Investigation on Different Control Methods for Single-Phase DVC

H. Hafezi, R. Faranda
Department of Energy, Politecnico di Milano
Via La Masa 34, 20156, Milano, Italy
hossein.hafezi, roberto.faranda@polimi.it

C. Gandolfi, R. Chiumeo
RSE spa
Via R. Rubattino 54, 20134, Milano, Italy
chiara.gandolfi, riccardo.chiumeo@rse-web.it

***Abstract*—Power Quality (PQ) conditioning in LV distribution networks is an increasing concern within modern power system and Smart Grid systems. Several phenomena have classified in standard, among those, voltage sags and rms voltage drifts have been reported as most significant and frequent ones in both MV and LV distribution systems. Several solutions have been proposed to deal with these voltage disturbances. Dynamic Voltage Restorer (DVR) and Dynamic Voltage Conditioner (DVC) are the most promising solutions. Controlling these series connected devices is a challenge especially in single-phase schema which is an appreciated solution for Distribution System Operator (DSO). This paper investigates difference control strategies for single-phase DVC system. Control methods are explained in detail and MATLAB based simulation results are reported. Investigated control methods performance dealing with example voltage drop event have been reported.**

***Index Terms*—Power Quality, Dynamic Voltage Restore (DVR), Dynamic Voltage Conditioner (DVC), Distribution System, Sliding Mode Control.**

I. INTRODUCTION

Power Quality (PQ) conditioning in LV distribution networks is an increasing concern within modern power system and Smart Grid systems [1]. The concept is in interest from several point of views. From end user point of, customer needs reliable and continuous service at their property. From Distribution System Operator (DSO) point of view, not only PQ requirements need to be respected according to standards [2] but also, DSO is interesting to have a kind of flexibility at their networks to increase controllability of their system and manage the power absorption during peak demand period.

PQ events have been classified in standard and several PQ conditioning apparatuses have been introduced in order to deal with different phenomena [3]. Installing a single device to deal with single event is not the best idea so, researchers are looking for multifunctional strategies in specific solutions [4] or even more recently to an universal PQ compensator in order to cover most of the PQ events using a single solutions [5].

Among PQ events, voltage sags and rms voltage drifts have been reported as most significant and frequent ones in both MV and LV distribution systems [6], [7]. One promising solution to deal with voltage sags and also long term rms voltage drifts is Dynamic Voltage Conditioner (DVC) system [8], [9]. The system topology is well known as series connected compensator or Dynamic Voltage Restorer (DVR) [10] but it can work continuously and it is able to deal with not only fast short-term events but also with long-term rms voltage drifts.

Although several research works have been conducted on DVR and DVC systems' control and functionalities, still it is necessary to investigate these systems control and functionality from several points of views. First; most of the control methods in the literatures are for three-phase systems and the control strategy are developed based on three-phase system and Park transformation [11]. However, single-phase solutions have been attracted immense interest recently in distribution network due to their economic advantages and also because single-phase solution is more compatible with LV distribution system where most of the loads have single-phase connection [12]. Second; the continuous operation of DVC system is not well analyzed in literature and still it is a new concept for PQ conditioning systems [9].

This paper will discuss three different control methods for single-phase DVC system. Control methods will be explained and the design procedure will be addressed in detail. Matlab based simulation model has been developed and the performance of different control methods will be studied. Rest of the paper is organized as follow: section II presents DVC system architecture. Section III introduces DVC working principle and the developed control methods. Section IV reports simulation study results and finally, conclusion remarks are pointed out in section V.

II. SINGLE-PHASE DVC

Figure 1. shows the single phase DVC scheme. The system composes of a coupling transformer (*Coupling TR*) which means to couple the device to the power line. It has a single-phase two level full bridge DC to ac inverter. *L* stands for device switching inductance and *CB* represents capacitor bank at inverter DC bus. Two low-pass filter capacitors have been

connected at inverter side and line side as those are shown in Figure 1. by C_f.

Although DVC hardware structure is equally the same as a DVR system but, its mission inside LV distribution system has been updated by authors recent study [8], [9]. DVC is able to cover all DVR functionalities and moreover, it is able to operate continuously in order to regulate voltage at Point of Common Coupling (PCC).

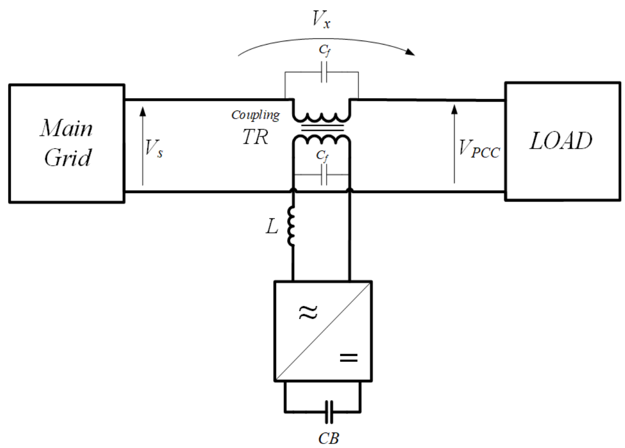

Figure 1. Single phase DVC scheme.

For continues operation, the DVC system has two options, either to include a kind of Distributed Generation (DG) resource to support the DC link voltage [13], [14], or to operate with pure reactive power control strategy during steady state working period. Integrating an external energy resource can increase the complexity of the system and also intermittent nature of DG system can decrease the reliability of the DVC itself. The aim of this research work is to develop an independent and standalone device. Therefore, in this study, voltage injection quadrature to line current control method (pure reactive control strategy) always will be considered as DVC control strategy.

III. DVC Control Methods

The working principle of DVC is to regulate voltage at PCC by injecting the compensation voltage in quadrature to line current. DVC pure reactive power operation principle is illustrated in Figure 2. in steady state condition with inductive load for both under V_{s2} and over voltage V_{s1} events [8], [9]. In the following three different control methods are described.

A. Calculation-MBC

DVC inverter needs a reference voltage to generate at its ac terminals. The calculation control method as it is reported in [8], [9], has been utilized in this study. Here only main formulas and control block diagram of the control method is summarized. The calculation is based on representation in Figure 2. as it is show in (1). This is the required rms value to be injected perpendicular to the line current.

$$V_{x\_cal} = V_{xi} = V_{PCC\_ref}\sin(\gamma) - V_s\sin(\theta_i) \qquad (1)$$

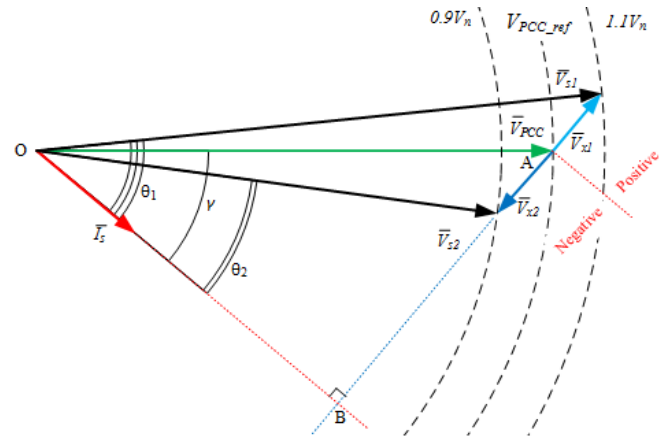

Figure 2. DVC reactive operation principle.

In order to generate the ac reference signal for inverter, an equation like (2) needs to be adapted where as it is illustrated in Figure 3. also, $V_{x\text{-}q}$ represents the quadrature (reactive) component and $V_{x\text{-}d}$ is the direct (active) component of DVC injected voltage. $V_{x\text{-}q}$ is the summation of calculation comes from (1) and a parallel PI controller in order to have better control on PCC voltage instead, $V_{x\text{-}d}$ comes from DC bus PI controller which is meant to keep DC bus voltage constant. The overall block diagram of the DVC inverter reference voltage generation is schemed in Figure 3.

$$v_x(t)^* = \sqrt{2}\cdot V_{x-q}\cdot\sin(\omega_{I_L}\cdot t \pm \frac{\pi}{2}) + \sqrt{2}\cdot V_{x-d}\cdot\sin(\omega_{I_L}\cdot t) \quad (2)$$

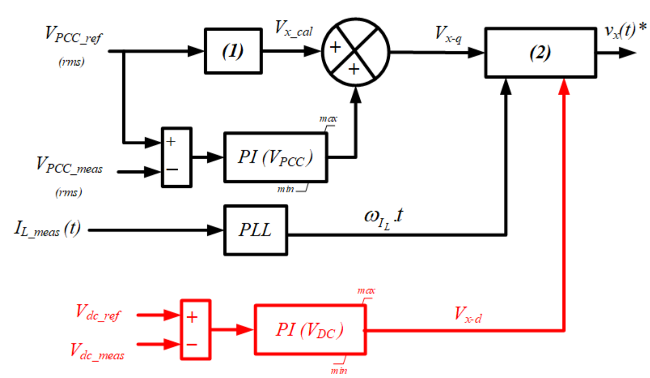

Figure 3. Calculation based control scheme to generate DVC reference voltage.

Reference voltage generated by Figure 3. is fed to inverter controller. Similar to what is presented in [8], [9], a double loop voltage-current controller is used with outer voltage controller and inner current control loop [15]. Here in order to improve ac voltage tracking performance, a P-Resonant controller is used as voltage controller ($PR(V_{inv})$).

In this control method, two PI and one PR controller have been adapted. The controllers setup parameters are listed in TABLE I.

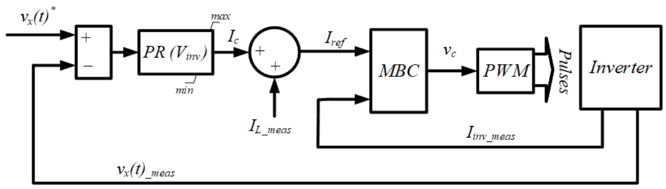

Figure 4. DVC inverter double loop controller, Calculation-MBC [15].

B. dq-SMC

Figure 3. shows one possible method to generate reference voltage, indeed it showed to perform well but, it has some short comings as it need both V_{PCC} and V_s voltages measurements and the phase displacement between V_{PCC} and V_s respect to the load current (γ and θ respectively). Figure 5. shows a dq transformation based controller which can be used as alternative to the block diagram showed in Figure 3. A PI controller is used to generate required injection voltage. The DVC concept is to work with pure reactive power in steady state conditions so, the main PI controller ($PI(V_{PCC})$) output is considered as quadrature (q) component. Since the application is single phase, zero component would not influence the control and it is set to zero. Another PI controller is used to regulate DC bus capacitor voltage around set value. The dq0 to abc transformation is performed respect to load/line current angular frequency so, the injected control voltage can be kept perpendicular to load current and pure reactive power compensation can be achieved.

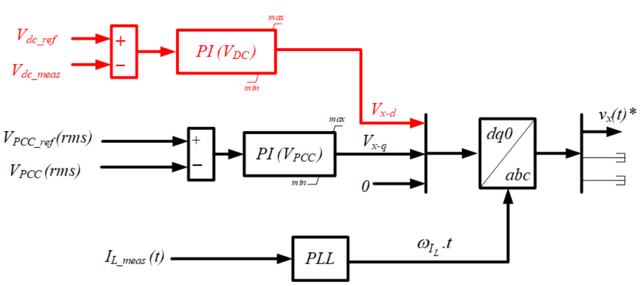

Figure 5. dq-PI control scheme to generate DVC reference voltage.

Sliding Mode Control (SMC) is a powerful technique to trace ac voltage or current reference in order to control DC/ac inverters and it is applicable for both single- and three-phase configurations [16]. Two possible control methods are analyzed and both will be discussed thoroughly.

1) dq-SMC Hybrid

Same as Calculation-MBC double loop control method, it is possible to use an outer voltage control with an inner current controller, in this case sliding mode current control. The control block diagram is shown in Figure 6. , where similar to previous case, a PR controller has been used as outer voltage control and the PR output is considered as control current (I_c). The control signal is added to the load current in order to produce reference current for the sliding mode current controller (I_{ref}). The error between inverter reference current and its measure, is added to the triangular signal in switching frequency in order to create the sliding mode surface ($\sigma(t)$). The sign of the sliding mode surface can be used as the switching pulses, the result is a modulation strategy with fixed frequency. In particular if the $\sigma(t)$ is positive the upper switch of the converter leg is commutated, if it's negative the lower one.

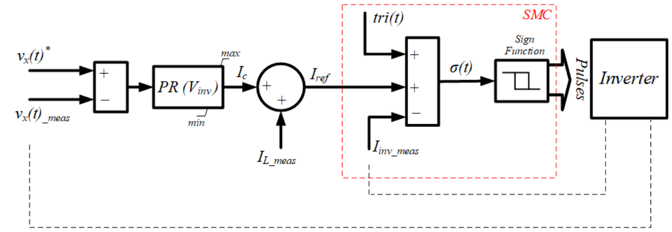

Figure 6. SMC-Hybrid control scheme

2) dq-SMC Pure

Instead of using a double loop control strategy to drive the inverter, it is possible to use single lop voltage controller and avoid current controller. Avoiding current controller stage, it is possible to use sliding mode control technique as voltage controller as it is depicted in Figure 7. In this control method, the voltage signal error between reference voltage ($v_x(t)^*$) and inverter terminals measure ($v_x(t)_{meas}$) is added up to the triangular signal in order to create the sliding mode surface ($\sigma(t)$). The modulation strategy is the same as SMC-Hybrid.

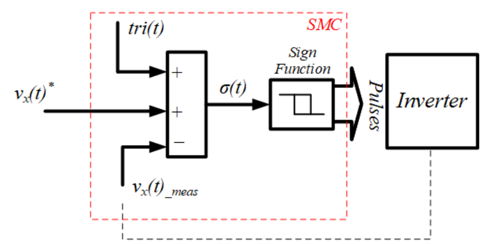

Figure 7. SMC-Pure control scheme

TABLE I. summarizes controller setup for all cases. As it can be noticed, the V_{PCC} PI controller ($PI\ V_{PCC}$) in first case (Calculation-MBC) has smaller values because in this case, PI controller is not the main controller for PCC voltage. DC bus PI and PCC voltage PR controller gains have been kept equal for all cases in order to make it possible to compare simulation results difference of presented control techniques.

TABLE I. CONTROLLERS SETUP

Controller	Calculation-MBC	dq-SMC Hybrid	dq-SMC Pure
$PI\ V_{PCC}$	K_p =0.25 K_i=7.5	K_p =1.5 K_i =50	K_p =1.5 K_i =50
$PI\ V_{DC}$	K_p =1 K_i =1.5	K_p =1 K_i =1.5	K_p =1 K_i =1.5
$PR\ V_{inv}$	K_p =1 K_r =0.1	K_p =1 K_r =0.1	-

IV. SIMULATION RESULTS

The explained control methods have been implemented in MATLAB simulation and their performance dealing with an example event will be reported in the following. The simulated scheme is the same as it is shown in Figure 1. and system parameters are reported in TABLE II.

TABLE II. SIMULATED SYSTEM PARAMETERS

Item	specification
Load	P = 12kW Q= 9kVar cos(φ) = 0.8
Switching Frequency	f_{sw} = 5kHz
Coupling Transformer (*TR*)	100 kVA turn ration 1.5
Switching Inductance (*L*)	4 mH
DC bus Capacitor (*CB*)	20 mF
Both LP filters (C_f)	100µF

In order to keep consistency in presented simulation results, control performance of all control methods are reported dealing with a 10% voltage drop. The simulation starts with no load, load is connected to the system at t=0.5s and system works without any voltage drop or disturbances till t=2s, at t=2s a long duration 10% voltage drop (rms drift) is simulated and it lasts till end of simulation. Results are reported in the following.

Figure 8. shows PCC voltage, PCC voltage reference (which during all simulation study is set to system nominal value, 230V) and grid side voltage (V_s). Results show that Calculation-MBC control method performs faster response because DVC reference voltage generation is based on calculation and it reacts faster than PI controller. Beside the speed difference, all three control methods response well for the voltage variation.

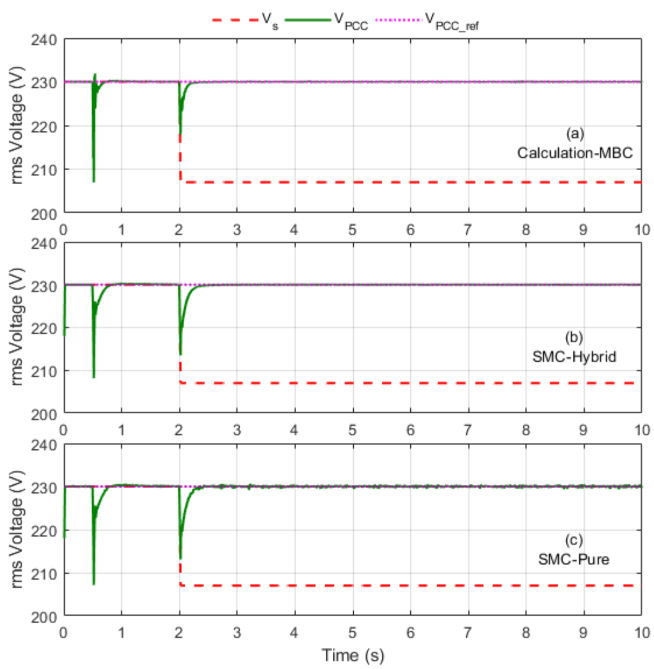

Figure 8. PCC voltage compensation behaviour

Figure 9. shows DC bus voltage variation for all three control methods. Referring to TABLE I. , DC bus controller setup remains equal for three control methods and as it can be noticed, DC bus voltage behavior is almost the same for three different control methods. From Figure 9. (c), it can be seen that DC bus voltage has less variation with SMC-Pure control method because basically SMC-Pure is a single-loop voltage controller. Indeed case (a) and (b) are double-loop voltage and current controller where the second current controller injects a small delay to the control loop and this may affect DC bus voltage controller performance.

Before t=0.5s the DC bus voltage drops because before this time the control voltage is not activated (no load) and DVC inverter follows zero voltage so, due to the losses on DVC components and also switching losses, the DC bus voltage drops. However, once the control is activated (load connection), the controller recovers DC bus voltage to the set value.

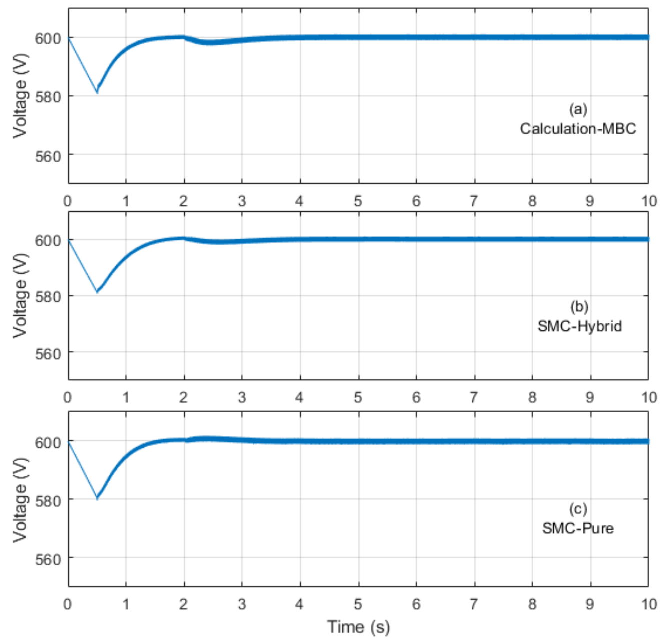

Figure 9. DC bus voltage variation

Figure 10. shows DVC inverter voltage controller performance for three control methods. In all cases the DVC inverter voltage reference and its generated voltage have been shown. It can be noticed that Calculation-MBC and SMC-Hybrid control methods' results are almost the same instead SMC-Pure single loop voltage control methods down perform respect to case (a) and (b). As it can be noticed from Figure 10. (c), the DVC inverter voltage has considerable ripples around peak value.

Figure 11. shows DVC inverter current signals for all three cases. Looking to DVC inverter current, it can be noted that, SMC-Hybrid control method performs better control. Calculation-MBC control method current has considerable switching ripples on current but still it can be acceptable. Looking to Figure 11. (c), it can be seen that DVC inverter has large ripples on its current. Actually SMC-Pure is a single-loop voltage control method and there is no control on DVC inverter current and this can be the reason behind its low performance on inverter current control. Figure 11. (c) shows only one current because in this single-loop control scheme, there is not any current reference signal.

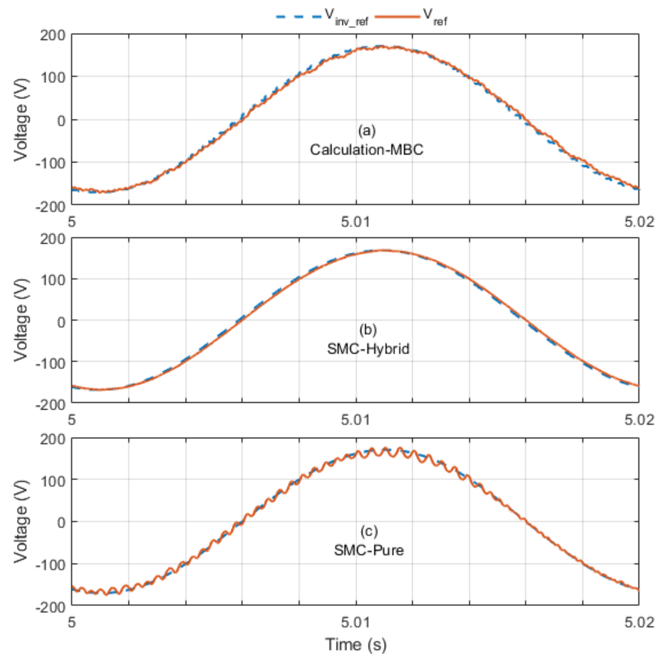

Figure 10. DVC inverter voltage

TABLE III. summarized three control methods' performance on compensation of the defined example event. It lists injected voltage rms value (V_x), DVC inverter voltage and current THDs and the DVC device losses during this event. THDs have ben evaluated using Matlab FFT analysis toolbox considering 10 cycles of voltages or currents.

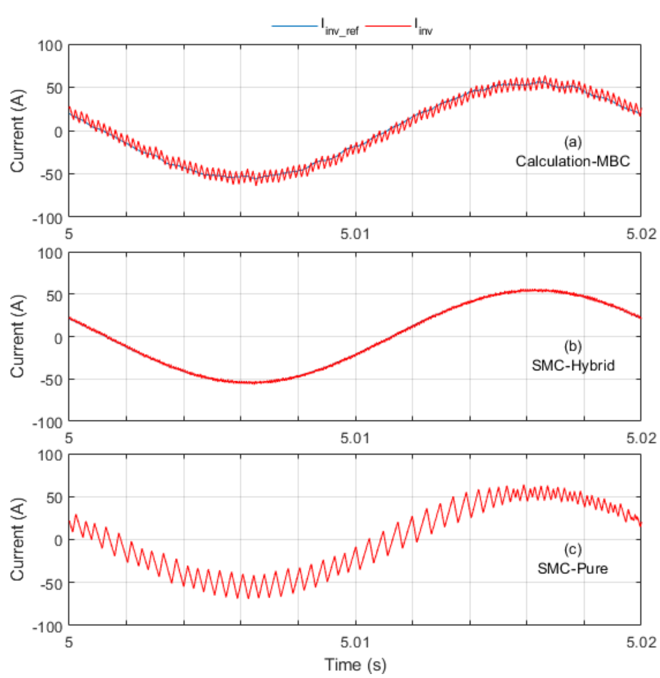

Figure 11. DVC Inverter current

TABLE III. CONTROLLERS PERFORMANCE SUMMARY

Controller / Indices	Calculation-MBC		SMC-Hybrid		SMC-Pure	
	t < 2s	t > 2s	t < 2s	t > 2s	t < 2s	t > 2s
V_x	50V	120.9V	50V	119V	50V	120.5V
V_{inv} THD	5.93%	2.09%	1.48%	0.44%	6.22%	2.77
I_{inv} THD	10.66%	10.91%	2.55%	2.77%	13.60%	14.56%
Losses	432W		430W		430W	

It can be noted from TABLE III. , SMC-Pure has lowest performance on both voltage and current control since their THD level stays out of standard limit. Calculation-MBC and SMC-Hybrid control methods performs better due to the adapted double-loop voltage and current controller indeed, SMC-Hybrid control methods has superior performance among other control methods. From losses point of view, all control methods have similar losses level.

It worth to mention that, from practical point of view PWM modulation strategy is preferred since most of Microcontrollers have this prepared modules and it is easy to implement however, SMC needs to be implemented and usually there is not a prepared module inside the Microcontrollers.

V. CONCLUSION REMARKS

This paper presents single-phase DVC as promising solution to deal with voltage disturbances in LV distribution network. Controlling the DVC is already a challenge and it is more difficult in single-phase configuration. In order to understand the control performance of the device, with the same hardware configuration and event, three different control methods for single-phase DVC have been studied. MATLAB simulation has been used as simulation tool to design and study each control method.

In particular the controls compared in the paper are Calculation-MBC, and dq-SMC in two different modality (dq-SMC Hybrid and dq-SMC Pure).

Each control method is described in the paper and it has been observed that, a double-loop voltage and current control scheme performs better since it contains an outer voltage and inner current controller. Therefore, Calculation-MBC method and dq-SMC Hybrid method have the better performance even if the second one has superior performance (low voltage and current THD). Indeed, simulation results reveals that, SMC-Hybrid control method has better performance comparing to other control methods studied through this work.

From losses point of view, all control methods have similar losses level.

Thanks to this study it is possible to conclude that Sliding Mode Control (SMC), even if usually there is not a prepared module inside the Microcontroller to implement easily this solution, is an attractive controller method and it can be applied not only for a single-phase DVC system.

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