

Energy storage system control algorithm for voltage regulation with active and reactive power injection in low-voltage distribution network

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ABSTRACT

The voltage drop affecting consumers at the end of distribution lines is one of the problems regarding power quality. The solutions applied to transmission lines are not fully effective in distribution lines, where line parameters are significantly high. In low-voltage distribution network, the reactive power compensation method is not as effective as active and reactive power compensation. This effect occurs on lines where the significant series resistance becomes remarkable in relation to the total line impedance. This paper presents the design and implementation of a four-wire, three-phase voltage source converter (VSC) with output current control for voltage regulation at the point of common coupling (PCC), using active and reactive power injection. A reactive power prioritization and minimization of active power strategy is proposed to overcome the problem of distribution line parameters. Digital design methodology is used to design the management controllers and loops, and a digital signal controller (DSC) is used for the entire implementation. The mathematical analysis results are validated using numerical simulation and proven with the construction of a 3.8 kVA prototype. The results showed that the converter accomplished an effective voltage regulation at the PCC with reduced active power.

1. Introduction

The increase in power consumption, the use of non-linear loads and the growth of distributed generation systems have led governments and regulatory agencies to demand increasingly better power quality [1]. Voltage drop is one of the most important power quality problems and can be found in consumers connected to low-voltage distribution lines [2]. Lines with a high impedance value form subsystems considered as weak grids, since they have a significant value of resistances and inductances in line distributed parameters. Problems such as efficiency loss, equipment malfunction and communication interference are some of the observed effects [3,4].

The use of static compensators (STATCOMs) is a solution for voltage regulation, through the injection of reactive power at the connection point of loads [5]. This strategy is effective when used in transmission or distribution systems with predominantly inductive line impedance. When applied to distribution lines, they are called DSTATCOMs [6–8]. However, in weak grids, the voltage regulation with a DSTATCOM requires excessive reactive power due to the high R/X line grid ratio, making reactive power regulation less effective in low-voltage grids [9–11]. That factor leads to two main problems: the need for a converter with a very high nominal power to ensure regulation, and

excessive reactive power circulation in the distribution transformer, which can lead to equipment damage. To try to get around such problems, a minimum power point tracking (mPPT) is proposed in [8], allowing the supply voltage to oscillate around the nominal voltage, respecting local regulatory standards. This paper demonstrates that, in practical situations, the power required for regulation may exceed the nominal power of the feeder by up to three times.

To overcome such problems, some papers propose the use of energy storage systems (ESS). Those systems can work at specific times or critical situations. ESS devices can be used to solve general power quality problems [10,11], such as voltage and frequency variations [12], or apply strategies to increase battery life [13] and work to complement intermittent energy sources [14], i.e. energy shifting and solar smoothing scenario [15,16].

Kabir et al. [10] proposes a decentralized control scheme to keep supply voltage within acceptable values in a distributed generation grid. In this scenario, the reactive capability of photovoltaic (PV) inverter is combined with droop-based battery energy storage (BES) system to address voltage regulation problem. The PV power generation is stored in the BES system for later voltage regulation. However, the strategy does not indicate whether there is any priority between active and reactive energy. Also, according to the results presented, the stored

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active energy is used even before the reactive energy, which can lead to a reduction in BES lifetime. Considering payback to consumers who have installed solar systems, reducing the active energy injected by the PV inverter is not an attractive option. A voltage control system presented by Carvalho et al. [11] uses reactive power to maintain the supply voltage without major disturbances, even with the injection of the active power from the distributed generation. Active energy injected into the network by the DG systems can produce voltage rise problems and network reactive power rating reduces the impact of high penetration of distributed generation.

An algorithm is proposed by Lee et al. [12] to control battery energy storage systems (BESS), where an improvement in power quality is sought by having the systems minimize frequency deviations and power value disturbances. As a result, the system acquires a smoother load curve, becoming more stable. The strategy uses the energy stored in the battery systems to improve the voltage and frequency deviation and produce an improvement in the load factor. Despite the advantages, such successive changes and discharges operations contribute to reduction of the BESS life span. Furthermore, large-scale BESS systems are still economically unfeasible due to the high cost of batteries, however the reactive energy usage with a hybrid strategy could reduce operating costs.

Another paper that uses ESS is presented in [13], however Nagarajan et al. aim to increase battery life, reduce operating costs and system losses. A modeling and optimization algorithm is used, which seeks to reduce the cycles and avoid high rates of battery charges and discharges. Although the focus is on the battery system of a network with intermittent PV generation and with appropriate results in energy shifting and solar smoothing strategies, the impacts of reactive energy are not clearly evaluated, for example, in moments of system inactivity or low battery state. These actions could improve the results by increasing the efficiency of the proposed system or even prolonging the state-of-health (SoH) of battery system.

Several voltage regulation techniques using active and reactive power can be found in the papers presented. However, no control strategy was found that searches for the least amount of active power coming from the storage systems for voltage regulation, a determining factor for the cost and service life of those storage systems.

This paper proposes an active and reactive power injection control scheme for voltage regulation in low-voltage power distribution grids. The proposed strategy is based on the search for the least amount of active power required for voltage regulation. The increase in service life and the reduction of maintenance costs for ESS devices, the improvement of voltage regulation in weak grids and the reduction of current stresses in the system's components are some of the advantages of the proposed system. There are different types of storage technologies available currently. The batteries are comprised mainly of ESS in current power systems, with control and power conditioning working together. The batteries are rated in terms of their energy and power capacities with some other important features like efficiency, lifespan, operating temperature, depth of discharge, self-discharge and energy density [17]. However, in this paper ESS devices are considered to be always available, fully loaded with independent current and voltage control, which is why storage system control is not described in this paper and usage can be found in related papers [18–20].

This paper is organized as follows. In Section 2, the voltage drop problem and the mathematical analysis of power circulation in low-voltage lines are presented. Section 3 is dedicated to the proposed compensation method and to the description of the operating algorithm. The system's configuration and the control loops are described in Section 4. In Section 5, the results of the experiments performed in the laboratory to validate this paper's studies are presented. In Section 6 a comparative analysis using a battery system is presented. Finally, the conclusion and discussions are presented in Section 7.

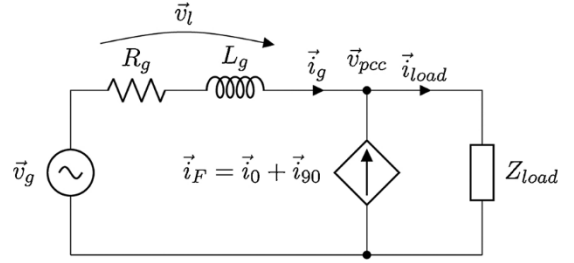


Fig. 1. Low-voltage grid single-phase equivalent model.

2. Voltage drop in distribution grid

Consider the scenario shown in Fig. 1, where a low-voltage grid with line-impedance is connected through the PCC to local loads and to the converter. The circuit represents one of the phases of the three-phase system. The converter uses sinusoidal references synchronized with the grid to generate the direct and quadrature currents, indirectly controlling the power that is injected into the PCC. Considering that the RMS voltage variation is low, the power can be assumed to have a direct relation with the current generated by the converter. The phasor representation of the equivalent circuit is given by:

$$\vec{v}_g = \vec{v}_{pcc} + \vec{v}_l = \vec{v}_{pcc} + \vec{Z}_g(\vec{i}_{load} - \vec{i}_F) \quad (1)$$

where $\vec{i}_F$ represents the converter current which is the sum of the in-phase current with the quadrature current.

Multiplying the equation by the term $\vec{v}_{pcc}^*$:

$$\vec{v}_g \vec{v}_{pcc}^* = \vec{v}_{pcc} \vec{v}_{pcc}^* + \vec{Z}_g(\vec{S}_{load}^* - \vec{S}_F^*) \quad (2)$$

where Z_g represents the line impedance, $\vec{S}_{load}$ the apparent power consumed by the load and $\vec{S}_F$ the apparent power supplied by the converter. Therefore, from (2) the real and imaginary portions are obtained, for $\vec{v}_{pcc} = V_{pcc} \angle -\theta^\circ$ and $\vec{v}_g = V_g \angle 0^\circ$:

$$V_g V_{pcc} \cos(\theta) = R_g(\Delta P') + X_g(\Delta Q') + V_{pcc}^2 \quad (3)$$

$$V_g V_{pcc} \sin(\theta) = R_g(\Delta Q') - X_g(\Delta P') \quad (4)$$

where:

$$\Delta P' = P_{load} - P_F \quad (5)$$

$$\Delta Q' = Q_{load} - Q_F \quad (6)$$

where P_{load} and Q_{load} are the active and reactive power consumed by the load and P_F and Q_F are the active and reactive power supplied by the converter. From (3) and (4), an expression for the RMS voltage at the PCC can be obtained, represented by:

$$V_{pcc}^4 + V_{pcc}^2(2A - V_g^2) + (B^2 + A^2) = 0 \quad (7)$$

where:

$$A = R_g(\Delta P') + X_g(\Delta Q') \quad (8)$$

$$B = R_g(\Delta Q') - X_g(\Delta P') \quad (9)$$

The function roots that satisfy the condition (7) are:

$$V_{pcc}' = \pm \sqrt{\frac{V_g^2 - 2A \pm \sqrt{(2A - V_g^2)^2 - 4(A^2 + B^2)}}{2}} \quad (10)$$

There are four solutions for (10), two positive and two negative, which can be disregarded, because they have no physical meaning. Among the positive solutions, only one is observed to be stable, which is the one adopted in this paper.

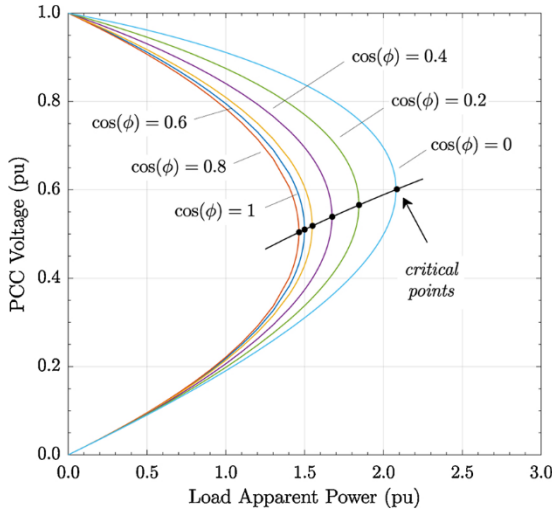


Fig. 2. Relationship between transmitted power and voltage for stability operation points.

There is a maximum value of active power that can be transmitted through an impedance from a voltage source. The critical operating point corresponding to maximum power represents the limit of satisfactory operation. Fig. 2 shows voltage at the PCC and power being transmitted to the load. Only the operating points above critical points are acceptable for a stable system operation [21,22].

3. Compensation method

The proposed compensation method consists of the injection of reactive and active power for voltage regulation at the PCC, prioritizing the reactive power in the regulation process. Initially, reactive power is used until it is no longer possible to increase the voltage to the desired level, due to the converter's power limitation. From that moment on, the active power is inserted, in addition to the reactive power.

This strategy's operation is demonstrated using the circuit in Fig. 1 and based on (7). From that, two voltage limits are defined at the PCC, called precarious and critical, represented respectively by the planes α and β , which are based on international standards [23,24]. A feeder supplying electricity to generic loads by a 30 kVA–13.8 kV/380 V three-phase transformer is considered as a test case network, with a 30 kVA–220/380 V three-phase power converter. In weak grids, loads are placed far away from main feeder transformer and have a high R/X line ratio. In this scenario, a distance of 400 m is considered with a 2.392 line ratio, to simulate weak parameters of line resistance and inductance [25]. A per-unit system is used, then the nominal phase-neutral voltage $V_{nom} = 220$ V is used as base voltage and the single-phase power rating of $S_{nom} = 10$ kVA is used as base power, given by:

$$\alpha = \frac{V_{\alpha}}{V_{base}} = \frac{200.95}{220} = 0.9134 \text{ pu} \quad V_g = \frac{V_{nom}}{V_{base}} = \frac{220}{220} = 1.0 \text{ pu} \quad (11)$$

$$\beta = \frac{V_{\beta}}{V_{base}} = \frac{188.82}{220} = 0.8583 \text{ pu} \quad S_g = \frac{S_{nom}}{S_{base}} = \frac{10,000}{10,000} = 1.0 \text{ pu} \quad (12)$$

The response graphs are presented for each of the possible compensation cases in Fig. 3. The vertical axes represent the voltage at the PCC for Fig. 3(a–c), the injected reactive powers for Fig. 3(d–f) and the injected active powers for Fig. 3(g–i). The horizontal axes represent the

power factor variation and the load apparent power, with the intent to cover all possible load conditions.

The three cases are presented in Table 1. In case I, no compensation is applied. Therefore, voltage regulation is not expected, even when voltage levels exceed their limits, as shown by the surface in Fig. 3(a). The values of power injected by the converter, Fig. 3(d, g), are null. In case II, the compensation is restricted to the reactive power, that is, only quadrature current is injected into the PCC. Thus, it can be seen in Fig. 3(b) that, under the highest load power conditions, violations are observed in the minimum voltage limits at the PCC. The reactive power injected by the converter reaches its limit, as shown in Fig. 3(e). Even then, the allowed voltage value is transgressed. The active power is kept null, as shown in Fig. 3(h).

Finally, in case III, references in phase and in quadrature are used, therefore, active and reactive power are used. It is then possible to regulate the RMS voltage at the PCC without increasing the total converter power, as shown by the surface in Fig. 3(c). In the case in which the regulation voltage value is set to $\alpha = 0.91$ pu, the lowest value allowed by the standard [26], little active power usage is observed for the voltage regulation, as shown in Fig. 3(f, i).

Based on the presented cases, it can be concluded that a control strategy that can use active and reactive power is advantageous for voltage regulation in distribution grids. Therefore, there is a need for a control algorithm that can work on current references and take the system to the best available use of power.

4. Control algorithm

The voltage regulation at the PCC is based on the injection of active and reactive power, through the dc-ac converter's current control. Fig. 4 shows the simplified load connection circuit and the converter with the diagram of the proposed control algorithm. In this system, a shunt power converter is connected between the grid and loads at the point of common coupling. The functional block diagrams of the control loops necessary for the operation of the converter, as well as the measured variables, are shown.

Fig. 5 shows, in detail, the used cascade control, which has an outer loop for voltage regulation at the PCC and an inner loop for current control. The active damping loop is used to attenuate the resonance of the output filter and to obtain a stable response from the control system.

The control algorithm was designed to maintain the voltage at the regulated PCC, fluctuating within the limits imposed by the standards. To achieve that, active and reactive powers are injected, and the role of the proposed algorithm is to coordinate the power injection. The inner and outer loops are designed independently between the phases, being able to operate with single-phase or three-phase unbalanced loads without affecting the strategy performance.

The control is designed to reject harmonic component disturbances that may be present in the grid voltage. Furthermore, high frequency is filtered by the LCL output filter. This filter only allows current with the fundamental component to be injected by the converter to the network.

4.1. Inner control loops

The model for the inner current control loop is obtained from the equivalent single-phase circuit in Fig. 6. The current transfer function due to the duty cycle applied to the converter, disregarding all parasitic resistances, is given by:

$$G_i(s) = \frac{i_{L2}(s)}{d(s)} = \frac{E}{L_1 L_2 C_1 s^3 + (L_1 + L_2) s} \quad (13)$$

This inner control loop receives the references from the outer loops,

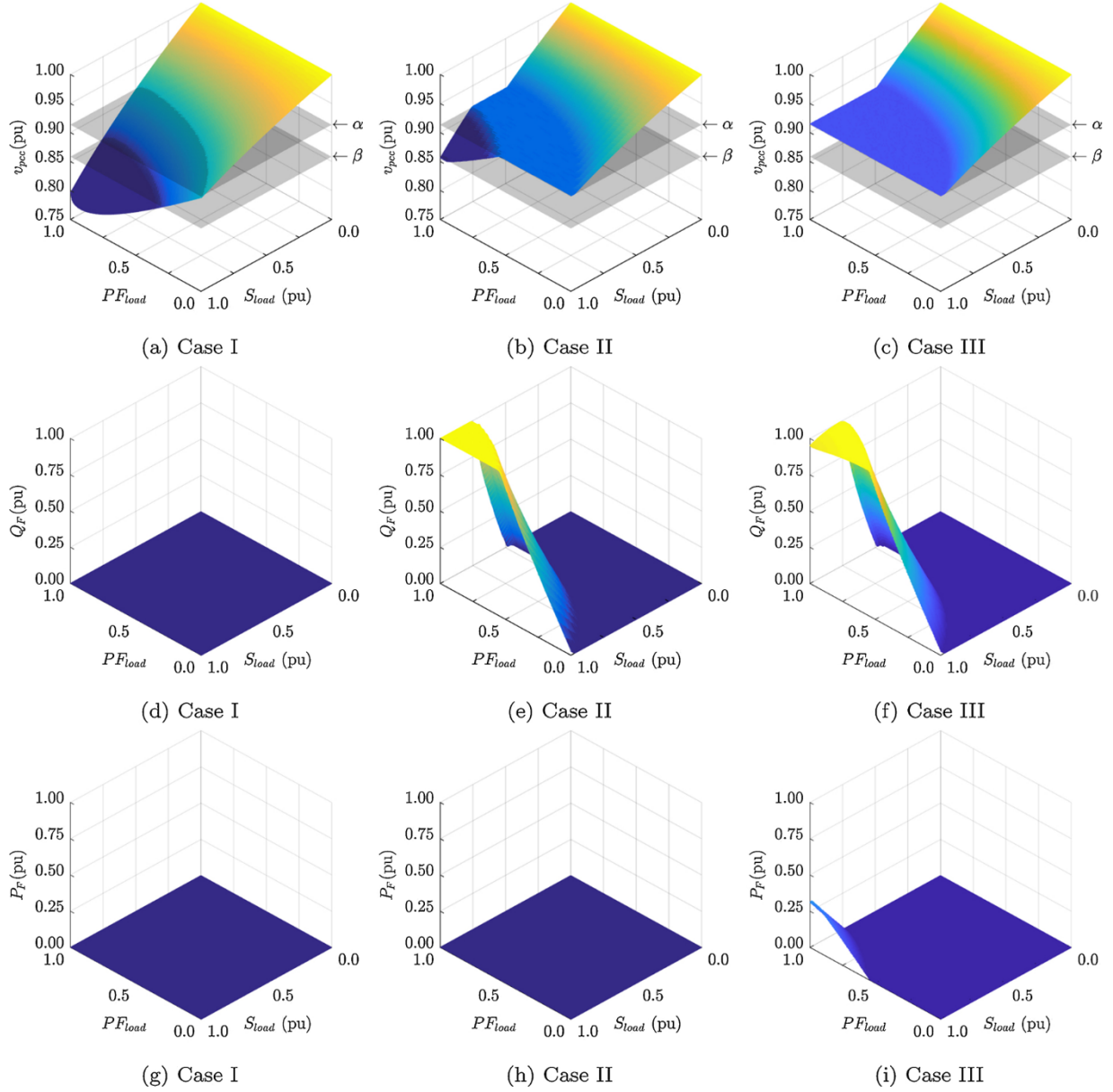


Fig. 3. (a–c) RMS voltage at the PCC (v_{pcc}), (d–f) reactive power supplied by the converter (Q_F), (g–i) active power supplied by the converter (P_F). Results for RMS voltage regulation at the PCC for the appropriate minimum voltage limit (α) in cases I, II and III. Simulation data: ($V_{min} = \alpha = 0.9134$ pu; $V_g = 1.0$ pu; $\beta = 0.8583$ pu; $R_g = 0.1600$ pu; $X_g = 0.0669$ pu, $R_g/X_g = 2.392$).

Table 1
Three different voltage regulation scenarios.

Case	Voltage regulation	Q_F	P_F	S_F
I	None	$= 0$	$= 0$	$= 0$
II	Partially	$0 < Q < 1$	$= 0$	$0 < S < 1$
III	Completely	$0 < Q < 1$	$0 < P < 1$	$0 < S < 1$

because of the cascade control. Control is done in the natural frame of reference abc and, therefore, proportional-resonant (PR) controllers are used. The practical PR controller is chosen because it only has high gain in the resonance frequency, unlike the ideal PR, which has infinite gain at that frequency, providing greater stability [27,28]. As multiple frequencies are desired to be controlled, multiple resonant controllers are placed in parallel [29]. The transfer function of a practical PR controller is given by:

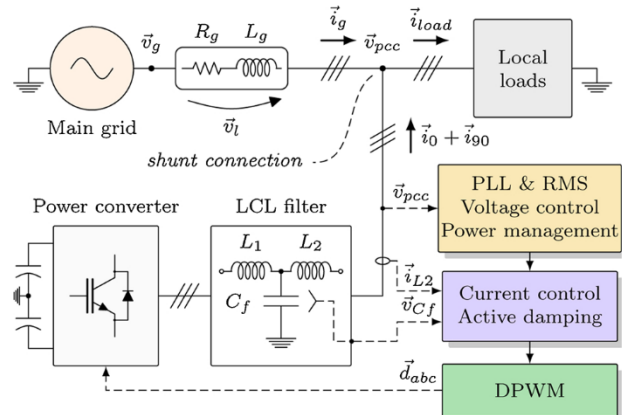


Fig. 4. Schematic diagram of shunt power converter connected between the local loads and low voltage grid at the PCC.

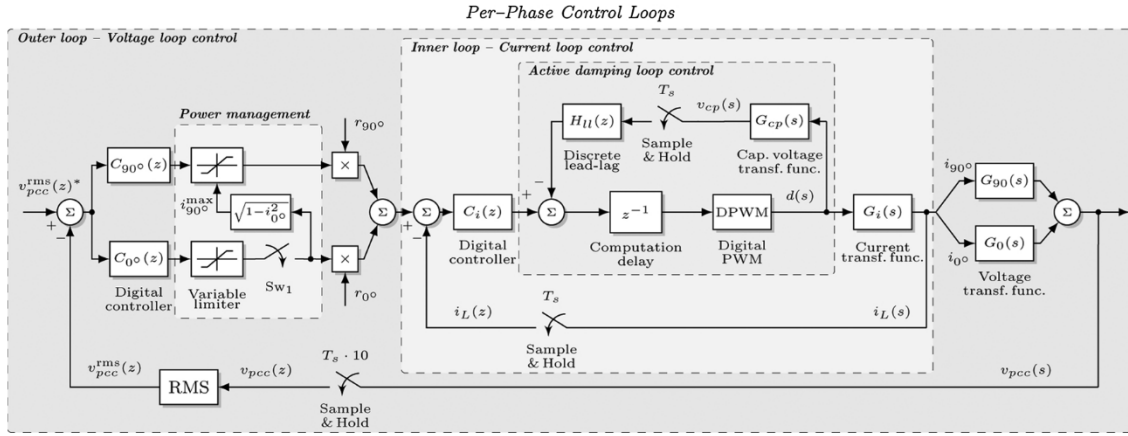


Fig. 5. Block diagram of inner control loop with current and resonance damping network, outer control with RMS voltage at PCC network and power management strategy of proposed ESS control algorithm.

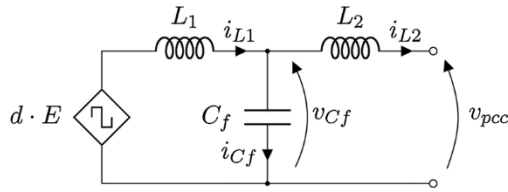


Fig. 6. Current single-phase equivalent model.

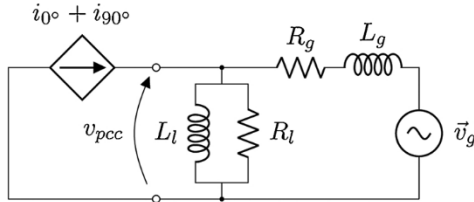


Fig. 7. Voltage single-phase equivalent model.

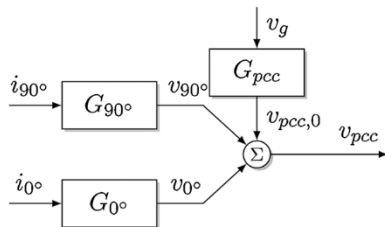


Fig. 8. Voltage single-phase equivalent model with coupled terms.

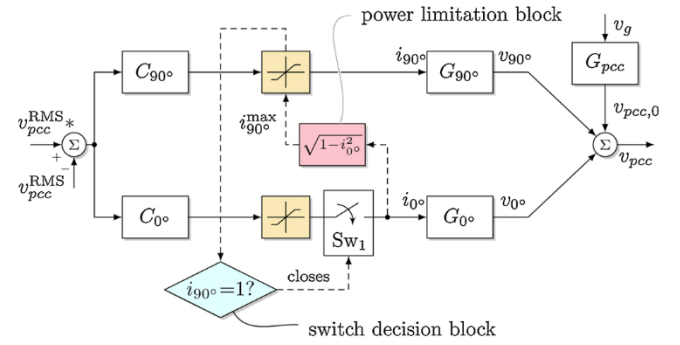


Fig. 9. Voltage loop control with proposed algorithm.

frequency $f_{c,i} = 645$ Hz, with respective gains $k_{i,h} = \{3, 1, 0.75, 0.5, 0.25\}$, damping factor $\zeta_{i,h} = 2\pi \cdot \{0.3\}$ and the proportional gain $k_p = 0.0105$. In this loop the sampling frequency is the same as the switching frequency of $f_{s,i} = 19.980$ kHz.

The current plant to be controlled has a resonance peak which, if not adequately attenuated, can lead to system instability. Such attenuation can be done using a capacitor current reading technique i_{Cf} . However, this technique that measures only the capacitor voltages v_{Cf} ,

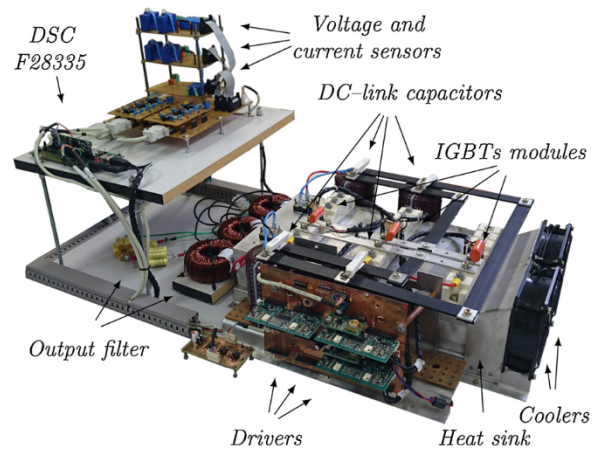


Fig. 10. Three-phase prototype built in laboratory.

$$C_i(s) = k_p + \sum_{h=1,3,5,7,9} k_{ih} \frac{(2 \cdot \zeta_h \cdot \omega_h) \cdot s}{s^2 + (2 \cdot \zeta_h \cdot \omega_h) \cdot s + \omega_h^2} \quad (14)$$

where k_p is the term relative to the proportional gain, k_{ih} is the term relative to the full gain of each harmonic, the part $\zeta_h \cdot \omega_h$ sets the sideband and ω_h is the harmonic resonance frequency, where $\omega_h = h \cdot \omega_f$ for $\omega_f = 2\pi \cdot 60$ rad.

Therefore, the controller designed in the harmonic components $h = \{1, 3, 5, 7, 9\}$ has a phase margin of $PM_i = 41.5^\circ$ with zero-crossing

Table 2
Parameters of experimental setup.

Parameters	Symbol	Value	Unit
Grid phase-neutral voltage	v_g	127	V (RMS)
Grid frequency	f_g	60	Hz
Grid resistance	R_g	3.10	Ω
Grid inductance	L_g	3.80	mH
Grid ratio	R_g/X_g	2.16	
Converter-side inductance	L_1	560	μ H
Grid-side inductance	L_2	1.0	mH
HF filter capacitance	C_f	5.0	μ F
Switching frequency	f_{sw}	19,980	Hz
Inner loop sampling freq.	$f_{s,i}$	19,980	Hz
Outer loop sampling freq.	$f_{s,o}$	1998	Hz
DC link voltage	v_{dc}	500	V

avoids the use of additional current sensors [30].

The active damping loop uses lead-lag controllers, as they allow the shunt action to be applied within a delimited frequency band, avoiding the occurrence of high frequency amplification, as can occur in a pure shunt. The controller used is presented by (15):

$$H_{ll}(s) = k_d \cdot C_f \cdot \omega_m \cdot \left(\frac{s + k_f \cdot \omega_m}{s + \omega_m / k_f} \right) \quad (15)$$

where k_f is given by:

$$k_f = \sqrt{\frac{1 + \sin(\varphi_m)}{1 - \sin(\varphi_m)}} \quad (16)$$

where the parameter C_f is the filter's capacitance, ω_m is the frequency at which the maximum phase shift is obtained, φ_m is the desired maximum angle itself and k_d is the gain of the lead-lag loop that must be properly tuned in order not to cause system instability [31].

For the lead-lag loop, two controllers in series were selected to obtain the phase-shift angle $\varphi_m = 157.69^\circ$, with the parameter $k_f = 0.0977$ centered on frequency $\omega_m = 2\pi \cdot \{3.757\}$ kHz and proportional gain adjusted to $k_d = 0.00566$.

4.2. Outer control loops

The RMS voltage at the PCC is controlled by an outer loop, which uses the model obtained from the equivalent circuit in Fig. 7. In this

single-phase model, the converter is represented by a controlled current source injecting current $i_{0^\circ} + i_{90^\circ}$, the loads are a type RL parallel arrangement, and the grid is composed of v_g and its line parameters of the RL type series.

By observing the equivalent circuit, it can be concluded that the final voltage at the PCC is a composition of three voltage portions. The first portion depends on the grid voltage and line parameters ($v_{pcc,0}$), another portion depends on the converter current in phase with the fundamental voltage component at the PCC (v_{0°) and the last portion depends on the converter current in quadrature (v_{90°). The transfer function representing the final voltage ratio (v_{pcc}) at the PCC is described as:

$$v_{pcc} = \underbrace{G_{pcc} \cdot v_g}_{v_{pcc,0}} + \underbrace{G_{0^\circ} \cdot i_{0^\circ}}_{v_{0^\circ}} + \underbrace{G_{90^\circ} \cdot i_{90^\circ}}_{v_{90^\circ}} \quad (17)$$

Such dependence is shown, in block diagram, in Fig. 8. The currents are represented in two portions due to the controller's ability to independently synthesize the reference currents i_{0° and i_{90° . Each current term produces an increase in voltage, whose regulation effectiveness directly depends on the line parameters R_g and L_g .

The transfer function which, in its complete form, represents the interdependence of variables, is presented in (18):

$$v_{pcc} = \frac{s(R_l L_l)}{s^2(L_g L_l) + s(L_g R_l + R_g L_l + R_l L_l) + R_g R_l} \cdot v_g + \frac{s^2(L_g R_l L_l) + s(R_g R_l L_l)}{s^2(L_g L_l) + s(L_g R_l + R_g L_l + R_l L_l) + R_g R_l} \cdot i_{0^\circ} + \frac{s^2(L_g R_l L_l) + s(R_g R_l L_l)}{s^2(L_g L_l) + s(L_g R_l + R_g L_l + R_l L_l) + R_g R_l} \cdot i_{90^\circ} \quad (18)$$

In Fig. 9, the proposed algorithm of voltage control loop at the PCC is shown. The scheme coordinates the current references in phase and in quadrature, to maintain the RMS voltage regulated, using the smallest possible amount of active power. For that to occur, the controller works in two steps: Initially, the switch Sw_1 remains open ($= 0$) and the voltage regulation takes place exclusively with reactive power injection. Therefore, active power will not be used if reactive power is enough to raise up the RMS voltage to the reference value v_{pcc}^{RMS*} .

The second step begins when there is value limitation of the reference $i_{90^\circ} = 1$ (in pu), indicating that the reactive power is no longer enough to raise the RMS voltage to the reference value. At that moment, the switch Sw_1 closes ($= 1$) and the control increases the current reference i_{0° , injecting active power into the PCC. To hold the apparent

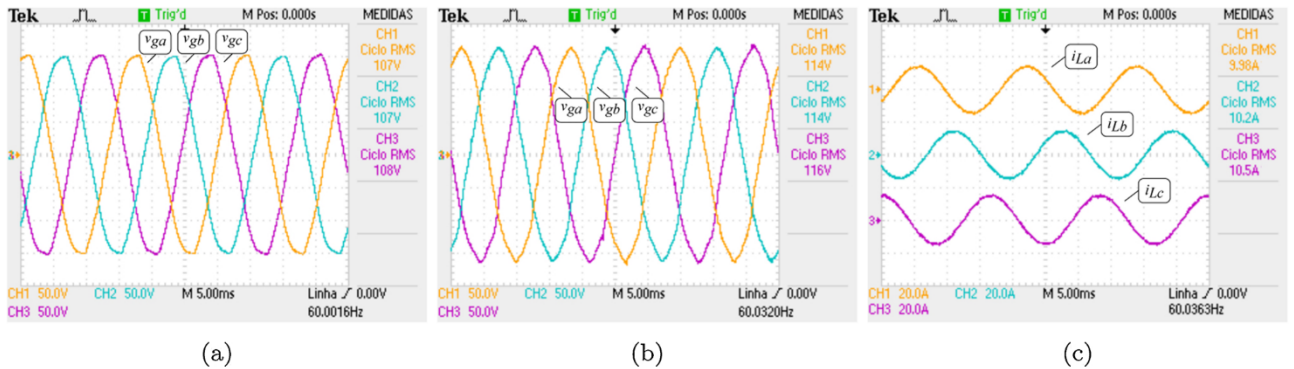


Fig. 11. Experimental steady-state performance with only reactive energy regulation. (a) Phase voltage at PCC without compensation. (b) Phase voltage at PCC with compensation, where reference voltage was not achieved. (c) Converter currents with reactive compensation only.

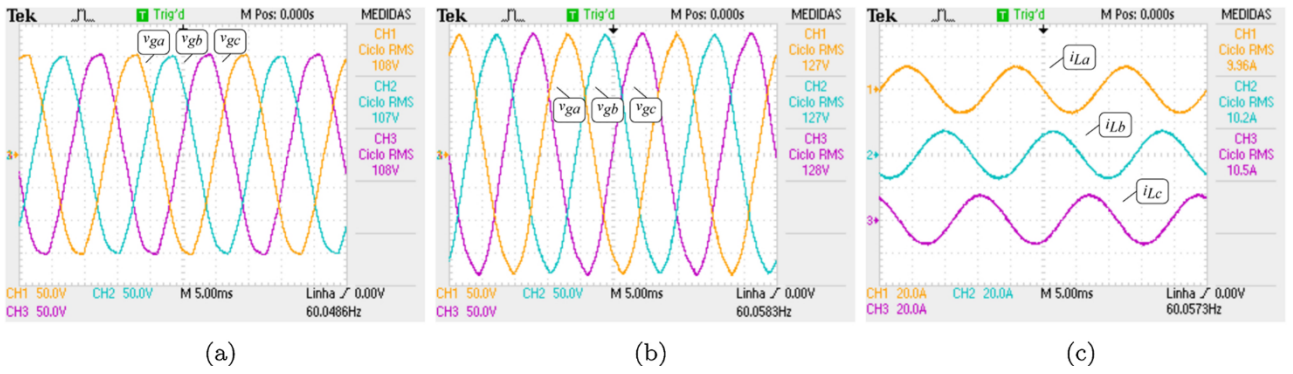


Fig. 12. Experimental steady-state performance with energy management algorithm. (a) Phase voltage at PCC without compensation. (b) Phase voltage at PCC with compensation, where reference voltage was achieved. (c) Converter currents with active and reactive compensation.

power within the limits of the converter, the term $\sqrt{1 - i_0^2}$ (in pu) in power limitation block imposes a saturation value ($i_{90}^{\max}$) for the current i_{90} . Therefore, only one controller operates inside the control loop avoiding overlapping of different control actions.

The switch Sw_1 closes according to the quadrature current i_{90} limiter state. The switch decision block sends a command signal when the limiter reaches its maximum allowable current level. This action is part of the proposed strategy, working independently and automatically.

A PI-type controller was chosen with proportional gain of $k_{pcc} = 0.0105$, zero-crossing frequency of $f_{c,pcc} = 2.5$ Hz, obtaining a phase margin $PM_{pcc} = 89.1^\circ$. The outer loop sampling frequency is ten times lower than inner loop sampling frequency, i.e. $f_{s,o} = 1.998$ kHz, essentially because the RMS voltage value varies slowly compared to current variation.

5. Experimental results

A three-phase, four-wire, 3.8 kVA prototype was built in the laboratory to demonstrate the operation of the proposed control algorithm, as shown in Fig. 10. The digital signal controller (DSC) TMS320F28335, from Texas Instruments*, was used to perform the digital control, in addition to synchronization, sampling and protection functions. Three Semikron power modules model SKM75GB063D with 75 A/600 V capacity are fixed on the aluminum heatsink with dimensions of 400 mm × 220 mm × 10 mm and forced air ventilation. At the DC bus, four EPCOS model B43586 electrolytic capacitors of 3300 μF/500 V each are used, coupled with 22 kΩ equalization resistors. The drive circuits used are SKHI 20 opA with isolated controls, with over-current protection on power switches and undervoltages. They are powered by isolated sources, model SKHI PS3, both from Semikron. For the output filter, Sendust-S26 toroidal type inductors Magmattec are used with inductance of 1.0 mH on grid-side and 560 μH on converter-side and five metallized film capacitors of polypropylene (MKT) EPCOS model B32232 of 1.0 μF/630 V associated in parallel, per phase. For the measurement system, model LA 55-P/50 A hall effect current transducers and voltage transducers, also Hall effect model LV 25-P/500 V, are used, both manufactured by LEM. The signals are conditioned and filtered to analog-digital conversion of the digital signal controller. Experimental results are divided into steady-state results and dynamic load change response. The experimental setup parameters are shown on Table 2.

5.1. Steady-state responses

The experimental steady-state results are divided into two parts. First, the results are shown for a regulation where only reactive power is used and then the results are shown using the proposed control technique. The voltage reference level has been set at 1.0 pu (127 V) to show that the adjustment capacity increases when active power is used. A static resistive load of $R_{ssr} = 3 \times \{15\} \Omega$ is used to show the steady-state responses. The adjustment is done in control software in order to disable active energy on the first test case. After that, in the second test case all the functionalities are released.

5.1.1. Reactive energy only

In Fig. 11(a–c) results for steady-state with regulation where reactive power only is used are shown. In this case, the voltages increase from {107, 107, 108} V to {114, 114, 116} V, although the 7 V increase in PCC voltage was not sufficient to raise voltage to adequate levels of regulation. The value is still 13 V below the 127 V reference voltage value. This effect occurs due to the high R/X line ratio and also because of the low inductive part ($\ll L_g$) in the weak lines. Therefore, the converter reaches its power and current limitation without raising to the voltage reference level.

5.1.2. Active and reactive energy

In Fig. 12(a–c) experimental results using the proposed control technique, with active and reactive energy available, are shown. In this case, the RMS voltage was at {107, 107, 108} V before, then increased to the reference voltage of 127 V in all phases. The 20 V raise in voltage corresponds to almost 16% of a drop in voltage value. This value is greater than that allowed by the standards for distribution lines [26], which consider a voltage drop of up to 8.7% precarious and up to 14.2% critical.

5.2. Load change responses

The energy supplied from the converter during the load changes has been recorded and is shown in Fig. 13(a, b). Two different loads were selected, one called light load $R_{ll} = \{50, 56, 61\} \Omega$, where only reactive power is enough to reach the voltage regulation. In addition, the loads are purposely slightly different from each other to show the independent phase control. And another called heavy load $R_{hl} = 3 \times \{18.67\} \Omega$, where the regulation will not be successful using only reactive power, requiring the proposed controller to identify this scenario and add the active power part in the voltage regulation.

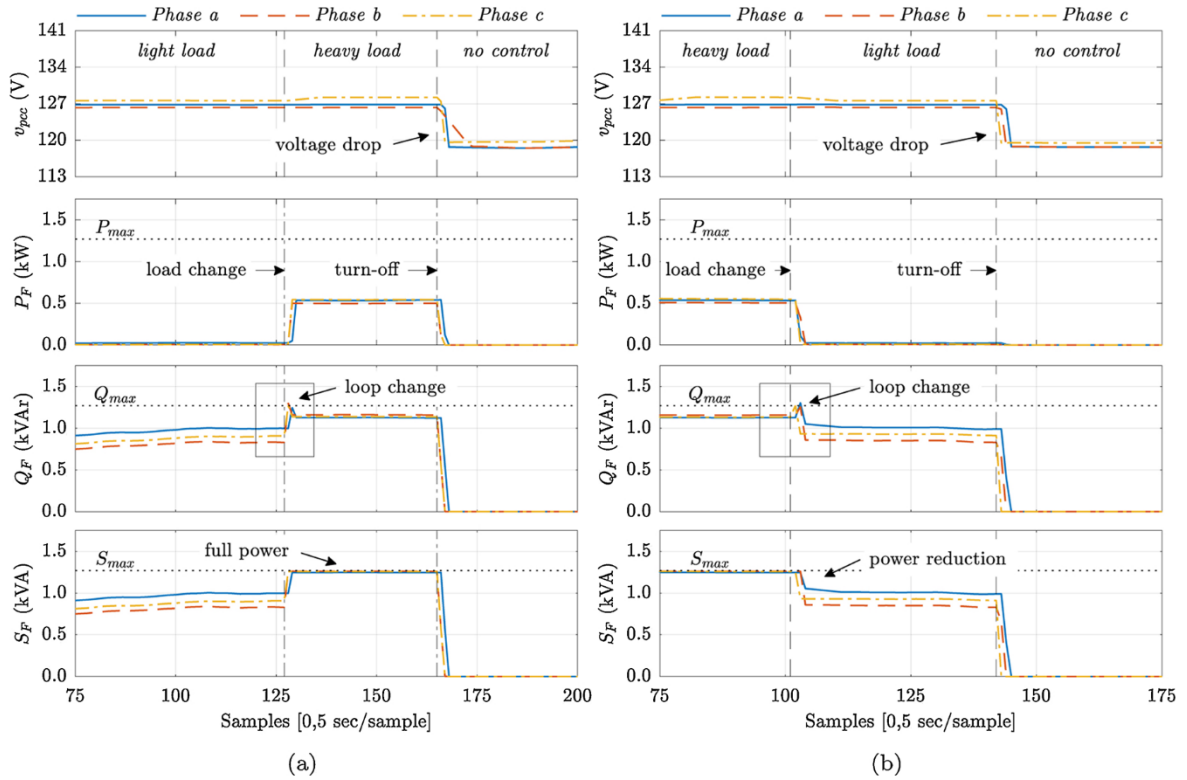


Fig. 13. Experimental results for load change: active (P_F), reactive (Q_F) and apparent (S_F) power injected by converter with energy management algorithm. (a) Load change sequence: light load, heavy load and no control. (b) Load change sequence: heavy load, light load and no control.

In Fig. 13(a) the first load change is shown. In the presence of the light load only reactive power is used, even with three slightly different loads. This results in null active¹ energy $P_{F,abc} = 0$ W and reactive¹ energy of $Q_{F,abc} = \{998.2, 907.8, 832.8\}$ VAR for the light load case. After the load exchange, the heavy load comes in place of the light load. This is done with the help of a circuit breaker which places loads in parallel and decreases the resistance. Now, with equal resistances the active and reactive powers of each of the three phases converge to the same value $P_{F,abc} = \{533.3, 542.9, 497.6\}$ W for active² energy, $Q_{F,abc} = \{1128, 1137, 1161\}$ VAR for reactive² energy and $S_{F,abc} = \{1248, 1260, 1263\}$ VA for apparent² energy, respecting the converter's total apparent power of $S_{F,total} = 3.8$ kVA.

In Fig. 13(b) an opposite situation is shown, where load reduction occurs or load resistance increase and consequently active power is no longer required. As expected, the proposed control reduces the active power to zero and only uses reactive power as pointed out previously. In both Fig. 13(a, b) the voltage control is switched off after load changes. Voltage control shut-down shows the voltage reduction from the nominal value 127 V to around 120 V without voltage regulation. This represents a 5.5% drop in nominal voltage.

6. Comparative analysis

In this section, a pack of batteries was selected for comparative analysis with the proposed system results. The storage unit is made of lithium-ion batteries providing 35 kWh of energy and 81 kW of power. These Li-ion cells are composed of a cathode of lithiated metal oxide (LiMO₂) and the anode is made up of carbon material. An electrolyte

made of lithium salts dissolved in organic carbonates with a separator made of some porous polymeric material, which insulates the electrodes and allow ionic exchanges. These lithium-ion batteries have been shown to be suitable for applications that require high energy density and a high efficiency cycle [17,32].

An independent battery management system (BMS) provides monitoring and voltage control functions in battery modules, discharge current limitation and fault management [33]. Electrical characteristics and operating conditions of the lithium-ion battery pack are shown in Table 3. Batteries are considered to be at 100% initial state-of-charge (SoC), and aging and temperature effects are not considered [34].

Performance testing considers the battery pack discharge with constant current equivalent to the power absorbed by the converter. Thus, it is possible to show the battery discharge curve and the advantages that the active and reactive power compensation brings to the batteries' lifetime, such as fewer cycles and lower working temperature due to the lower drained current [35].

The discharge model for a typical lithium-ion battery is represented by [36]:

$$E_{batt} = E_0 - R \cdot i - K \cdot \left(\frac{Q}{Q - \int i dt} \right) \cdot i^* - K \cdot \left(\frac{Q}{Q - \int i dt} \right) \cdot \int i dt + A \cdot e^{-B \cdot \int i dt} \quad (19)$$

where, E_{batt} is the battery voltage at the terminals, E_0 is constant voltage, R is the internal resistance, i is the battery current, i^* is the filtered current, K is the polarization constant, Q is the battery capacity, A is exponential voltage and B is exponential zone time constant. These parameters can be calculated according to the procedures presented in [36,37] and also shown in Table 3.

The batteries were fully charged and have been discharged until the cut-off voltage and they are considered discharged when they reach the

¹ Value read in sample 125 in Fig. 13(a).

² Value read in sample 150 in Fig. 13(a).

Table 3
Electrical characteristics and operating conditions of lithium-ion battery pack.

Saft Intensium® Smart 35M—17 × Synerion® Modules	
Parameter	Value
Nominal voltage	424 V
Operation voltage	357–479 V
Energy (C/5 rate, +25 °C)	35 kWh
Continuous discharge power (SoC 50%, +25 °C)	81 kW
Continuous charge power (SoC 50%, +25 °C)	36 kW
Maximum discharge current (SoC 50%, +25 °C)	191 A
Maximum charge current (SoC 50%, +25 °C)	85 A
Cycle efficiency, η	> 95%
Self-discharge	≤ 5% per month
Constant voltage, E_0	460 V
Internal resistance, R	5.1394 mΩ
Polarization constant, K	0.038503 (Ah) ⁻¹
Exponential voltage, A	35.6058 V
Exponential zone time constant, B	0.74014 (Ah) ⁻¹

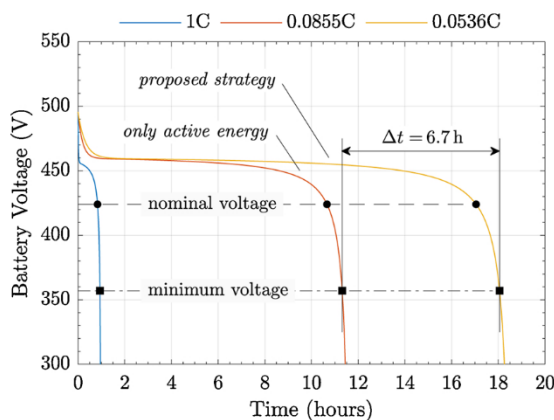


Fig. 14. Discharge curve of lithium-ion battery type for proposed cases.

minimum operating value. In Fig. 14, the results of the previous analysis are presented. Three different curves are shown. A reference measurement of battery lifetime at 1C is shown. The battery lifetime will last 0.95 h in this nominal discharge current. Another curve is the active energy only. In this case the voltage would be regulated however will use 0.0855 C from current capacity of the batteries. Finally, for the proposed strategy where reactive and active energy are used, the lifetime of the batteries will be 6.7 h longer than the other case with less drained current (0.0536 C). Battery life will extend from 11.3 h in the active case to 18.0 h in the active and reactive proposed strategy or an increase of almost 60% the lifetime. Using only reactive energy for voltage regulation will not drain energy from the batteries, so this case is not presented in this comparative analysis.

7. Conclusion

In this paper, a control system for voltage regulation at the PCC with the selective use of active and reactive power was proposed. The reduced use of active power in the voltage regulation at the PCC was proven, contributing to increased autonomy and service life of the storage system. With this strategy, the voltage values at the PCC remained within the regulatory values defined by the standards, being able to avoid equipment damage and loss for the connected consumers.

The experimental results prove not only that the PR current control had good reference tracking and disturbance rejection, but also that the output filter's active damping technique had a good response with the system in closed loop, even with the load switches. The power control

algorithm was able to keep RMS voltage at the PCC stable under the load switches. Through two cases, the control was proven to have used active power in cases where the reactive power was not enough to regulate voltage at the PCC.

The power control uses a simple digital algorithm to generate the current references, not requiring great computational efforts to execute the technique. The battery system analysis showed increased battery autonomy, and consequently a reduced number of cycles and increase in lifespan. Therefore, this technique is effective in solving voltage drop problems, especially in high R/X ratio distribution grids.

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References

- [1] X. Yu, C. Cecati, T. Dillon, M. Simoes, The new frontier of smart grids, *IEEE Ind. Electron. Mag.* 5 (3) (2011) 49–63, <https://doi.org/10.1109/MIE.2011.942176>.
- [2] Y. Wang, K.T. Tan, X.Y. Peng, P.L. So, Coordinated control of distributed energy-storage systems for voltage regulation in distribution networks, *IEEE Trans. Power Deliv.* 31 (3) (2016) 1132–1141, <https://doi.org/10.1109/TPWRD.2015.2462723>.
- [3] Y.W. Li, J. He, Distribution system harmonic compensation methods: an overview of DG-interfacing inverters, *IEEE Ind. Electron. Mag.* 8 (4) (2014) 18–31, <https://doi.org/10.1109/MIE.2013.2295421>.
- [4] J. Kaniewski, P. Szczesniak, M. Jarnut, G. Benysek, Hybrid voltage sag/swell compensators: a review of hybrid AC/AC converters, *IEEE Ind. Electron. Mag.* 9 (4) (2015) 37–48, <https://doi.org/10.1109/MIE.2015.2404350>.
- [5] B. Singh, R. Saha, A. Chandra, K. Al-Haddad, Static synchronous compensators (STATCOM): a review, *IET Power Electron.* 2 (4) (2009) 297–324, <https://doi.org/10.1049/iet-pel.2008.0034>.
- [6] M.B. Latran, A. Teke, Y. Yoldas, Mitigation of power quality problems using distribution static synchronous compensator: a comprehensive review, *IET Power Electron.* 8 (7) (2015) 1312–1328, <https://doi.org/10.1049/iet-pel.2014.0531>.
- [7] C.B. Fischer, J.R. Tibola, L.G. Scherer, R.F. de Camargo, Proportional-resonant control applied on voltage regulation of standalone SEIG for micro-hydro power generation, *IET Renew. Power Gener.* 11 (5) (2017) 593–602, <https://doi.org/10.1049/iet-rpg.2016.0857>.
- [8] R.T. Hock, Y.R. de Novaes, A.L. Batschauer, A voltage regulator for power quality improvement in low-voltage distribution grids, *IEEE Trans. Power Electron.* (2018) 2050–2060, <https://doi.org/10.1109/TPEL.2017.2693239>.
- [9] A. Samadi, R. Eriksson, L. Söder, B.G. Rawn, J.C. Boemer, Coordinated active power-dependent voltage regulation in distribution grids with PV systems, *IEEE Trans. Power Deliv.* 29 (3) (2014) 1454–1464, <https://doi.org/10.1109/TPWRD.2014.2298614>.
- [10] M.N. Kabir, Y. Mishra, G. Ledwich, Z.Y. Dong, K.P. Wong, Coordinated control of grid-connected photovoltaic reactive power and battery energy storage systems to improve the voltage profile of a residential distribution feeder, *IEEE Trans. Ind. Inform.* 10 (2) (2014) 967–977, <https://doi.org/10.1109/TII.2014.2299336>.
- [11] P.M.S. Carvalho, P.F. Correia, L.A.F.M. Ferreira, Distributed reactive power generation control for voltage rise mitigation in distribution networks, *IEEE Trans. Power Syst.* 23 (2) (2008) 766–772, <https://doi.org/10.1109/TPWRS.2008.919203>.
- [12] S.J. Lee, J.H. Kim, C.H. Kim, S.K. Kim, E.S. Kim, D.U. Kim, K.K. Mehmood, S.U. Khan, Coordinated control algorithm for distributed battery energy storage systems for mitigating voltage and frequency deviations, *IEEE Trans. Smart Grid* 7 (3) (2016) 1713–1722, <https://doi.org/10.1109/TSG.2015.2429919>.
- [13] A. Nagarajan, R. Ayyanar, Design and strategy for the deployment of energy storage systems in a distribution feeder with penetration of renewable resources, *IEEE Trans. Sustain. Energy* 6 (3) (2015) 1085–1092, <https://doi.org/10.1109/TSTE.2014.2330294>.
- [14] J. Philip, C. Jain, K. Kant, B. Singh, S. Mishra, A. Chandra, K. Al-Haddad, Control and implementation of a standalone solar photovoltaic hybrid system, *IEEE Trans. Ind. Appl.* 52 (4) (2016) 3472–3479, <https://doi.org/10.1109/TIA.2016.2553639>.
- [15] N. Korada, M.K. Mishra, Grid adaptive power management strategy for an integrated microgrid with hybrid energy storage, *IEEE Trans. Ind. Electron.* 64 (4) (2017) 2884–2892, <https://doi.org/10.1109/TIE.2016.2631443>.
- [16] D.V. de la Fuente, C.L.T. Rodríguez, G. Garcerá, E. Figueres, R.O. Gonzalez, Photovoltaic power system with battery backup with grid-connection and islanded operation capabilities, *IEEE Trans. Ind. Electron.* 60 (4) (2013) 1571–1581, <https://doi.org/10.1109/TIE.2012.2196011>.
- [17] K. Divya, J. Østergaard, Battery energy storage technology for power systems – an overview, *Electr. Power Syst. Res.* 79 (4) (2009) 511–520, <https://doi.org/10.1016/j.epsr.2008.09.017>.

- [18] R.V.A. Monteiro, G.C. Guimarães, F.A.M. Moura, M.R.M.C. Albertini, F.B. Silva, Long-term sizing of lead-acid batteries in order to reduce technical losses on distribution networks: a distributed generation approach, *Electr. Power Syst. Res.* 144 (2017) 163–174, <https://doi.org/10.1016/j.epsr.2016.12.004>.
- [19] M.R. Sarker, M.D. Murbach, D.T. Schwartz, M.A. Ortega-Vazquez, Optimal operation of a battery energy storage system: trade-off between grid economics and storage health, *Electr. Power Syst. Res.* 152 (2017) 342–349, <https://doi.org/10.1016/j.epsr.2017.07.007>.
- [20] M.-T. Tsai, C.-E. Lin, W.-I. Tsai, C.-L. Huang, Design and implementation of a demand-side multifunction battery energy storage system, *IEEE Trans. Ind. Electron.* 42 (6) (1995) 642–652, <https://doi.org/10.1109/41.475505>.
- [21] P. Acharjee, Identification of maximum loadability limit and weak buses using security constraint genetic algorithm, *Int. J. Electr. Power Energy Syst.* 36 (1) (2012) 40–50, <https://doi.org/10.1016/j.ijepes.2011.10.021>.
- [22] J.E. Tobón, J.M. Ramirez, R.E.C. Gutierrez, Tracking the maximum power transfer and loadability limit from sensitivities-based impedance matching, *Electr. Power Syst. Res.* 119 (2015) 355–363, <https://doi.org/10.1016/j.epsr.2014.10.013>.
- [23] ES/EN 50160: Voltage characteristics of electricity supplied by public electricity networks.
- [24] ANSI/C84.1: Electric power systems and equipment – Voltage Ratings (60 Hertz), National Electrical Manufacturers Association (NEMA).
- [25] A. Oury, R. Bergeron, A. Laperriere, Source impedances of the Canadian distribution systems (residential and industrial), *Electricity Distribution. Part 1: Contributions. CIRED. 14th International Conference and Exhibition on (IEE Conf. Publ. No. 438), Vol. 1* (1997), <https://doi.org/10.1049/cp:19970501> 34/1-34/8 vol.2.
- [26] ANEEL, Module 8 – Power Quality, PRODIST – Electricity Distribution Procedures in the National Electric System.
- [27] L. Herman, I. Papic, B. Blazic, A proportional-resonant current controller for selective harmonic compensation in a hybrid active power filter, *IEEE Trans. Power Deliv.* 29 (5) (2014) 2055–2065, <https://doi.org/10.1109/TPWRD.2014.2344770>.
- [28] F. Blaabjerg, R. Teodorescu, M. Liserre, A.V. Timbus, Overview of control and grid synchronization for distributed power generation systems, *IEEE Trans. Ind. Electron.* 53 (5) (2006) 1398–1409, <https://doi.org/10.1109/TIE.2006.881997>.
- [29] L.R. Limongi, R. Bojoi, G. Griva, A. Tenconi, Digital current-control schemes, *IEEE Ind. Electron. Mag.* 3 (1) (2009) 20–31, <https://doi.org/10.1109/MIE.2009.931894>.
- [30] J. Dannehl, F.W. Fuchs, S. Hansen, P.B. Thogersen, Investigation of active damping approaches for PI-based current control of grid-connected pulse width modulation converters with LCL filters, *IEEE Trans. Ind. Appl.* 46 (4) (2010) 1509–1517, <https://doi.org/10.1109/TIA.2010.2049974>.
- [31] R. Pena-Alzola, M. Liserre, F. Blaabjerg, R. Sebastian, J. Dannehl, F.W. Fuchs, Systematic design of the lead-lag network method for active damping in LCL-filter based three phase converters, *IEEE Trans. Ind. Informat.* 10 (1) (2014) 43–52, <https://doi.org/10.1109/TII.2013.2263506>.
- [32] M.S. Guney, Y. Tepe, Classification and assessment of energy storage systems, *Renew. Sustain. Energy Rev.* 75 (2017) 1187–1197, <https://doi.org/10.1016/j.rser.11.2016102>.
- [33] L. Maharjan, S. Inoue, H. Akagi, J. Asakura, State-of-charge (SOC)-balancing control of a battery energy storage system based on a cascade PWM converter, *IEEE Trans. Power Electron.* 24 (6) (2009) 1628–1636, <https://doi.org/10.1109/TPEL.2009.2014868>.
- [34] X. Han, M. Ouyang, L. Lu, J. Li, A comparative study of commercial lithium ion battery cycle life in electric vehicle: capacity loss estimation, *J. Power Sources* 268 (2014) 658–669, <https://doi.org/10.1016/j.jpowsour.06.2014111>.
- [35] N. Omar, M.A. Monem, Y. Firouz, J. Salminen, J. Smekens, O. Hegazy, H. Ghaulous, G. Mulder, P.V. den Bossche, T. Coosemans, J.V. Mierlo, Lithium iron phosphate based battery – assessment of the aging parameters and development of cycle life model, *Appl. Energy* 113 (2014) 1575–1585, <https://doi.org/10.1016/j.apenergy.09.2013003>.
- [36] L.H. Saw, K. Somasundaram, Y. Ye, A.A.O. Tay, Electro-thermal analysis of lithium iron phosphate battery for electric vehicles, *J. Power Sources* 249 (2014) 231–238, <https://doi.org/10.1016/j.jpowsour.10.2013052>.
- [37] O. Tremblay, Experimental validation of a battery dynamic model for EV applications, *World Electric Veh. J.* 3 (2009) 289–298.