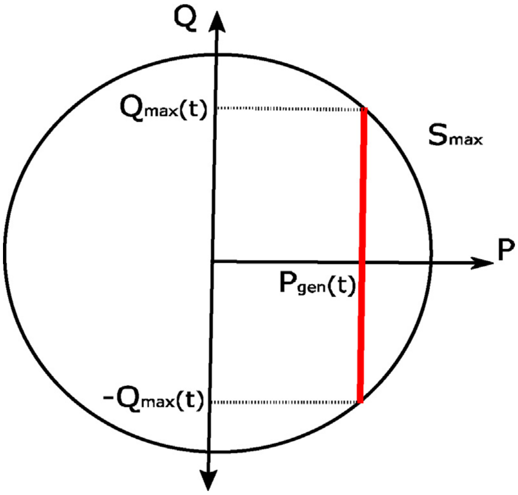

**Fig. 1.** Inverter reactive power capability curve.

Section 2 presents the proposed distributed coordinated algorithm of RPC and APC for GTIs. Section 3 provides the MAS based architecture, comprising token transversal through network, for the implementation of the proposed distributed voltage control of inverters. Section 4 describes a case study that is conducted on a test network and the results of the simulation are discussed and compared with the existing RPC methods. Section 5 discusses the practical implementation relating communication latency among agents and future works. Finally, the paper concludes in Section 6 with a brief review of the proposed method and the main findings of the performed simulations.

## 2. Distributed voltage control algorithm based on RPC and APC co-ordination

The devices like OLTC and SVCs are liable to failure and tap changing cannot be done frequently. Other options for PVDGs integration would be the dedicated feeders and energy storage devices, which are effective but not economical [19–21]. So recent research is concentrating on RPC of the inverters to optimally mitigate the voltage fluctuation problem. Till date, the proposed GTI characteristics include fixed Power Factor (PF) control, PF(P) control (PF varies with the real power input of PVDG),Q(U) control (control dependent on node voltage) and PF(U) control (PF varies with the node voltage) [22–24]. On the contrary, if RPC of inverter is not enough to remove the voltage violation, APC can be employed i.e. P (U) control (decrement in real power output of PVDG as a function of measured node voltage).

RPC of PVDG arises from the capability of inverter. As inverter, most of the time, operates below the rated power output, so RPC capability is always available. Apparent power of the inverters limits the maximum reactive power capability during voltage fluctuations. Real power of PVDG sets the $Q_{max}$, that can be supplied or absorbed at a particular generation point of PVDG, as shown in Eq. (1) and Fig. 1.

$$Q_{max}(t) = \sqrt{S_{max}^2 - P_{gen}^2(t)} \tag{1}$$

RPC droop characteristics are usually opted for voltage fluctuations. But only one droop characteristics might not be able to fully mitigate the voltage variations caused by the intermittency and high generation periods of PVDGs. The proposed DCVC algorithm will utilize Q (U), PF (U) and P (U) droop characteristics, dependent on the power generation value of PVDG, as well as the node voltage. It dynamically co-ordinates among the various droop char-