

Dynamic Voltage Conditioner: A New Concept for Smart Low-Voltage Distribution Systems

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Abstract—Power Quality (PQ) improvement in distribution level is an increasing concern in modern electrical power systems. One of the main problems in low voltage (LV) networks is related to load voltage stabilization close to the nominal value. Usually this problem is solved by smart distribution transformers, hybrid transformers and solid-state transformers, but also dynamic voltage conditioners (DVC) can be an innovative and a cost effective solution. The paper introduces a new control method of a single-phase DVC system able to compensate these long duration voltage drifts. For these events, it is mandatory to avoid active power exchanges so, the controller is designed to work with nonactive power only. Operation limits for quadrature voltage injection control is formulated and reference voltage update procedure is proposed to guarantee its continuous operating. DVC performance for main voltage and load variation is examined. Proposed solution is validated with simulation study and experimental laboratory tests. Some simulation and experimental results are illustrated to show the prototype device's performance.

Index Terms—Dynamic voltage conditioner (DVC), dynamic voltage restorer (DVR), LV distribution system, power conditioning, power electronics, power quality, smart grid.

I. INTRODUCTION

POWER quality (PQ) in modern power systems is an high demanding concern in both medium voltage (MV) and low voltage (LV) networks for all industrial, commercial, and domestic users [1].

Different PQ problems has been reported and categorized [2]. Among those voltage rms deviations, that may be caused by different reasons in power systems, are most often reported as important issues. In particular, recent fast development and high grid penetration of renewable energies, made it more difficult and challenging to respect to the rms voltage standards [3]. Indeed, European standards persuades distribution system operators (DSOs) to provide the LV users voltage within standard range [4]; so, voltage regulation within the standard range is becoming more and more important for DSOs especially within future modern and smart grid systems [5]. Therefore, it is economically and technically rational for DSOs to investigate flexible and advance PQ conditioners for LV distribution networks.

Manuscript received March 8, 2017; revised June 15, 2017 and October 4, 2017; accepted November 6, 2017. Date of publication November 12, 2017; date of current version June 22, 2018. Recommended for publication by Associate Editor J. M. Guerrero. (*Corresponding author: Hossein Hafezi.*)

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Nowadays, in order to deal with long duration voltage drifts, DSO can adapt smart distribution transformers, hybrid transformers and solid-state transformers that are among strongly developing group of voltage conditioners [6], [7], while, rarely ac electronic compensator devices, as Static Var Compensator (STATCOM) [8], dynamic voltage restorer (DVR) [9], unified power quality conditioner (UPQC) [10] and open unified power quality conditioner (Open UPQC) [11], are adapted because those are too expensive or have limited functionalities. So an economic active voltage conditioner, which perfectly covers long-term events, has the ability to operate continuously in order to regulate voltage at PCC and to protect a group of downstream end users from several voltage disturbances, can be very interesting for DSO.

A device that can perfectly satisfy modern power system requirement is the Dynamic Voltage Conditioner (DVC). Indeed, its mission is regulation and not only restoration, so it can operate to deal with short- and fast-term voltage disturbances, as a typical DVR [12], and it can operate to deal with long-term voltage disturbances in the range $\pm 10\%$ of the nominal value.

Several topologies and control algorithms for DVR have been presented and analyzed in literature [13], [14], as the topology proposed by Babaei *et al.* in [15]. In phase voltage injection (with active power) is the easiest method to compensate the voltage variation but it needs large storage system for short-term events [16] and it cannot be applied for long duration voltage drifts compensation. To reduce energy storage, energy optimized control method has been introduced [17]. However, to compensate longer voltage variation as voltage variation between $\pm 10\%$ nominal value and voltage fluctuations in LV networks, quadrature (respect to the line current) voltage injection is needed (with nonactive power).

In literature, the proposed control methods are always for three-phase systems and it is based on three-phase measurement, synchronous rotating frame (SRF) calculations and $d-q$ transformation as reported in [12] and [18].

However, most domestic, commercial, and some industrial loads are single-phase; so, in LV distribution level and with mostly single-phase users as domestic one, a cost effective, and practical PQ solution can be a single-phase device without an expensive storage system. This configuration in practice can give to the DSO the possibility to move all problematic loads on a specific phase of the feeder equipped with a single-phase device, reducing installation costs [19]. A single-phase configuration has been attracted immense interest recently because it is more convenient with mostly single-phase final users and also

it is always possible to build a three-phase system linking three single-phase units together.

Therefore, an active voltage conditioner able to cover both long-, short- and fast-term events, can perfectly satisfy modern power system requirements as the DVC proposed by the authors in their previous work through simulation study [20].

This paper presents a single-phase DVC as an economic voltage controller for LV distribution smart grid systems, which makes the proposal an appreciated solution for DSO [21]. Coupling transformer and device sizing is evaluated. New single-phase and fast calculation based controller for DVC system is proposed, and device operation principle based on nonactive compensation method is presented. For first time in literature, the single-phase DVC operation limits of quadrature voltage injection method is formulated. To guarantee device stability, for the first time in literature, a new PCC reference voltage update procedure is suggested in order to update the V_{PCC_ref} if the system goes outside its operation limits. Even if the device has the capability to support short- and fast-term voltage variations for few cycles with active power coming from DC bus capacitor storage system, only DVC long-term operation limits will be analyzed in detail here, so sag/swell will not be covered by this work because several solutions are just presented, as in [12] and [13], and they can be implemented and added to the DVC functions. MATLAB based simulation and laboratory experimental results are reported to validate the presented solution.

Rest of the paper is organized as follow; Section II explains operation principle and limits. The proposed DVC controller and its inverter controller is presented in Section III. Simulation and laboratory based experimental results in the grid voltage range from 0.9 to 1.1 p.u. are reported at Section IV and finally discussions and conclusions are pointed out at Section V.

II. DVC OPERATION PRINCIPLE

Hardware configuration of the DVC is equally the same as a DVR, only its control logic is updated by this article to add several new important functionalities and enable its continuous operating, in particular to compensate long duration voltage drifts, within smart grid system.

A. DVC-Injected Control Voltage

The hardware configuration of the proposed single-phase DVC is shown in Fig. 1. The system consists of a full bridge converter with capacitor bank as DC bus. The converter is connected in series to the line by means of a coupling transformer. The system is equipped with *Bypass* switch in order to bypass the device in case of any fault of the DVC device and also to protect DVC inverter and other components against possible damages originated from LV network side. In Fig. 1, \bar{V}_s stands for grid voltage. The DVC is meant to keep PCC voltage (\bar{V}_{PCC}) at set value (V_{PCC_ref}) by injecting proper voltage (\bar{V}_x) in series to the line. So at any instance, the KVL (1) needs to be satisfied

$$\bar{V}_{PCC} = \bar{V}_s + \bar{V}_x. \quad (1)$$

For the proposed DVC, \bar{V}_x has to be perpendicular to the line current, \bar{I}_L . So, the device can work with nonactive power

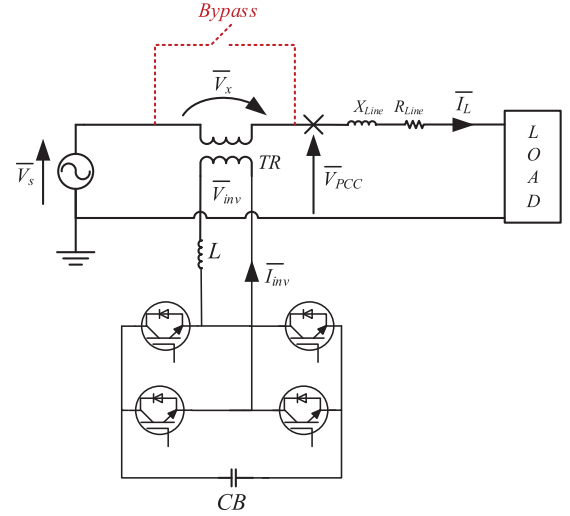


Fig. 1. DVC single-phase configuration.

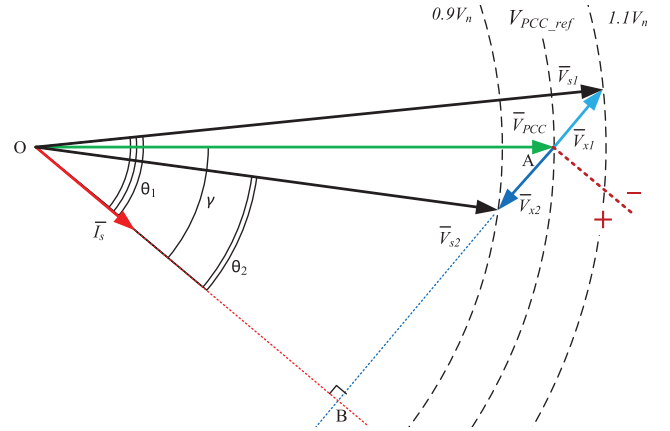


Fig. 2. DVC nonactive operation principle.

without absorbing active power from the grid. Fig. 2 shows the system working principle in steady state condition with inductive load for both under \bar{V}_{s2} and over voltage \bar{V}_{s1} events.

From Fig. 2, using trigonometric equations in right triangle OAB , the injected voltage magnitude can be calculated as (2). In (2), i can be either 1 or 2 depending on compensation state and γ is the phase difference between PCC voltage and line current, θ_i is the phase difference between network voltage and line current and V_{xi} is the calculated injected voltage magnitude. As it can be noticed from Fig. 2 and (2), the formula gives negative and positive values for V_{xi} in different compensation scenarios

$$V_{x_cal} = V_{xi} = V_{PCC_ref} \cdot \sin(\gamma) - V_s \cdot \sin(\theta_i). \quad (2)$$

Equation (2) gives the magnitude of DVC-injected voltage. This value should be injected perpendicular to the line current. So, the angular frequency of line current should be moved 90° to get the right injected voltage angular frequency.

B. Operation Limits

The proposed DVC, depends on device nominal voltage ($|V_{x,max}|$), load power angle (γ), and requested reference

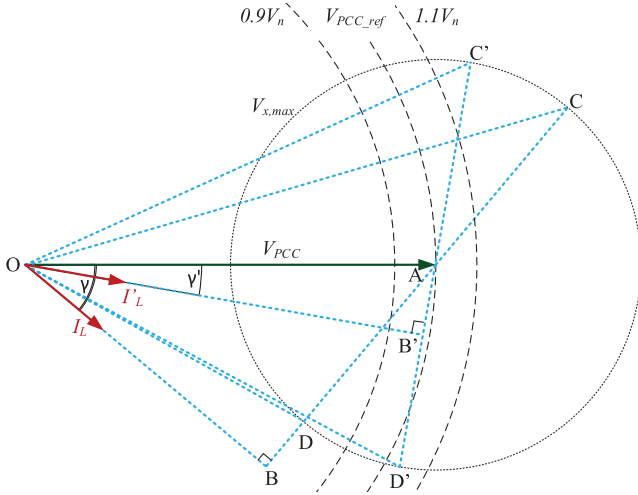


Fig. 3. DVC nonactive operation, voltage compensation limits.

voltage ($|V_{PCC,ref}|$), has upper and lower compensation limits on V_s . Fig. 3 shows these limits for two different load conditions, with two different load currents I_L, I'_L and corresponding load power angles γ, γ' . It can be noticed that, based on V_s value and independent from the load condition, there are two cases; over voltage *Case 1* and under voltage *Case 2*. Both cases limits are evaluated in the following.

1) *Case 1, Over Voltage*: From Fig. 3, triangle OAC or OAC' can be used to evaluate the upper limit in two different load conditions. The maximum value of over voltage, that can be compensated with nonactive power only, is proportional to the segment OC or OC' . The (3) represents the maximum grid voltage that can be compensated with nonactive power only and it is required to get the nominal V_{PCC} voltage for the first load condition

$$\begin{aligned} \overline{OC} &\equiv |V_{s,max}| \\ &= \sqrt{|V_{PCC,ref} \cdot \sin(\gamma) + V_{x,max}|^2 + |V_{PCC,ref} \cdot \cos(\gamma)|^2} \end{aligned} \quad (3)$$

According to (3), over voltage compensation range characteristics can be shown versus inverter rating voltage ($V_{x,max}$) and γ variation as it is shown in Fig. 4.

It can be noted that increasing both $V_{x,max}$ and γ , the over voltage compensation range increases. The $V_{x,max}$ is a design parameter and it would be fixed during design procedure and cannot be changed. Indeed, γ depends on load and it varies continuously during operation. This characteristics function is useful during hardware design procedure to set inverter rated voltage and also to design the control method. For the first one; analyzing the feeder over voltage history, the load power factor profile and knowing the interested over voltage compensation range, it is possible to use these data to properly design the DVC inverter hardware. For the second one; the limits are used inside control method in order to guarantee safe and continues operation of the device, as it is described in the following.

During operation, if V_s is more than maximum value, the DVC can injects active power for few periods only so after that,

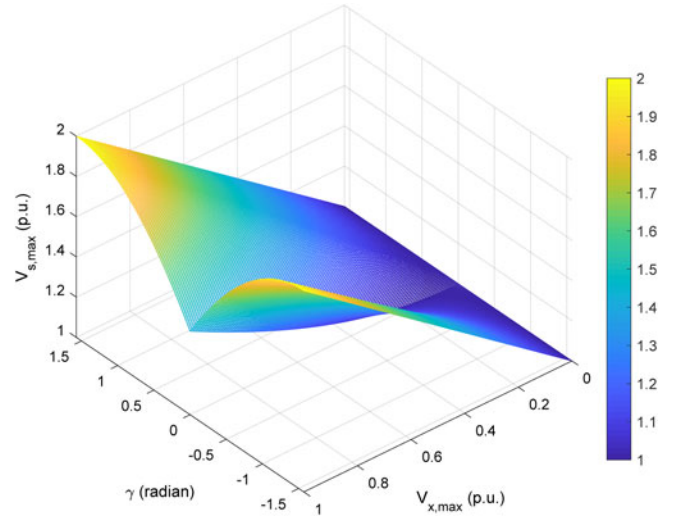


Fig. 4. DVC over voltage compensation range versus inverter rating voltage and load power angle variation.

if the voltage variation is a long event, the $|V_{PCC,ref}|$ has to be updated because the DVC cannot reach the reference value. By solving (3) with respect to $V_{PCC,ref}$, a second order polynomial equation can be obtained and solving it, two values can be got. Negative value will require large V_x injection, so, it is not the optimal solution. The positive one (4), is the new achievable reference for $V_{PCC,ref}$ in order to update the control method and find new injection voltage (V_x)

$$\begin{aligned} V_{PCC,ref} &= -V_{x,max} \cdot \sin(\gamma) \\ &+ \sqrt{(V_{x,max} \cdot \sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \end{aligned} \quad (4)$$

2) *Case 2, Under Voltage*: In this case, DVC has two possible limits and it is necessary to evaluate both of those and finally decide on the right one.

a) *Limit Due to $V_{x,max}$* : From Fig. 3, the inverter nominal voltage ($V_{x,max}$), imposes limits on under voltage compensation range that can be evaluated by the triangle OAD or OAD' . The minimum value of under voltage that can be compensated with nonactive power only, is proportional to the segment OD or OD' . Equation (5) represents the minimum grid voltage due to $V_{x,max}$ that can be compensated with nonactive power for the first load condition

$$\begin{aligned} \overline{OD} &\equiv |V_{s,min,a}| \\ &= \sqrt{|V_{PCC,ref} \cdot \sin(\gamma) - V_{x,max}|^2 + |V_{PCC,ref} \cdot \cos(\gamma)|^2} \end{aligned} \quad (5)$$

b) *Limit Due to Power Angle (γ)*: From Fig. 3, the load power angle (γ), imposes limits on compensation ranges that can be evaluated by the triangle OAB or OAB' . The minimum value of under voltage that can be compensated with nonactive power only, is proportional to the segment OB or OB' . Equation (6) represents the minimum grid voltage due to γ that can be compensated with nonactive power for the first load condition

$$\overline{OB} \equiv |V_{s,min,b}| = |V_{PCC,ref} \cdot \cos(\gamma)|. \quad (6)$$

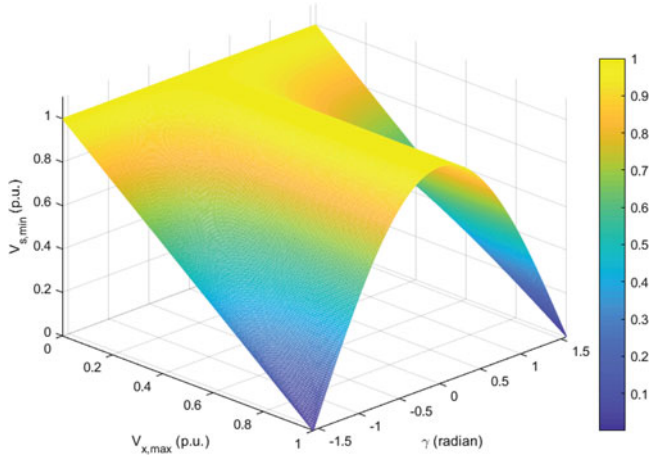


Fig. 5. DVC under voltage compensation range versus inverter rating voltage and load power angle variation.

Depends on the system condition, either (5) or (6) has to be considered as control limit for *Case 2*, so if $V_{x,max} > V_{PCC} \cdot \sin(\gamma)$ the $V_{s,min}$ has to be evaluated by (6) else by (5). When $V_{x,max} = V_{PCC} \cdot \sin(\gamma)$, (5) and (6) give the same results.

Same as over voltage case, considering (5) and (6), the characteristics of under voltage compensation range can be shown respect to DVC inverter rating voltage and load power angle, as it is shown in Fig. 5.

These information are used during hardware design as well as control method design procedure.

During operation, if the V_s is less than minimum value, the DVC can inject active power for few periods only so after that, if the voltage variation is a long event, the $|V_{PCC,ref}|$ has to be updated to the limit value that can be achieved by the DVC. To update the new reference value, reverse calculation of (5) and (6) has to be performed with respect to $V_{PCC,ref}$. Therefore, there are two different limits and it is necessary to evaluate both of them for corresponding condition.

a-update) Limit due to $V_{x,max}$: If the limit is due to $V_{x,max}$, *case a*, solving (5) with respect to $V_{PCC,ref}$ will lead to a second order quadratic equation and two possible solutions can be found. Again in this case, the negative value should be ignored and the positive one, (7), is the optimal solution

$$V_{PCC,ref} = V_{x,max} \cdot \sin(\gamma) + \sqrt{(V_{x,max} \cdot \sin(\gamma))^2 + V_s^2 - V_{x,max}^2} \quad (7)$$

b-update) Limit due to power angle (γ): In this case, the new achievable reference, $V_{PCC,ref}$, can be found as

$$V_{PCC,ref} = \frac{|V_s|}{\cos(\gamma)} \quad (8)$$

In this condition, when the minimum limit is reached, it is necessary to evaluate if $V_{x,max} > V_{PCC} \cdot \sin(\gamma)$; so, the $V_{PCC,ref}$ should be updated by (8) otherwise by (7). When $V_{x,max} = V_{PCC} \cdot \sin(\gamma)$, (7) and (8) give the same result.

In order to guarantee DVC intrinsic stable continuous operation, $V_{PCC,ref}$ update procedure has to be implemented inside the control system.

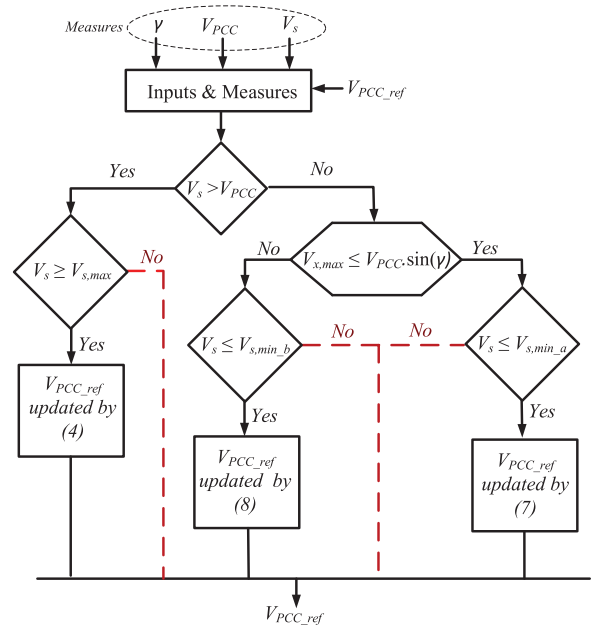


Fig. 6. DVC, PCC reference voltage update flowchart for V_x calculation.

C. $V_{PCC,ref}$ Update

Considering limits, complete flowchart to update the $V_{PCC,ref}$ for V_x evaluation is shown in Fig. 6. The flowchart in Fig. 6 is implemented following the same concept as the limits of the system were extracted. First, the measured V_s voltage is compared with V_{PCC} in order to understand in which case (*Case 1* or *Case 2*) the system is, then, by checking corresponding equation, it has been evaluated that either the system exceeded its limits or not. If the system exceeds the corresponding limit, $V_{PCC,ref}$ needs to be updated otherwise, the system is inside the limits and it can continue operating with nominal or set $V_{PCC,ref}$. The only point is when the system is in *Case 2*, under voltage condition, where it is important to understand which limit should be considered, limit due to $V_{x,max}$ or limit due to γ . To do so, $V_{x,max}$ is compared with $V_{PCC} \cdot \sin(\gamma)$ instantaneous value in order to chose the right limit (due to $V_{x,max}$ or due to γ). If it is necessary, the $V_{PCC,ref}$ value should be updated and the new value has to be used in (2) to find the V_x magnitude for $v_x(t)$ calculation, as it is reported in the next section.

The situations, shown by dashed lines in Fig. 6, are for the conditions where the system is inside its compensation range and $V_{PCC,ref}$ does not need to be updated. So, it depends on system operation condition, either original $V_{PCC,ref}$ or the updated one will be used as $V_{PCC,ref}$ to generate $v_x(t)$ for inverter voltage controller. Implementing this strategy, the system can continue to operate even if the load power angle and grid voltage are not enough to guarantee the set $V_{PCC,ref}$. Instead the reference value will be updated, DVC will do its best and the system can avoid any instability and failure.

III. CONTROLLER DESIGN

Several control strategies for series connected compensator are proposed in literature, such as single loop voltage control, voltage control with feedforward signal, and double loop control

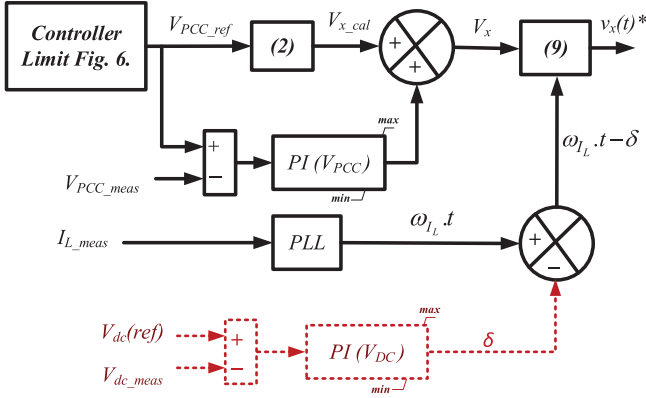


Fig. 7. DVC reference voltage generation block diagram.

with outer voltage control and inner current loop [17]. The double loop control method has been found more suitable for proposed DVC, due to its capability to manage wide load current variation and avoid current distortion during both short-, fast- and long-term voltage variations [22]. The proposed controller needs instantaneous voltage reference to be followed by DVC inverter. Therefore, a sinusoidal reference signal need to be generated as reference for inverter voltage controller. In order to generate this reference signal, it is important to take into account the system limits as it was explained in Fig. 6 flowchart. With the output of Fig. 6 ($V_{PCC.ref}$), it is possible to evaluate $V_{x.cal}$ by (2). To have better control on PCC voltage, an extra PI controller ($PI(V_{PCC})$) is also used and the output is added to the calculated value by (2), as it is shown in Fig. 7. The output is considered as V_x to generate the reference voltage value as it is reported in (9)

$$v_x(t)^* = \sqrt{2} \cdot V_x \cdot \sin\left(\omega_{I_L} \cdot t \pm \frac{\pi}{2} - \delta\right). \quad (9)$$

The injected voltage angular frequency should be perpendicular to the line current angular frequency (ω_{I_L}). ω_{I_L} is extracted from I_L measure using a PLL system. Evaluated ω_{I_L} needs to be shifted 90° and it has been implemented by adding $\pm\pi/2$ to the I_L angular frequency. $\pm\pi/2$ is due to the nature of the load (if inductive, $\pi/2$ is subtracted from the line current angular frequency, while if the load is capacitive, $\pi/2$ should be added) so positive or negative sign in (9), are for capacitive and inductive loads, respectively.

During the working period, the DVC has some losses and it is necessary to compensate those. In real working condition, this can be obtained by changing the voltage injection phase of the angle δ . In this way, the DC bus voltage can be managed to be quite constant around set value. It should be noted that, DC bus voltage control capability of DVC, is function of load current. This controller has been put in evidence by dashed line inside Fig. 7. The DC bus PI controller is designed much slower than main controllers, in order to avoid any effects on mains voltage compensation performance.

When $V_{PCC.ref}$ is inside the standard limits or it can be obtained with nonactive power injection, the DVC control strategy can use the generated voltage $[v_x(t)^*]$ as reference voltage for inverter, otherwise any other DVR control strategy can be used

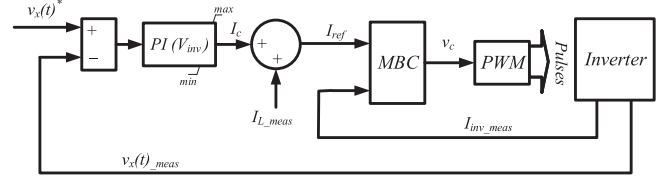


Fig. 8. DVC inverter double loop controller.

TABLE I
PI CONTROLLERS DESIGNED GAIN VALUES

| | |
|---------------|------------------------|
| $PI(V_{PCC})$ | $k_p = 2.0, k_i = 40$ |
| $PI(V_{DC})$ | $k_p = 0.5, k_i = 5.0$ |
| $PI(V_{inv})$ | $k_p = 0.2, k_i = 2.0$ |

[12]–[17]. For the proposed DVC control system, the obtained reference voltage $[v_x(t)^*]$, is fed to voltage source inverter controller, as it is shown in Fig. 8.

Inverter controller is meant to produce reference $v_x(t)^*$ voltage at its ac side terminal. The inverter should operate as a voltage generator and several works have suggested to use a PWM-based voltage controller. However, since the DVC is a series connected device, as a typical DVR and as it has been analyzed in [22], during transient the system can disturb the line current. In distribution system, the load can change significantly and in uncontrolled manner and this can worsen the DVC operation. Thus, it has been recommended to use a double loop controller for such systems [22]. Therefore, a double loop controller has been used as inverter controller where the outer voltage controller is a PI controller indeed, as inner current controller a model based current controller (MBC) is adapted as it was explained in [23]. Inverter double loop controller is illustrated in Fig. 8. Three different PI controllers have been used inside the control system. Since the system model is quite complex and nonlinear one, Ziegler–Nichols method has been used to design the PI controllers [24]. The three PI controllers designed gain values are reported in Table I.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. System Design Consideration

In [25], several design aspects of a DVR are evaluated, so this paper can be used as a good reference to design the DVC series connected device. Before following [25], two important correlated aspects need to be defined to correctly size the DVC: the first one is related to the presence of a fast protection system (as a fast static switch bypass system or a fault current limiting system [26], [27]) and the second one is related to the coupling transformer turn ratio. In order to illustrate the working principle of the DVC only, in current work the system is designed according to full power of the line (50 kVA), so the fast protection system is not included and, to limit over sizing on inverter IGBT switches (400 A/1200 V), the coupling transformer is designed with a turn ratio k equal to 1.5 (detail analysis of these systems' functionalities and the choice of the turn ratio will be covered in future publications). Selecting the coupling

TABLE II
SIMULATION AND EXPERIMENTAL SETUP PARAMETERS

| Symbol | Object | Specification |
|-------------|---|---|
| – | IGBT modules | 400 A to 1200 V |
| TR | Coupling transformer | Turn ration 1.5 to nominal power 50 kVA |
| CB | Inverter DC bus capacitor bank | 74.8 mF 1000 V-DC |
| $V_{x,max}$ | DVC maximum injection capability | 200 V rms AC |
| L | Switching inductance | 1 mH to 300 A |
| C_f | Inverter and line side low-pass filters | 100 μ F to 240 V AC |
| – | Inverter switching frequency | 4 kHz |

transformer k , it is straight forward to design inverter DC bus voltage, its switching inductance (1 mH/300 A) and low-pass filters (100 μ F/240 V) for inverter and line side, according to [25] and [28].

In particular, the inverter DC bus capacitance is designed according to the required energy to support the full load in case of fast-term voltage variations (sag/swell events) for about 20 cycles with a maximum DC voltage variation of about 200 V. By these consideration, the DC bus is designed with 74.8 mF/1000 V capacitor bank and it has been controlled about 600 V; however, during fast-term voltage variation (sag/swell) it is allowed to drop till minimum 400 V or increase till 800 V.

It is worth to mention that the proposed DVC if it works inside its operation limits, it is able to regulate voltage at PCC to its nominal/set value using mainly nonactive power only, but this does not mean that outside operation limits the device is useless. Actually outside its operation limits it is able to deal with short- and fast-term voltage variations as a same sized DVR.

Results presented in this work are focused on long-term voltage drift rather than short- and fast-term voltage variations. Indeed, voltage compensation in the range from 0.9 to 1.1 p.u is very important, and often not considered in literature, mainly for DSO (they can manage their network power profile [29] and improve voltage profile when the network voltage touches the minimum standard limit [19], [30]).

The DVC configuration shown in Fig. 1 is simulated by MATLAB software and a laboratory prototype is realized. The simulation and experimental prototype parameters are reported in Table II.

MATLAB-based simulation is performed with discrete fixed step solver and as experimental prototype Texas Instrument TMS320F28335 microcontroller is used to apply the control logic. The realized DVC experiment setup is shown in Fig. 9. The device is the series unit of an Open UPQC [19]. In order to verify proposed device performance, several scenarios are reported in the following.

B. Operation Limits and V_{ref} Update

Section II has shown that over voltage compensation limits is mostly function of DVC inverter rating voltage while under voltage compensation limits is mostly function of load power factor.

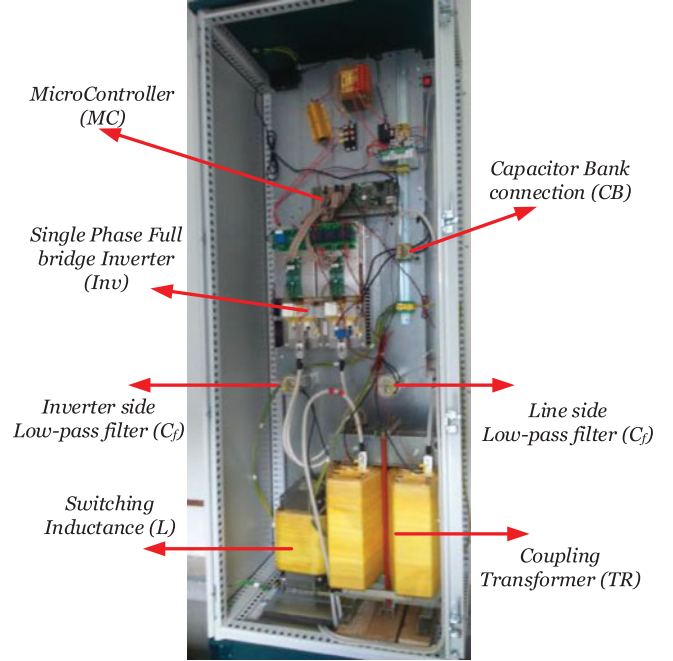


Fig. 9. DVC experiment setup.

Considering that under voltage is most probable than over voltage, here as most relevant issue, under voltage event is reported for $V_{PCC,ref}$ update. Therefore, in case of an under voltage event, if $V_{x,max}$ is close to the nominal voltage network and with a low load power factor, (6) is always valid to find the minimum under voltage compensation limit $V_{s,min}$. But if the grid side voltage V_s and/or the load power factor $\cos(\gamma)$ are/is decreasing, the DVC would not be able to compensate the voltage drop with nonactive power only. So, the reference value has to be updated to the maximum achievable PCC reference value $V_{PCC,ref}$, which can be found from (8), in order to avoid DVC instability. Therefore, in order to show the $V_{PCC,ref}$ updating procedure of DVC, the following simulation is reported.

The simulation is carried out with constant under voltage at grid side and a load power factor equal to 0.9 till $t = 2$ s ($P = 8000$ W and $Q = 3875$ Var), therefore, in this contest the procedure has to be updated immediately. Considering the inverter maximum voltage, $V_{x,max}$ equal to 200 V the $V_{x,max}$ is greater than $V_{PCC} \cdot \sin(\gamma)$ and (6) is valid to find under voltage operation limits rather than (5). With $\cos(\gamma) = 0.9$ and using (6), the minimum grid side voltage is equal to 207 V so till $t = 2$ s the DVC is able to compensate 10% voltage drop with nonactive power compensation method as it is shown in Fig. 10 when V_s is equal to 207 V and $V_{PCC,ref} = 230$ V.

At $t = 2$ s till the end of simulation, the load is simulated to have a reactive power step change (load became $P = 8000$ W and $Q = 2630$ Var) so, the load power factor increases to 0.95 and new $V_{s,min}$ has to be calculated from (6), and replacing $\cos(\gamma)=0.95$, it becomes 218.5 V, as it is shown in Fig. 10(a). With this new values, the DVC is not able to compensate 10% voltage drop, but only 5.5%, with nonactive power only. So, the reference value is updated to the maximum achievable PCC reference value which can be found from (8). Using (8), new reference value can be found and it is equal to $V_{PCC,ref} = 217$ V

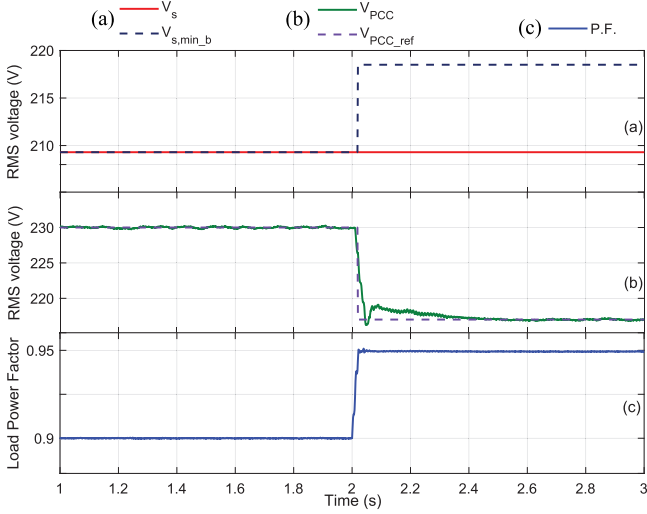


Fig. 10. Simulation – DVC operation limit update procedure under voltage – limits due to γ : Case 2.b) – (a) grid and minimum grid voltage, (b) PCC and PCC reference voltage, and (c) load power factor.

as it is presented in Fig. 10(b). Fig. 10(c) shows load side power factor variation.

C. Load Variation

Several load variation simulation results are addressed in [20], here experimental results are reported to verify device operation under load variation. The test under investigation is an over voltage test in which the grid side voltage is constant and equal to 220 V and the PCC voltage reference is set to 215 V (to make sure that DVC will operate inside its working limit during the test). So, as before, the voltage control has to be instantaneous because the device works inside its limits. Fig. 11 shows the DVC recorded response – adding and removing a resistive 1400 W load to the initial or final load of about 1200 VA ($P = 800$ W and $Q = 850$ Var), respectively.

Fig. 11(a)–(c) results show the DVC response to adding 1400 W load at about $t = 0.085$ s. Fig. 11(a) shows the PCC voltage, it experiences very small and negligible disturbance. Fig. 11(b) shows the DVC-injected voltage that, due to the small difference between V_s and PCC reference voltage during all the experiment, has a small magnitude (around 10 V rms) even when adding load causes phase and magnitude change on it. Fig. 11(c) shows load current that without any over or under shoot sees a step change after adding the load, thanks to the implemented double-loop controller and specially MBC as DVC current controller.

Fig. 11(d)–(f) results show the DVC response to removing 1400 W load at about $t = 0.07$ s. So, the DVC starts working with $P = 2200$ W and $Q = 850$ Var constant load. Fig. 11(d) shows V_{PCC} profile during this transient. As it can be noticed, removing the load has almost no effect on PCC voltage profile. DVC-injected voltage, V_x , sees small phase and magnitude variation as it is shown in Fig. 11(e). Same as previous case, the injected voltage during the experiment had about 10 V rms value because the grid side voltage and PCC set values were close to each other.

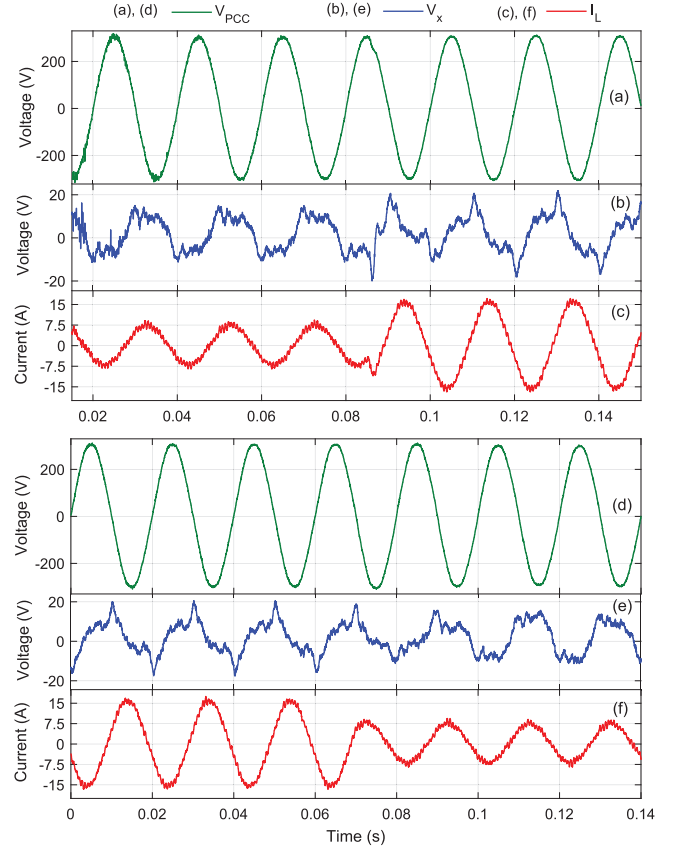


Fig. 11. Experimental – DVC response to load variation, adding, and removing the load – (a), (d) PCC voltage, (b), (e) DVC-injected voltage, and (c), (f) load current.

Finally load current variation is illustrated in Fig. 11(f) and as it was expected, it experiences a phase shift during transient but again thanks to adapted controller, there is no rapid changes on its magnitude.

D. Over and Under Voltage Compensation Performance

Here experimental results are reported to verify device voltage compensation in the range from 0.9 to 1.1 p.u. The voltage variations are simulated by means of a Variac connecting the DVC device at the output of it. By moving the Variac output, it is possible to create about 10% voltage variation. The grid measured voltage value during the test was about 218 V, so in the over voltage case, the Variac output voltage and the $V_{PCC,ref}$ have been set to 90% of the input value, while in the under voltage case, the Variac output voltage and the $V_{PCC,ref}$ have been set to 100% of the input value.

Fig. 12 shows the experimental results in the over voltage case. The device was working in steady state and at about $t = 0.22$ s, the Variac output has been increased to 100% in 6–7 periods. As it can be noticed from Fig. 12(a), that shows the instantaneous voltages V_{PCC} and V_s , voltages are equal before the event, once the over voltage is triggered, the DVC manages the PCC voltage constant by nonactive power compensation strategy. Due to the adapted strategy, there is only a small amount of phase displacement between V_{PCC} and V_s , when V_x

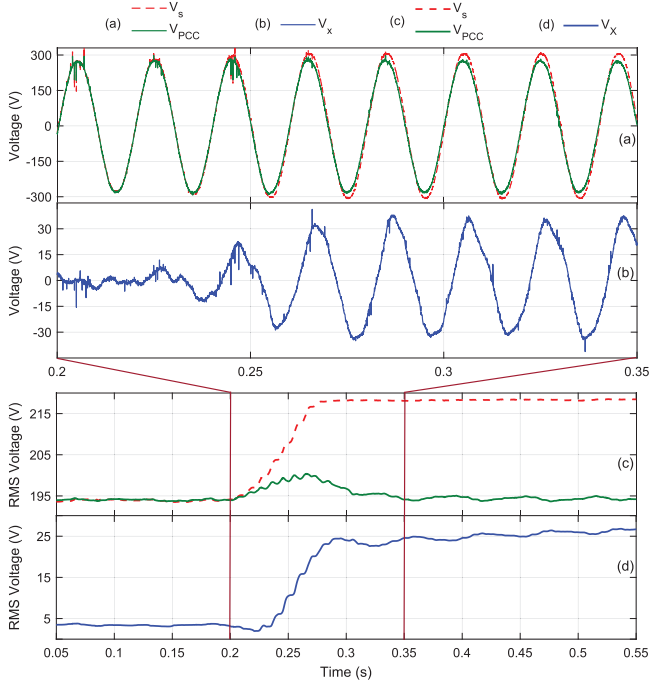


Fig. 12. Experimental – DVC over voltage compensation – (a), (b) transient response grid side, PCC and DVC-injected voltages, and (c), (d) grid side, PCC and DVC injected rms voltages.

magnitude changes, however, it is not possible to detect this effect in Fig. 12(a). Fig. 12(b) depicts V_x instantaneous voltage, when the event starts, its magnitude and phase change to compensate the over voltage. Fig. 12(c) shows the V_{PCC} and V_s rms values before and during the explained over voltage event. During it, the DVC keeps the voltage at PCC unaffected by means of injected voltage which is shown in Fig. 12(d). The results in Fig. 12(c) shows that before the over voltage event, DVC injects about 3 V which means to compensate DVC losses in order to keep its DC bus voltage constant at set value. During the over voltage event, DVC injects about 25 V to compensate the event. It is worth to mention that, when the over event starts, the inverter DC bus voltage increases slightly and once the DC bus voltage controller starts to regulate the DC bus voltage, it restores DC bus voltage to the set value slowly. In experiment, it took about 10 s to restore the DC bus voltage to its set value.

Fig. 13 shows the experimental results in the under voltage case. The device was working in steady state and at about $t = 0.2$ s, the Variac output has been decreased to 90% in 6–7 periods. Fig. 13(a) shows the instantaneous voltages V_{PCC} and V_s . Before $t = 0.2$ s, the V_{PCC} and V_s were completely matched to each other, while, when the voltage drop is triggered, the controller is able to restore the V_{PCC} ; so, the V_{PCC} voltage with minor variation is kept unaffected to any distortion. As previous case, the small amount of phase displacement between V_{PCC} and V_s is present, even if it is not possible to detect this effect in Fig. 13(a). Fig. 13(b) illustrates V_x instantaneous voltage when the event begins, its magnitude and phase change to compensate the under voltage. Fig. 13(c) and (d) show experimentally recorded V_{PCC} , V_s , and V_x rms voltage values for the

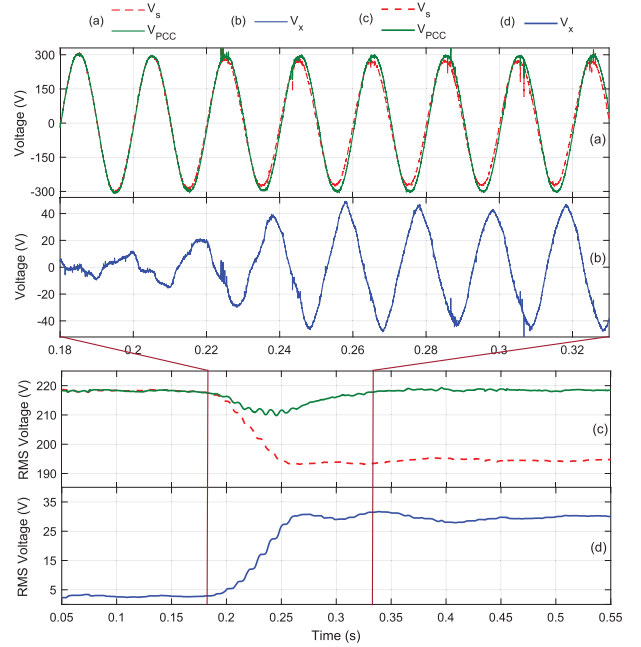


Fig. 13. Experimental – DVC under voltage compensation – (a), (b) transient response grid side, PCC and DVC-injected voltages, and (c), (d) grid side, PCC and DVC injected rms voltages.

explained event. Similar to the previous case, when the PCC and grid side voltages are equal, the DVC injects about 3 V in order to compensate system losses and to keep DC bus voltage regulated, while, after the under voltage event, the DVC injects about 30 V to compensate voltage drop at grid side and regulate voltage at PCC by means of nonactive power compensation strategy. When the event happens, the inverter DC bus voltage changes but contradictory to the previous case, the DC bus voltage decreases slightly during the voltage drop. Once the DC bus voltage controller starts to regulate the DC bus voltage, the controller restores its DC bus voltage to the set value slowly, it takes about 10 s to reaching the set value.

V. DISCUSSIONS AND CONCLUSIONS

A new device concept, which goes beyond typical DVR functionalities, is presented. The proposed device is named DVC, it is an active voltage conditioner able to cover both short- and fast-events, as a typical DVR, and long-events (in the grid voltage range from 0.9 to 1.1 p.u.). So it can perfectly satisfy modern power system DSO requirements. In particular the paper presents only the control strategy that can be adapted during steady state condition (long-events) for a single-phase DVC. Indeed, the steady state condition is not reported in literature and the single-phase configuration seems to be the best economic solution for smart grid LV distribution system. The device controller, here introduced for first time, has been designed to operate with nonactive power during steady state condition. So, to guarantee DVC continuous working, the paper describes a control method to generate DVC reference voltage considering its limits. Moreover, single-phase design can decrease device initial cost and it is also more compatible with LV distribution and mostly single-phase domestic loads.

Designed control method is verified by MATLAB-based simulation and laboratory experimental testbed. Results show that the device has good performance and it can improve PQ level of the installed distribution Smart Grid network effectively (mainly in the grid voltage range from 0.9 to 1.1 p.u.). This is essential for, nowadays, modern network because the proposed DVC can give flexibility to the system operator in order to move all problematic single-phase loads on a specific phase (where the DVC is installed).

Even if the paper analyzed a single-phase system, all the theoretical analysis on device limits can be extended for three-phase system and it will be addressed in future works. It should be noted that this solution, since it injects the compensation voltage in quadrature to line current, creates phase shifting on installed phase voltage and this can impose voltage unbalance issues to the supplied three-phase loads. Therefore, this device can be used effectively in LV distribution network with single-phase loads only.

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