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Voltage Support for Critical Buses with Consensus Control of Electric Springs in Distribution Systems

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Abstract: In modern society, some energy consumers have a higher requirement on power quality than others and technological advances can allow for this. However, at the distribution level, as more renewable energy penetrates into the system and increases the voltage fluctuations which maybe unacceptable for the critical customers. The voltage fluctuation problem of such critical buses is hard to solve by traditional methods. With the introduction of the new smart load device, the electric spring, the network voltages of the distribution system with high renewable penetration can be better regulated. This paper proposes a voltage management scheme for the critical buses to maintain their desired voltage profile. In the control scheme, the voltage regulation responsibility is shared among the electric springs (ES) in a distributed way via consensus control, which is suitable for a system with limited communication capabilities. The proposed operation method of the ES is not constrained by the network topologies while compensating the inflexibility of traditional voltage control methods, such as tap-changers and capacitor banks. The proposed management scheme is verified on a modified IEEE 15-bus distribution network. The results show that the ES can work together to maintain the voltage of the critical buses by sharing the responsibility in the proposed scheme.

Keywords**:** Distribution System, Electric Spring, Voltage Management, Consensus Control

1. INTRODUCTION

IN recent years, the penetrations of renewable energy like wind and solar are increasing significantly in both developed and developing countries for decarburization. By 2030, wind and solar power could avoid 170 megatons of CO2 per year in the United States alone (Hart et al., 2012). According to (Izadian et al., 2013), the individual energy management users will reach 63 million by 2020. We can see that renewable distributed generation (DG) is getting closer to common use through many countries where working incentives and policies have developed to encourage use of renewable energy.

In a conventional distribution system, voltage regulation is performed to overcome the voltage drop along the feeder by typical means such as Load Tap Changer (LTC) and Capacitor Banks (CB). Classic control algorithms and device models were proposed to keep the system within constraints (Roytelman et al., 1995). However, the actions of LTC and CB are not flexible enough to mitigate the voltage fluctuations (Garcia et al., 2001). In some cases, the critical customers require a stable voltage supply, which is difficult to be realized by conventional operation methods. Especially in modern distribution systems with significant renewable energy penetration, the high intermittent nature of the supply causes increased number of tap operations and capacitor switchings (Valerde et al., 2013) (Ranamuka et al., 2014) (Baghsorkhi and Hiskens, 2012a) (Baghsorkhi and Hiskens, 2012b). Meanwhile, due to distributed generation (DG) resources generally, the most common problem is a shift from voltage drop to voltage rise, for which LTC and CB are ineffective to handle adequately. As such, new control devices and control approaches including both centralized and distributed control schemes appear to be needed for voltage regulation in distribution systems with renewable DG integration.

Energy storage systems are sized for voltage regulation and peak load shaving in (Ye et al., 2014). In (Sugihara et al., 2013), the customer-side energy storage system is used to solve the voltage fluctuation problem. However, the high cost limits the usage of energy storage system. Most of the energy storage systems are integrated for advanced regulation or emergent operation (Gouveia et al., 2013) (Hajizadeh et al., 2010). Demand response is another way to regulate the system voltage actively. Different load controllers are developed to support the system (Scott et al., 2002)

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(Douglass et al., 2014). The detailed cooperation mechanisms and stimulation policies are still under development. The device of most concern is DG whose active and reactive output can both affect the system status (Carvalho et al., 2008) (Huijuan et al., 2010) (Robbins et al., 2013) (Bonfiglio et al., 2014) (Farag et al., 2013) due to the high R/X ratio of distribution system. Carvalho et al., (2008) provides a solution for distribution network operation to keep traditional task by controlling the DG so as not to cause voltage rise. Distributed reactive power control methods are proposed in (Huijuan et al., 2010) (Robbins et al., 2013) (Bonfiglio et al., 2014). DG along with various voltage regulators can be coordinated for voltage support and the effectiveness is demonstrated in (Ranamuka et al., 2014) (Farag et al., 2013). Though many researches show the huge potential of DG in voltage support, until now most DG are requested to operate at unity power factor and track the maximum power point without providing voltage regulation services. Considering the limitations of the above voltage regulation devices, an alternative smart load technology, electric springs (ES), has been reported and is being further developed (Shu Yuen et al., 2013) (Siew-Chong et al., 2012). These devices have been purpose designed to achieve balancing and voltage control in an integrated way.

The ES was first proposed in (Shu Yuen et al., 2013) to give a counterpart to Hooke's law in electric systems. The device is represented as a current-controlled voltage source connected in series with the appliances. The general characteristics of ES and a droop control approach for system stabilizing are demonstrated in simple system (Siew-Chong et al., 2012) (Chi Kwan et al., 2013). The results verified the capability and flexibility of ES in supporting the voltage of critical buses. Previous research did not consider the following points, a) use of a communication network; b) the influence of load characteristics in more general network structures; c) uncertain voltage profile caused by renewable energy along the feeder.

In this paper, a voltage management scheme is proposed to deal with the above problems and enhance the application of ES in power distribution systems. For simplicity, it is assumed that the LTC and CBs are dispatched hourly according to the voltage profile of the system. The ESs are operated with high frequency according to the proposed scheme to maintain the voltage of the critical buses. The ESs are allocated along the distribution lines and operated with co-ordination to support the voltages. The voltage injection of ES affects the connected customer. It is important to share the responsibility among the customers participating in the ES scheme. A distributed algorithm is more suitable in this case than a centralized control where large computations and reliable communications are required. The droop control method is realized in (Chi Kwan et al., 2013) to coordinate a set of ESs. However, the global information of the distribution system is needed in this operation scheme. Consensus control techniques have been proposed for power management in distribution systems – see for instance (Alyami et al., 2014) (Ziang et al., 2012) (Mokhtari et al., 2013). The need for all smart loads to reach a consensus contribution fits the fundamental theory of such distributed control algorithms. In this paper, a consensus algorithm with a smart load model is proposed to mitigate the voltage fluctuation of critical buses. The voltage regulation capability is maximized by equally sharing the responsibility among all smart loads.

This paper is organized as follows. After the introduction section, an ES model is briefly presented with load modelling. After that, the voltage management scheme and the corresponding consensus control algorithm is presented and discussed. And then, the proposed consensus operation strategy is verified on a modified IEEE 15-bus distribution network, and the voltage profile of the critical bus is shown. Conclusions and further developments are discussed in the last section.

2. ELECTRIC SPRING AND SMART LOAD MODELLING

2.1Basic Concept of Electric Springs

As references (Shu Yuen et al., 2013) (Siew-Chong et al., 2012) state, the main power circuit of an ES is a full-bridge power inverter or half bridge inverter. The capacitor at the DC side of the inverter is charged to provide DC voltage source for the ES. The AC output of the inverter is controlled by pulse-width-modulated (PWM). Through an LC filter, a controllable sinusoidal voltage source with the same frequency to the grid is generated. Without an energy storage system, the vector of the output voltage is controlled to be quadrature to the vector of the current to avoid energy consumption or generation. Through this way, the ES is considered as a pure capacitor or inductor connected in series with the appliance. The basic schematic of ES and distribution system is showed in Fig.1. The ES is connected in series with the load and controlled by the modulation index signal. The voltage and the reactive power output of ES can be calculated by following equations:

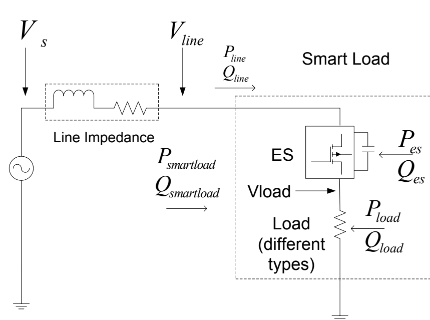

Fig. 1. Basic schematic of the smart load

$$V_{es} = k \cdot M \tag{1}$$

$$P_{es} = 0 \tag{2}$$

$$Q_{es} = V_{es} \cdot I_{es} \tag{3}$$

where, V_{es} , V_{load} ,and V_{line} are the voltage of the ES, the load and the bus, respectively. M is the modulation index of the ES. k is the ratio between the output voltage and the