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A novel control scheme to reduce the reactive power processed by a Multifunctional Voltage-Quality Regulator

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ABSTRACT

Solving voltage regulation in underrated grid networks can be very time consuming and costly for operators and unpleasant for customer, who constantly experience equipment malfunctions due poor voltage quality. Active solutions such as Multifunctional Voltage-Quality Regulator (MVQR) work well as a quick fix in these cases, bringing voltages to the right levels as soon as installed, feeding active or reactive power into their point of connection. Unfortunately, current solutions can be fastidious, adjusting voltage levels that are already adequate for customer services to a specific fixed setpoint, unnecessarily spending energy, overusing distribution networks, wearing out energy-storage components and eventually not optimizing the equipment's regulation capacity. To address the aforementioned problems, this manuscript proposes a control scheme to reduce the reactive power processed in an existing MVQR. The MVQR was based in a distribution static compensator (DSTATCOM) with active harmonic filtering feature. Where voltage-magnitude regulation is achieved by reactive power injection only, while harmonic mitigation is performed by harmonic injection based on PCC-voltage-detection-method (PCC-VDM). The proposed MVQR control scheme reduces the reactive energy injection when the voltage level at PCC is within limits of relevant standards. The main contribution of this paper is the detailed mathematic analysis of the scheme for reducting the reactive energy injection, which had not been found in literature. This analysis shows how to design this scheme to obtain better regulation, guarantee dynamic decoupling from other control loops, as well as ensure closed-loop system stability. Simulation and experimental results were carried out for validation of the proposed control method. The proposed MVQR had shown itself an efficient and effective addition, reducing significant processed reactive power using wisely resources, likely available in similar MVQR topologies.

1. Introduction

Low voltage distribution networks can struggle to supply an adequate voltage to consumer when the load demands more than the available infrastructure can supply. Voltage can be designated as inadequate mostly due to its high harmonic content and/or improper amplitude. An example of an issue would be an underrated long distribution grid powering a large load distributed across its extension.

Poor voltage regulation affects not only customer who constantly experiences equipment malfunctioning but also utility companies, who must comply with several power quality requirements, such as regulation of voltage's magnitude and harmonic content [1]. When costs associated to having poor voltage quality are high enough, utilities companies might look for quick solutions, that are able to fix voltage quality issues without demanding major analysis of the system, like locating problematic loads or evaluating the current infrastructure. Thus, active solutions may be chosen as they can offer a fast installation followed by an immediate voltage magnitude correction and harmonic distortion reduction, among other features [2–5]. Nevertheless, in this context, the voltage quality issue is not fixed by any active solution due the fact that a fast installation in a distributed power system does not allow a proper inspection of the system to map loads, line impedance, transformer's characteristics, generators, etc. Therefore, active systems solutions must be narrowed to those who do not require specific load or source information to adjust the voltage quality.

Several different active schemes have been developed to solve voltage-quality issues, such as Active Power Filters (APF) with reactive compensation [6–22], Distribution Static Synchronous Compensators (DSTATCOM) [23,24,47–50], and multifunctional converters [2–4,25–33]. Among these solutions, classified as a Multifunctional

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Voltage-Quality Regulators (MVQR), DSTATCOMs with voltage harmonic mitigation at the point of common coupling (PCC) have presented themselves as most suitable solutions for the voltage quality issue in the context presented in the paper.

Control scheme of a MVQR DSTATCOM can be based on voltage or current strategies. A voltage-controlled DSTATCOM directly control the PCC voltage, aiming voltage magnitude regulation, phase balancing, and reduction of voltage's Total Harmonic Distortion (THD) [25,28,34,35,44,45]. On the other hand, a current-controlled DSTATCOM directly controls its output current and indirectly controls the PCC voltage. Although slower than voltage controlled strategies, the current controlled DSTATCOMs present natural protection against transients and a more stable operation [27,29,31,33,37]. As part of the selection of the most suitable design strategy for the voltage quality issue a harmonic mitigation strategy must be chosen.

Strategies for harmonic mitigation of PCC voltages in MVQR can be implemented based on current or voltage detection [11]. Current detection schemes require additional current sensors to measure the current from specific loads or from specific points of the distribution system, that increases the cost and the complexity for the equipment installation as well as is required an evaluation of which sources and loads should be measured. Moreover, it is difficult to determine which is the current from the source and from the loads in grids, mainly in systems with distributed generation (DG). Differently, voltage detection schemes are based on PCC voltage measurements. Although more complex, the main advantage of voltage detection approach is that voltage measurements must always be done to provide synchronization, resulting in a solution with no additional sensors [34,44,45].

Several voltage detection schemes have been presented in literature. Methods based on emulation of resistances presented [11,13,26,36] do not eliminate completely the PCC harmonics. In Ref. [14] a method was presented based on emulation of tuned active filters, of which the main drawback is occurrence of potential resonances due to undesigned loads [18]. Adaptive and non-linear techniques have good performance [4,30,31,37,38], but also have chattering problems and a more complex implementation in comparison to linear techniques. Internal-model based controllers based on resonant [6,29,39] or repetitive controllers [10] have good reference tracking and good rejection of periodic disturbances.

Unfortunately, current suitable solutions for the voltage quality issue inserted in the context presented in this paper can be fastidious, adjusting voltage levels that are already adequate for customer services to a specific fixed setpoint, unnecessarily spending energy, overusing distribution networks, wearing out energy-storage components and eventually not optimizing the equipment's regulation capacity. This problem is addressed by this paper, where an addition of a control scheme is proposed to reduce the reactive power processed in an existing MVQR.

Recently a few papers addressed the reduction of unnecessary reactive power processing in low voltage regulators [34,35,37,44,41,46]. Setting a suitable voltage magnitude at the PCC can lead to great reactive power reduction [34], which has been commonly regulated at 1.00 p.u. [42,43]. However, the PCC voltage magnitude must comply with local standards. American standard ANSI C84.1 defines the adequate voltage range from 0.95 p.u. to 1.05 p.u. [40], while European standard EN 50160 sets a 0.90 p.u. to 1.10 p.u. range [41]. The methods for reactive power reduction presented in Refs. [35] and [37] are formulated with the need of extra sensoring of grid or load currents and grid parameters to determine the suitable PCC voltage magnitude. On the other hand, Ref. [34] presented a method using only the output apparent power to track the PCC voltage magnitude in which the processed power is minimal.

This paper proposes a simple and novel control scheme to reduce the reactive power processed by a Multifunctional Voltage-Quality Regulator (MVQR) as an alternative for methods presented in Refs. [34,35,37]. The technique was implemented in an existing MVQR solution based in a distribution static compensator (DSTATCOM) with active harmonic filtering feature presented in Ref. [51]. The voltage-magnitude regulation was achieved by reactive power injection only, while harmonic mitigation was performed by harmonic injection based on PCC-voltage-detection-method (PCC-VDM). The proposed MVQR control scheme addition reduces the reactive energy injection when the voltage level at PCC is within limits of relevant standards. The main contribution of this paper is the detailed mathematic analysis of the scheme for reduction the reactive energy injection, which had not been found in literature. This analysis shows how to design this scheme to obtain better regulation, guarantee dynamic decoupling from other control loops, as well as ensure closed-loop system stability. Simulation and experimental results were carried out for validation of the proposed control method.

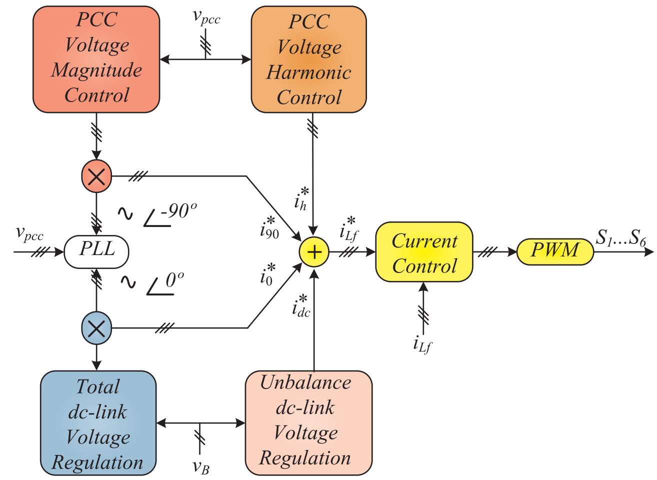

Fig. 1. Block diagram of proposed control for MVQR.

2. Control scheme of proposed MVQR

Proposed PCC voltage regulation scheme is based on a current-controlled DSTATCOM. Fig. 1 presents the basis of proposed scheme, where four outer voltage loops are used for PCC magnitude and harmonics voltage control as well as for dc-link voltage regulation. The combination of the outer voltage loops outputs generate the reference i_{Lf}^* for an inner current control scheme, responsible for the imposition of the injected current on PCC. Fig. 2 presents the proposed three-phase four-wire MVQR control system, where blocks match the colors of Fig. 1 to facilitate the identification of each control loop.

The voltage magnitude and harmonics control at PCC are performed for each phase independently due to three-phase four-wire circuit topology. One can observe that any of the three phases of the inverter can be used for dc-link voltage regulation. However, in order to minimize current unbalance among the phases, the same control action is applied in all the phases to obtain a balanced current of compensation.

PCC voltage magnitude control loop is designed to maintain the magnitude of v_{pcc} within the acceptable limits defined by the grid code. This loop changes the reactive power absorbed or injected in the PCC depending on rms value of v_{pcc}. So the signal i_{90}^* is sinusoidal component in quadrature with v_{pcc}. Additionally, PCC voltage harmonic control loop adds to the current reference signal the content to mitigate the PCC voltage harmonics. The signal i_h^* is generated from a scheme based on the voltage-detection method.

Total dc link voltage control loop is designed for regulation of the sum of voltages across the dc-link capacitors. The dc link voltage regulation is achieved by absorbing or injecting active power from PCC. The magnitude of the sinusoidal v_{pcc} in-phase current reference i_0^* controls the active power exchanged with the PCC. Although not presented in this manuscript, this voltage loop can also be used to control