




Article

Optimal Microgrid–Interactive Reactive Power Management for Day–Ahead Operation

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Abstract: The replacement of conventional generation sources by DER creates the need to carefully manage the reactive power maintaining the power system safe operation. The principal trend is to increase the DER volume connected to the distribution network in the coming years. Therefore, the microgrid represents an alternative to offer reactive power management due to excellent controllability features embedded in the DER, which enable effective interaction between the microgrid and the distribution network. This paper proposes a microgrid–iterative reactive power management approach of power-electronic converter based renewable technologies for day-ahead operation. It is designed to be a centralised control based on local measurements, which provides the optimal reactive power dispatch and minimise the total energy losses inside the microgrid and maintain the voltage profile within operational limits. The proposed optimal-centralised control is contrasted against seven local reactive power controls using a techno-economic approach considering the steady-state voltage profile, the energy losses, and the reactive power costs as performance metrics. Three different reactive power pricing are proposed. The numerical results demonstrate the optimal microgrid–interactive reactive power management is the most suitable techno-economic reactive power control for the day-ahead operation.

Keywords: day-ahead reactive power costs; microgrid; optimal-centralised reactive power management; reactive power pricing; smart converters



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1. Introduction

The reactive power is one main factor in ensuring the voltage remains within safe limits across the whole power system. The voltage-reactive power dependency must carefully be controlled, especially now when the power system is experiencing a fast and exceptional transition to become a zero-carbon industry [1]. The continuously evolving power system is mainly involving the replacement of conventional generation sources by low and zero-carbon energy sources, known as DER. The principal trend is to increase the DER volume connected to the distribution network in the coming years [2]. However, the main change is yet to come when fossil fuels are no longer used to produce electricity. It raises the need for new energy sources to provide reactive power support at transmission and the distribution level.

The microgrid, which commonly is defined as a cluster of interconnected loads and DER able of operating as a single controllable entity connected to the distribution network, has been used as an alternative to providing active power support to the main network [3]. However, its potential capabilities to provide reactive power services have not widely been examined. The DER in the microgrid are equipped with modern power electronic inverters used as an interface to connect to the network. The power electronic

converters are also called smart converters due to its excellent controllability features. They enable the microgrid to manage critical variables of the network, such as frequency and voltage [4], controllability features. Moreover, the smart converters enable more effective interaction between the microgrid and the distribution network, allowing the microgrid to be an option to deliver services and enhancing the distribution network operation and, therefore, transmission system [3]. As a result, according to the information provided by DSO, TSO has adapted its existing operational procedures and released several reactive power requirements. For instance, in the Demand and Connection Code document of the European grid code, it is requested that large renewable energy plants have the capability to restrict the reactive power flowing from distribution to transmission system [5]. The IEEE 1547–2018 standard request to DER a minimum reactive power exchange (44% of its apparent nominal power) and to be able to operate under four different reactive power control strategies [6]. Meanwhile, the IEEE 2030.7-2017 standard defines the microgrid operation and control guideline [7]. Nevertheless, the IEEE 1547–2018 standard and the IEEE 2030.7-2017 standard only refer to technical requirements; neither of those documents addresses the economic issue of active and reactive power exchanges between the DER at the microgrid and the network.

In contrast with the active power market, which has competitive established mechanisms for the pricing (e.g., novel co-optimisation mechanisms emerging in Europe [8]), reactive power procurement has a weak and limited structure. The reactive power management policies vary depending on the different deregulated electricity markets, as shown in Table 1. Consequently, the lack of regulations, pricing, and market structure for reactive power services open the door to developing new reactive power commercial frameworks that actively allow the microgrids to provide reactive power services.

Table 1. Reactive power management policies in different countries [9,10].

Country	Economic Compensation	Reactive Power Procurement	
		Transmission Level	Distribution Level
USA		—	
GB	Only reactive power services coming from synchronous generators are paid.	Special tenders for covering the reactive power needs.	At least until March 2020, there is no competitive approach to reactive power services procurement. It is handled through connections agreements which conditioning the power factor limits.
Australia		—	
Nordic countries	Reactive power services are not paid.	Mandatory reactive power provision by bilateral contracts.	
Germany		—	
Denmark	—	Special tenders for covering the reactive power needs.	

The recent scientific literature has several methodologies to address reactive power control. For instance, in [11], a centralised optimisation approach involving an adaptive power factor control and coordinated voltage control to reactive power management is proposed. In [12], a method is introduced to mitigate reactive power and current unbalance while DER are set to have a constant PQ control. In [13], a control strategy based on a multi-agent system for voltage regulation in a distributed network with high DER penetration is proposed. The authors of [14] propose a consensus-based distributed approach to local reactive power control by considering that DER provides a specified amount of reactive power. A local droop control based methodology to regulate the microgrid power flow, frequency and voltage is implemented in [15,16]. In [17], it is evaluated the impact of two reactive power control methods on the on-load tap changer and voltage regulator using active power losses and voltage as the performance index. In [18], an optimal

reactive power approach based on a voltage sensitivity matrix is introduced to minimise the voltage variation when several DER are simultaneously disconnected. In [19], an optimal multiobjective approach to regulate the active and reactive power delivered by DER in low-voltage microgrids is proposed. The main objective is maximising the active power generation and minimising the reactive power flow and current unbalance. Finally, in [20], a reactive power control strategy combining the power factor-active power and voltage-reactive power control methods are proposed. It computed the reactive power output based on DER active power dispatch and local voltage measurement to improve voltage regulation while reducing the network losses. Even though the mentioned methodologies achieve the goal of regulating the reactive power and improving the voltage profile, some of them, such as [13,14,18,20], do not address a global solution for the reactive power management due to being designed to act locally. Meanwhile, the centralised methods, such as [12,15,16,19], are developed to achieve a global solution to minimise the active power losses or the voltage deviation but not necessarily are developed to address the reactive power control as a service that can provide the microgrid.

Even though maintaining the power system safe operation is the main goal of the TSO-DSO, the economic aspect is also a key factor that cannot be ignored when it comes to services procurement. Therefore, this paper investigates the near future at which a reactive power market will be well-established, and the microgrids will actively offer ancillary services to the distribution and transmission system. Thus, this paper answers the research question: Can a microgrid grid-interactive be used as an enhancement mechanism of reactive power regulation for smart converters based renewable technologies and provide better techno-economic performance using a centralised control approach than a local control strategy? The main objective is establishing the most suitable reactive power control strategy at the microgrid to enhance the reactive power regulation, which produces the best techno-economic benefit.

In this paper, seven local reactive power management strategies available in the literature for smart converters are considered. An optimal microgrid-interactive reactive power management approach for a day-ahead operation is proposed. The day-ahead operation is considered as the schedule energy trade between the microgrid and the distribution network to supply the demand of the whole network. The optimal microgrid-interactive reactive power management approach provides the smart converters reactive power dispatch every 15 min. It is designed to be a centralised control providing a global solution to minimise the total energy losses inside the microgrid and maintain the voltage profile within operational limits. The local and centralised reactive power management strategies are assessed using the MV distribution Benchmark system. The full details of the test system parameters, load profile and PV profiles are available in [21]. The economic performance is assessed using historical price data of active and reactive power available in [22,23].

The principal contribution of this paper is unfolding below.

- The performance of seven local reactive power management strategies available in the literature for smart converters is evaluated considering system indicators: impact on steady-state voltage and energy losses of the microgrid (Section 2.1).
- The concept of a microgrid-interactive reactive power management for smart converters based renewable technologies is proposed in this paper. It is designed to work in a centralised way providing reactive power production signals to the smart converters to ensure a proper operation of the steady-state voltage profile and minimise the total energy losses inside the microgrid (Section 2.2).
- Three different approaches for reactive power price are proposed: (i) a fixed price, (ii) a variable price based on the active power price curve (iii) a variable price based on the reactive power needs (see Section 2.2.1).
- A new local and overall voltage profile index is presented, which allows determining the voltage profile of the microgrid without masking the real voltage profile of each bus (Section 2.2.2).

- The evaluation of the techno-economic benefit produced by optimal microgrid-interactive reactive power management. It is compared to the local reactive power management strategies. The numerical results demonstrate the implementation of the optimal microgrid-interactive reactive power management creates a reduction of the day-ahead active power losses and maintains the voltage profile of the microgrid within its permissible values (Section 3).

The paper is organised as follows. Section 2 lays the groundwork for the optimal microgrid-interactive reactive power management approach. First, Section 2.1 describes the local reactive power management strategies for the smart inverters available in the literature. Section 2.2 fully describes the proposed optimal-centralised reactive power management strategy, including the baseline to calculate the day-ahead energy costs (Section 2.2.1) and the performance metrics considered to assess the reactive power management strategies (Section 2.2.2). Section 3 presents the evaluation of the local and centralised reactive power strategies and its principal results. Section 4 introduces a discussion of the results and findings of this paper. Finally, Section 5 depicts the main conclusions of this paper.

2. Proposed Optimal Microgrid-Interactive Reactive Management

The microgrid control is obliged to provide several operational features established in the IEEE 2030.7-2017 standard [7]: (i) enable the microgrid to self-regulate either in autonomous operation or connected to the network so the microgrid can be seen as a single self-controlled entity, (ii) ensure a safe reconnection and resynchronisation of the microgrid with the network when it is required, (iii) capable of regulating the active power flow in the microgrid to prevent surpassing the power flow limits of the cable/lines and (iv) provide active and reactive power regulation to maintain frequency and voltage within its permissible limits during autonomous operation [3]. Moreover, the IEEE 2030.7-2017 standard states that the management of a microgrid can be done through four hierarchical control levels which can be categorised based on the timescale at which acting [7] and it is depicted in Figure 1.

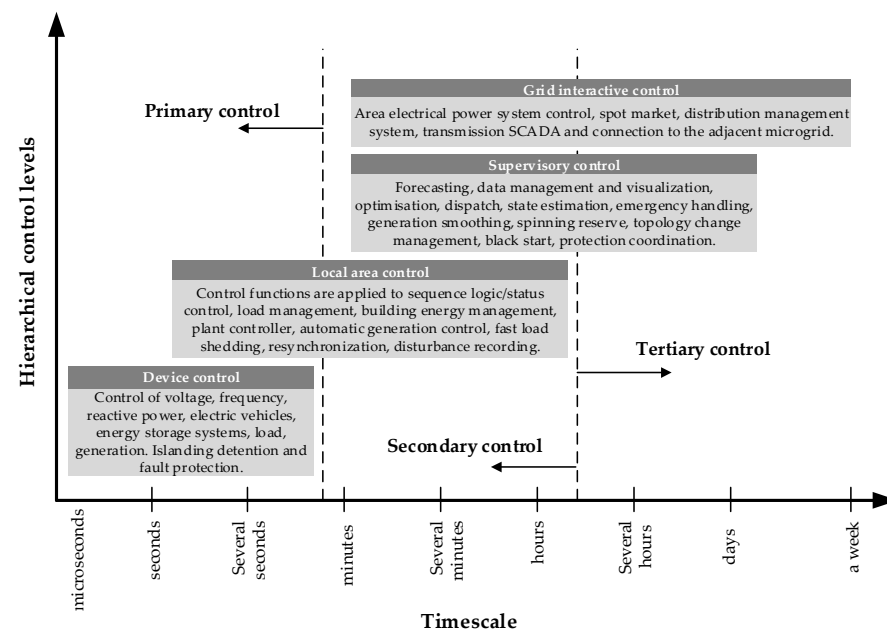


Figure 1. Hierarchical control levels to microgrid management categorised based on the timescale at which it is acting.

The microgrid control requirements established by the IEEE 2030.7-2017 standard are of paramount importance to ensure the secure operation of the microgrid and the distribution/transmission system. However, these controls are designed to meet the

microgrid interconnection requirements at PCC due to the distribution/transmission system seen the microgrid as a single controllable entity. Consequently, the controllability features offered by the DER in the microgrid are not entirely exploited, and the iteration between the microgrid and the distribution/transmission system is limited.

Traditionally, the reactive power needs of the power system have been covered by the synchronous generators and devices such as shunt capacitors/reactors and FACTS. However, the increasing replacement of synchronous generators by DER technologies and the disadvantages of the devices (low adaptability and high cost of implementation) become the smart converter installed in the microgrids a very attractive alternative to using it as local reactive power regulator this due to its controllability capabilities.

The microgrid can be designed and operated under different topologies, and all those topologies have in common that the microgrid has a single PCC to interconnect to the distribution/transmission system. Meanwhile, the DERs are connected to the microgrid through its smart converter at PoC.

The reactive power control enabled at the smart converter is usually designed to be local functionality. It means local variables are measured at the terminals of the converter, and the control algorithm is embedded in the controller of the smart converter. Typical reactive power control is designed to respond (or not) to a voltage variation at its PoC (V_{PoC}) by adjusting the injection/absorption of reactive power, as is shown in Figure 2. Several reactive power controllers have been proposed in the literature, and they are explained in Section 2.1. One of the advantages of the local controller is no need to use communication mechanisms. However, this approach does not take advantage of the potential benefit of using coordination between the smart converters and reaching a global objective instead of a sub-optimal local performance.

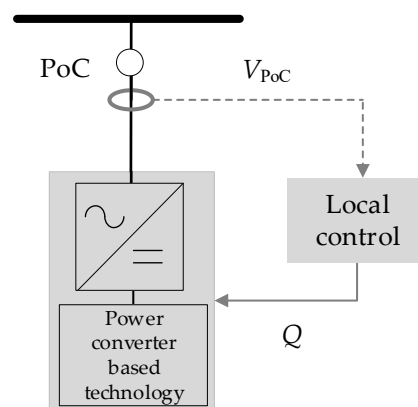


Figure 2. General scheme of the local reactive power control of a DER.

This paper takes advantage of the power converters controllability features, which are embedded in the DER, and propose a fully coordinated optimal microgrid-interactive reactive management using a centralised control approach based on local measurements. This optimal-centralised control approach, in general, uses the local measurement as input data, and the output is the control signals for each DER.

A general configuration of zero-carbon microgrid connected to the distribution system at MV level is used to illustrate the proposed optimal microgrid-interactive reactive management, and it is depicted in Figure 3. The zero-carbon microgrid has n_B number of buses, and it is equipped with n_L number of loads and n_{DER} number of DER, which are assumed to have an enabled smart converter. The optimal-centralised control inputs are $\mathbf{V} = [V_1 V_2 V_3 \dots V_i \dots V_{n_B}]$, where V_i is the i -th bus voltage; $\mathbf{P}_L = [P_{L,1} P_{L,2} P_{L,3} \dots P_{L,j} \dots P_{L,n_L}]$, where $P_{L,j}$ is the active power of the j -th load; $\mathbf{M}_k = [V_{PoC,k}, P_{DER,k}]$, where $V_{PoC,k}$ is the voltage and $P_{DER,k}$ is the active power at PoC of the k -th DER, respectively. Moreover, the measurements at PCC are the voltage (V_{PCC}) and the active power exchange with the distribution/transmission system contained in the vector $\mathbf{M}_{PCC} = [V_{PCC}, P_{D/T-S}]$.

The control signal of the k -th DER (CS_k) is the reactive power production/consumption ($Q_{P/C,k}$). The full description of this optimal-centralised control is presented in Section 2.2.

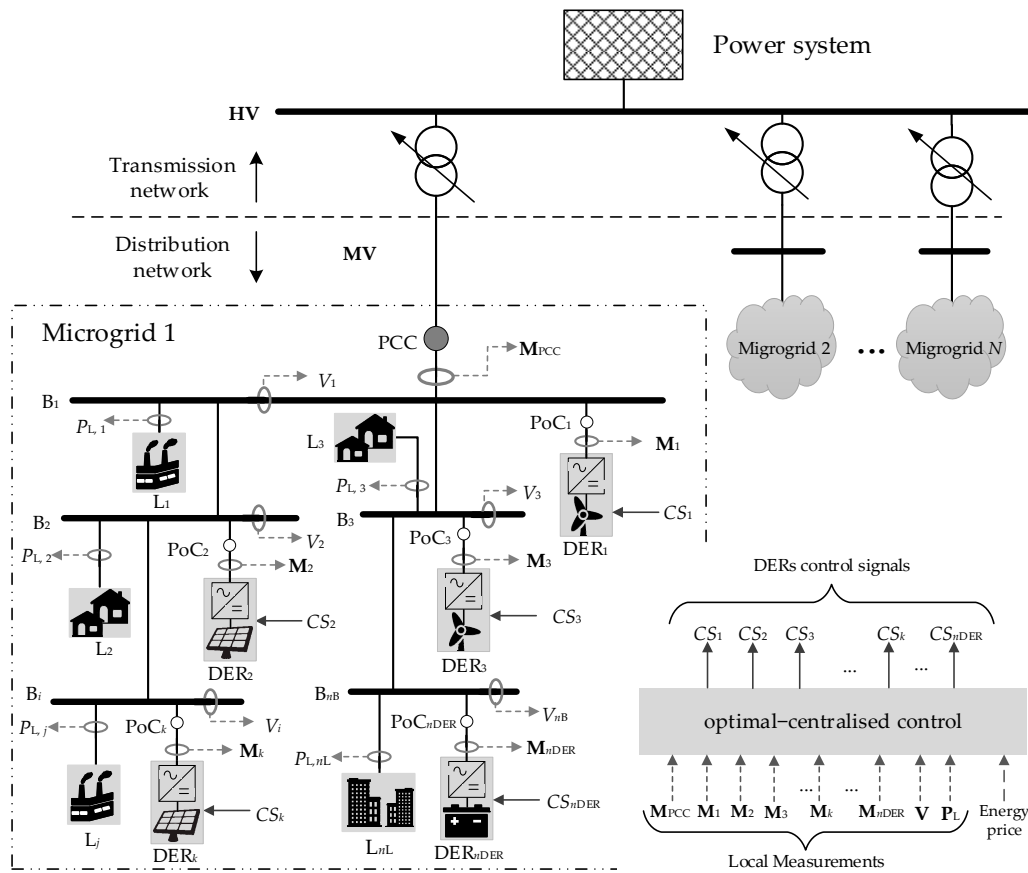


Figure 3. Illustrative scheme of the proposed optimal microgrid-interactive reactive management indicating the inputs and outputs of the optimal-centralised control.

The proposed concept of a microgrid grid-iterative management system of the reactive power power-electronic converter based renewable technologies for day-ahead operation originates the hypothesis of this paper: the optimal-centralised control can manage the reactive power of the microgrid by computing an optimal reactive power dispatch of the smart converter and ensure the operational requirements. It can provide better techno-economic performance than local individual control strategies.

The next subsections describe the local-reactive power management containing seven reactive power controls [6,24]. Moreover, it presents the optimal-centralised control of the proposed optimal microgrid-interactive reactive management, its performance metrics based on the voltage profile and active power losses, the formulation of the day-ahead energy cost and the energy price.

2.1. Local-Reactive Power Management

2.1.1. Constant Voltage Control (CVC)

The constant voltage control main task is to regulate the reactive power injection/absorption of the smart converter to keep V_{PoC} in a specified $V_{setpoint}$ value; in the meantime, it maintains P_{DER} constant. The $V_{setpoint}$ is commonly established as the nominal voltage in per unit values, i.e., $V_{setpoint} = 1.0$ pu, and the injection/absorption of the reactive power is restricted by the smart converter operational limits.

2.1.2. Voltage Q-Droop Control (VQC)

The voltage Q-droop control is formulated based on a classical proportional control model shown in Figure 4a. This control uses Q_{setpoint} and V_{setpoint} as a reference to compute $Q_{P/C}$ by the smart converter using the following equation.

$$Q_{P/C} = Q_{\text{setpoint}} + (V_{\text{setpoint}} - V_{\text{PoC}})S_n G_{Q\text{-droop}} \quad (1)$$

where S_n is given in pu and $G_{Q\text{-droop}}$ is a constant gain computed as $G_{Q\text{-droop}} = 100/K_{\text{droop}}$.



Figure 4. Proportional control based reactive power control strategy at smart converter: (a) Voltage Q-droop control; (b) Voltage I_q -droop control.

2.1.3. Voltage I_q -Droop Control (VI_qC)

The voltage I_q -droop control is also formulated based on a classical proportional control model (see Figure 4b), but this control regulates the reactive current (I_q) of the smart converter, instead of $Q_{P/C}$, to maintain V_{PoC} equal to the V_{setpoint} . The voltage I_q -droop control computes I_q output in proportion to the voltage deviation at PoC and K_{droop} as following:

$$I_q = (V_{\text{setpoint}} - V_{\text{PoC}})G_{I_q\text{-droop}} + I_{q,\text{setpoint}} \quad (2)$$

$$G_{I_q\text{-droop}} = \frac{100S_n PF}{\sqrt{3}K_{\text{droop}}V_n}$$

where $I_{q,\text{setpoint}}$ is a specified reactive current setpoint, S_n is given in VA, V_n is given in V, and $PF = \cos(\varphi)$.

2.1.4. Constant Reactive Power Control (CQC)

The constant reactive power control mainly keeps the reactive power output of the smart converter at a certain Q_{setpoint} , i.e., $Q_{P/C} = Q_{\text{setpoint}}$, while it maintains the active power output constant. Therefore, using this control enables the smart converter to perform as a PQ type node. This control strategy restricts the smart converter controllability features.

2.1.5. Watt-Var-Characteristic Based Control (W-V-C)

The Watt-Var-characteristic based control determines the reactive power output of the smart converter based on its P_{DER} following a user-defined piecewise characteristic, as shown in Figure 5a. According to the Watt-Var-characteristic, $Q_{P/C}$ can be calculated using the following equation:

$$Q_{P/C} = \begin{cases} Q_{\text{max}} & P_{\text{DER}} < P_{\text{min}} \\ \frac{Q_{\text{min}} - Q_{\text{max}}}{P_{\text{max}} - P_{\text{min}}}(P_{\text{DER}} - P_{\text{min}}) + Q_{\text{max}} & P_{\text{min}} \leq P_{\text{DER}} \leq P_{\text{max}} \\ Q_{\text{min}} & P_{\text{DER}} > P_{\text{max}} \end{cases} \quad (3)$$

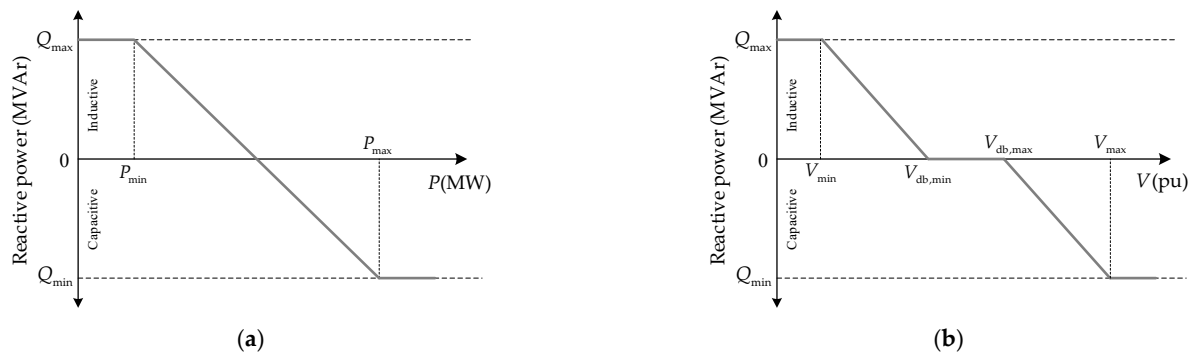


Figure 5. Curve characteristic based reactive power control at smart converter: (a) Watt–Var–characteristic; (b) Volt–Var–characteristic.

2.1.6. Volt–Var–Characteristic Based Control (V–V–C)

The Volt–Var–characteristic based control computes the $Q_{P/C}$ of the smart converter using the V_{PoC} measurement and the piecewise Volt–Var–characteristic presented in Figure 5b. The Volt–Var–characteristic is defined by the following equation:

$$Q_{P/C} = \begin{cases} Q_{max} & V_{PoC} < V_{min} \\ Q_{max} \left(1 - \frac{V_{PoC} - V_{min}}{V_{db,min} - V_{min}} \right) & V_{min} \leq V_{PoC} \leq V_{db,min} \\ 0 & V_{db,min} < V_{PoC} < V_{db,max} \\ Q_{min} \frac{V_{PoC} - V_{db,max}}{V_{max} - V_{db,max}} & V_{db,max} \leq V_{PoC} \leq V_{max} \\ Q_{min} & V_{PoC} > V_{max} \end{cases} \quad (4)$$

where $V_{db,min}$, and $V_{db,max}$ the minimum and maximum voltage of the deadband. If $V_{PoC} < V_{min}$ or $V_{PoC} > V_{max}$, the Volt–Var–characteristic based control acts as CQC keeping $Q_{P/C}$ constant at Q_{max} or Q_{min} depending on V_{PoC} value. On the other hand, if V_{PoC} is within the deadband values, i.e., $V_{db,min} < V_{PoC} < V_{db,max}$, the smart converter does not deliver/consume reactive power, therefore, $Q_{P/C} = 0$. Finally, if $V_{min} \leq V_{PoC} \leq V_{db,min}$ or $V_{db,max} \leq V_{PoC} \leq V_{max}$, $Q_{P/C}$ of the smart converter is determined by the actual V_{PoC} and the slope of the Volt–Var–characteristic.

2.1.7. Constant Power Factor Control (CPFC)

The power factor control seeks to maintain constant the power factor at the PoC of the smart converter by regulating the reactive power injection/absorption. The reactive power output is calculated as:

$$Q_{P/C} = P_{DER} \tan^{-1}(\varphi) \quad (5)$$

where P_{DER} is the active power output of the smart converter and $\varphi = \cos^{-1}(PF_{setpoint})$.

The seven local control strategies compute the reactive power limits of the k -th DER using the following equation:

$$-Q_{min,k} = Q_{max,k} = \sqrt{S_{n,k}^2 - P_{DER,k}^2} \quad \forall k = 1, 2, \dots, n_{DER} \quad (6)$$

Table 2 present a summary of the principal features of the local reactive power management strategies.

Table 2. Summary of the main characteristic of local reactive power control strategies.

Local Reactive Power Management Strategies	Designed Based on	Monitored Variables	Parameters	Adaptable Operation Point
CVC	Fixed settings	V_{PoC}	$V_{setpoint}$	X
VQC	Proportional control	V_{PoC}	$V_{setpoint}, Q_{setpoint}$	X
$V I_q C$	Proportional control	V_{PoC}	$V_{setpoint}, I_{q, setpoint}$	X
CQC	Fixed settings	–	$Q_{setpoint}$	–
W-V-C	Characteristic	P_{DER}	$P_{min}, P_{max}, Q_{min}, Q_{max}$	X
V-V-C	Characteristic	V_{PoC}	$V_{db, min}, V_{db, max}, V_{min}, V_{max}$	X
CPFC	Fixed settings	P_{DER}	$P_{F, setpoint}$	–

2.2. Optimal–Centralised Reactive Power Management (OQM)

The networks bus voltage is directly influenced positively or negatively depending on the lack or excess of the reactive power flow through the network. Moreover, it also mainly determinates the active power losses amount. An incorrect amount of reactive power injection/absorption produced by the DER will cause an increase in the active power loss and/or deterioration of the network voltage profile. Therefore, the principal reason to develop appropriate reactive power controls that easily be enabled at the DER is to ensure the secure network operation and reduce the active power losses representing an economic issue to the TSO and DSO.

The main goal of proposing the OQM is to optimally determinate the reactive power output of the DER installed in the microgrid, at the same time as minimising the active power losses at PCC, ensuring the bus voltages of the microgrid and the reactive power of the DER are within it permissible limits.

Using as reference the zero-carbon microgrid depicted in Figure 3, the total active power loss at PCC ($P_{loss, PCC}$) of the microgrid is determined as follows:

$$P_{loss, PCC} = P_{T/D-S} + \sum_{k=1}^{n_{DER}} P_{DER, k} - \sum_{j=1}^{n_L} P_{L, j} \quad (7)$$

where $P_{T/D-S}$ is the active power exchange with the distribution/transmission system at PCC, n_{DER} is the total number of DER, and n_L is the total number of loads.

The objective function to minimise the active power loss is formulated as follows:

$$\min_{\mathbf{Q}} [P_{loss, PCC}(\mathbf{Q})] = \min \left(P_{T/D-S} + \sum_{k=1}^{n_{DER}} P_{DER, k} - \sum_{j=1}^{n_L} P_{L, j} \right) \quad (8)$$

with the vector of controlled variables (\mathbf{Q}) defined as

$$\mathbf{Q} = [Q_{P/C, 1} \quad Q_{P/C, 2} \quad \dots \quad Q_{P/C, k} \quad \dots \quad Q_{P/C, n_{DER}}] \quad (9)$$

The reactive power output of k -th DER is restricted inside its safety operative limits which are computed as

$$\begin{aligned} Q_{lim, k} &= \sqrt{S_{n, k}^2 - P_{DER, k}^2} \\ Q_{max, k} &= Q_{lim, k}; Q_{min, k} = -Q_{lim, k} \end{aligned} \quad (10)$$

where $S_{n, k}$ is the apparent nominal power of the k -th DER, respectively. Therefore, the vector of controlled variables is bounded as

$$\mathbf{Q}_{min} < \mathbf{Q} < \mathbf{Q}_{max} \quad (11)$$

The reactive power injected/absorbed by the DER will directly influence the voltage profile. Therefore, it is necessary to ensure voltages at all buses remains inside its permissible operational limits and is determined by evaluating the following inequality equation:

$$|V_n - V| < \Delta V \quad (12)$$

where V is the actual voltage, and ΔV is the maximum permissible voltage deviation at steady-state operation (typically $\pm 5\%$ of V_n). The voltage limits evaluation is incorporated into the optimisation and is formulated as an inequality constraints vector as

$$\mathbf{C} = [c_1 \quad c_2 \quad \cdots \quad c_i \quad \cdots \quad c_{n_B}] < 0, \quad \forall i = 1, 2, \dots, n_B \quad (13)$$

$$c_i = |V_n - V_i| - \Delta V$$

where V_i is the voltage at the i -th bus, and n_B represents the total number of buses in the microgrid.

2.2.1. Day-Ahead Energy Costs

The active power has a very well-established pricing mechanism across the different deregulated electricity markets. Moreover, the pricing regulations and the active power price (b_p) of the day-ahead operation is open access data. The day-ahead historical data of b_p can be obtained in 15-min periods, 30-min periods, or hourly depending on the different electricity markets. Figure 6 depicts an illustrative b_p -curve with one-hour periods for 24 h.

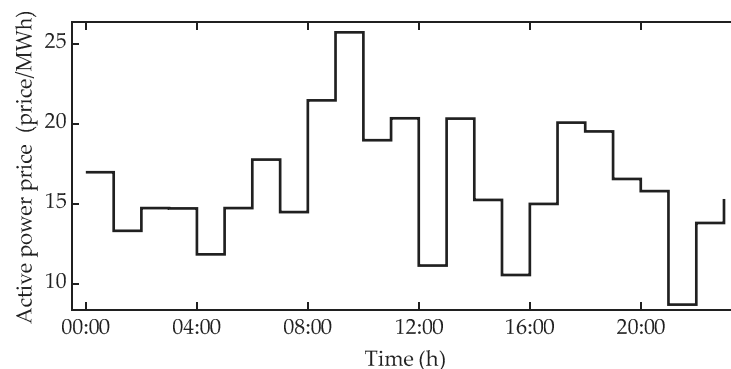


Figure 6. Illustrative active power price curve (b_p -curve) with 1-h periods for 24 h period.

On the other hand, there is no specific market for reactive power procurement. The reactive power pricing at the transmission-level depends on the particular tenders; meanwhile, at the distribution level, there are no mechanisms for the pricing. Consequently, in this paper, the authors decided to follow the requirements of the procurement for reactive power in the UK. Even though this regulation applies only to the transmission system, in the near future, any installation that has the plant/apparatus that can absorb or inject reactive power can be in the reactive power market.

The National Grid has two different mechanisms to manage the reactive power procurement at the transmission level. The first mechanism is the MV (ORSP); it has two separate guidelines (one for synchronous generators and another for non-synchronous generators) [25,26]. The second mechanism is the enhancement reactive power service (ERPS), it is not a mandatory requirement, and it is used as a complement of ORSP. It is available for all providers with any plant able to inject/absorb reactive power, and the service is procured through tenders organised every six months [27].

The providers of reactive power under ERPS mechanism are paid depending on the available capacity price, synchronised capacity price and utilisation price. Meanwhile, the ORSP mechanism has a default payment rate defined based on the calendar month and a utilisation factor. The latest default payment rate reported is available on [22]. Under the steady-state conditions, the provider under ORSP and ERPS mechanism must keep the reactive power output fully available within a voltage range of $\pm 5\%$ of nominal voltage. Moreover, the providers must supply the rated active power at a power factor between 0.95 lagging/leading for ORSP mechanism (non-synchronous generators) [25] and a power factor between 0.85 lagging and 0.95 leading for ERPS mechanism [27].

In this paper, the reactive power price (b_Q) based on the default payment rate document [22]. Due to b_Q fixed price, two reactive power price curves over a 24-h period are proposed:

- b_{Q-p} -curve: This curve is based on the b_p -curve, which is normalised and then multiplied by b_Q .
- b_{Q-D} -curve: This curve is based on the reactive power demand curve. The reactive power demand curve is normalised and then multiplied by b_Q .

Considering the day-ahead energy (active or reactive power) is discretised in nT periods of T minutes each hour, the day-ahead energy cost (E_{cost}) is calculated as:

$$E_{cost} = \frac{T}{60} \sum_{h=1}^{24} \sum_{t=1}^{nT} b_h E_t \left[\frac{\text{cost}}{\text{day}} \right] \quad (14)$$

where E is the energy (either active or reactive power) at the PCC, b is the hourly energy price and nT is the total number of periods computed as $nT = 60/T$.

2.2.2. Performance Metrics of Reactive Power Management

The reactive management using the local and optimal-centralised controls is evaluated using two key variables of the network, the voltage profile and the energy loss of the microgrid.

The steady-state voltage is usually allowed to vary within a range of $\pm 5\%$ of V_n to endure the secure operation of the power system. Moreover, it is one of the key variables of the power system that is directly influenced by the reactive power. Therefore, it is important to have a metric to quantify the voltage profile of each bus as well as the voltage of the entire network. Authors of [28] proposed two mathematical expressions to calculate the voltage profile index for each bus and overall system. However, the overall voltage index does not represent the real picture of the voltage in each bus, i.e., it can mask if there is a voltage violation at any bus. Therefore, in this paper, two new mathematical expressions to compute the voltage profile index are proposed: the local voltage index and overall voltage index.

The local voltage index (V_{LI}) is formulated to compute the voltage profile of each individual bus as follows:

$$V_{LI,i} = \frac{1}{2} \left| \frac{V_{\max} - V_i}{V_{\max} - V_n} - \frac{V_i - V_{\min}}{V_n - V_{\min}} \right| \quad (15)$$

where V_i represents the voltage in the i -th bus voltage. This index is formulated in a way that $V_{LI,i}$ will take values between zero and one ($0 \leq V_{LI,i} \leq 1.0$) when the voltage is within the permissible values and values above one ($1.0 > V_{LI,i}$) when violating its limits. This is expressed following as:

$$V_{LI,i} = \begin{cases} 0 & V_i = V_n \\ 1 & V_{\min} = V_i \text{ or } V_{\max} = V_i \\ (0, 1) & V_{\min} < V_i < V_{\max} \\ > 1 & V_i < V_{\min} \text{ or } V_i > V_{\max} \end{cases} \quad (16)$$

Equation (16) clearly defines the boundaries of V_{LI} and allows easily identifies if there is a voltage violation at the bus. When it comes to defining a single voltage that represents the voltage profile of the whole system, it is essential to ensure bus voltage violations are not masked. Therefore, the overall voltage index (V_{OI}) is formulated based on the V_{LI} of all buses. V_{OI} is calculated by taking the maximum V_{LI} of all buses as:

$$V_{OI} = \max([V_{LI,1} \quad V_{LI,2} \quad \cdots \quad V_{LI,i} \quad \cdots \quad V_{LI,n_B}]) \quad \forall i = 1, 2, \dots, n_B \quad (17)$$

where n_B represents the total number of buses in the power system. V_{OI} follows the same rules described in (16). If V_{OI} is greater than one ($V_{OI} > 1$) indicates that at least one node has its voltage outside the permissible limits. On the other hand, if V_{OI} takes values within zero and one ($0 \leq V_{OI} \leq 1$) indicates all buses voltage are inside the allowable voltage limits.

The total energy loss (E_{loss}) of the network is important for the TSO-DSO because it has an economic effect on them. Considering a day-to-day active power loss (P_{loss}) discretised in periods of T minutes, the day-ahead energy losses is calculated as:

$$E_{loss} = \frac{T}{60} \sum_{i=1}^{n_T} P_{loss,i} \left[\frac{\text{MWh}}{\text{day}} \right] \quad (18)$$

where n_T is the total number of periods over 24-h and is calculated as:

$$n_T = \frac{60}{1} \left[\frac{\text{min}}{\text{h}} \right] \times \frac{24}{T} \left[\frac{\text{h}}{\text{min}} \right] \quad (19)$$

3. Results

The seven local reactive power managements, as well as the proposed optimal-centralised reactive management, were assessed using the MV distribution Benchmark system developed by the International Council on Large Electric Systems Task Force C6.04, which is fully described in the report title "Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources" [21]. The distribution Benchmark system was developed in two versions: North America style at 60 Hz and European style at 50 Hz. In this paper, the European MV distribution Benchmark network was implemented in DIGSILENT® PowerFactory™ assumed to be symmetrical and balanced. It consisted of two three-phase feeders operating at 20 kV nominal voltage connected to the main network through two transformers of 110/20 kV. It had installed 10 residential loads and eight commercial/industrial loads. The European MV distribution Benchmark network had three switches (S1, S2 and S3), allowing it to be operated in radial or meshed topology. In this paper, switch S1 was closed and switches S2 and S3 were open. Moreover, the European MV distribution Benchmark network was equipped with eight solar photovoltaic technologies and one wind, as is shown in Figure 7. The network parameters are described in [21].

The techno-economic assessment of the proposed optimal microgrid-interactive reactive management described in Section 2 was carried out by performing the day-ahead steady-state of the test system in Figure 7, considering 15-min resolution periods. The technical component was evaluated using the performance metrics (energy losses and voltage profile index) defined in Section 2.2.2. The economic factor was assessed by calculating the day-ahead cost of the energy losses and the cost produced by the reactive power delivered by the smart converters at the PCC of the microgrid. In order to fairly compare the OQM approach against the seven local-reactive power management types, the parameters settings of each local-reactive power management strategy were defined by performing a parameter sensitivity analysis. This analysis used a set of possible values that the local strategy parameters can take, then the performance metrics were calculated. The most suitable set of values were selected based on the best performance of each local-reactive power strategy in terms of voltage index profile and energy losses. The set of values considered to carry out the parameter sensitivity analysis are defined in Appendix A. Table 3 depicts the principal parameter settings of the local and optimal-centralised reactive management strategies evaluated in this paper.

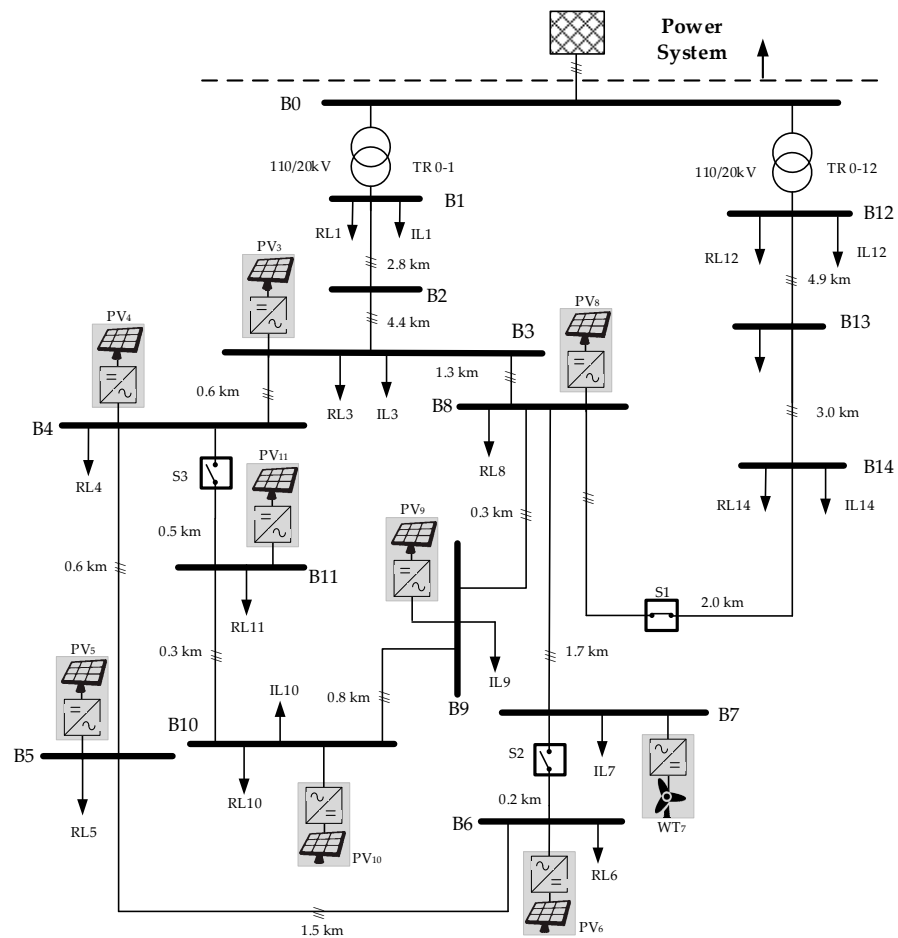


Figure 7. Schematic representation of the European MV distribution Benchmark network equipped with DER technologies (seven solar photovoltaic and one wind).

Table 3. Parameters settings of the local and optimal-centralised reactive management strategies enabled at the smart converters.

Reactive Power Management Strategies	Parameters Settings
CVC	$V_{\text{setpoint}} = 0.99 \text{ pu}$
VQC	$K_{\text{droop}} = 5\%; 0.95 \text{ pu} < V_{\text{setpoint}} < 1.05 \text{ pu}$
$V I_q C$	$K_{\text{droop}} = 5\%; 0.95 \text{ pu} < V_{\text{setpoint}} < 1.05 \text{ pu}$
CQC	$Q_{\text{setpoint}} = 0.35 S_n$
V-V-C	$P_{\text{min}} = 0 \text{ pu}; P_{\text{max}} = 1 \text{ pu}$
V-V-C	$V_{\text{min}} = 0.94 \text{ pu}; V_{\text{max}} = 1.06 \text{ pu}; V_{\text{db,min}} = 0.99 \text{ pu}; \text{ and } V_{\text{db,max}} = 1.01 \text{ pu}$
CPFC	$PF_{\text{setpoint}} = 0.95 \text{ inductive}$
OQM	$\Delta V = 5\% V_n = 0.05 \text{ pu}$

The proposed optimal-centralised reactive power management strategy was implemented in Python programming language and automated to be solved by creating an interface Python–DigSILENT® PowerFactory™. The optimisation was solved using a meta-heuristic algorithm named improved harmony search algorithm [29], and its parameter was set up as in [30].

The active power prices for 24 h of 19 August 2020, used in this paper, are taken from the UK system electricity historical price data [23]. The b_P -curve is presented in Figure 8. Meanwhile, the fixed reactive power price is taken from the default payment rate document [22], for August 2020, which is $b_{Q\text{-fixed}} = 2.337227\text{€}/\text{MVarh}$ assuming a

utilisation factor of one. The proposed variable reactive power price curves (b_{Q-p} -curve and b_{Q-D} -curve) are depicted in Figure 9.

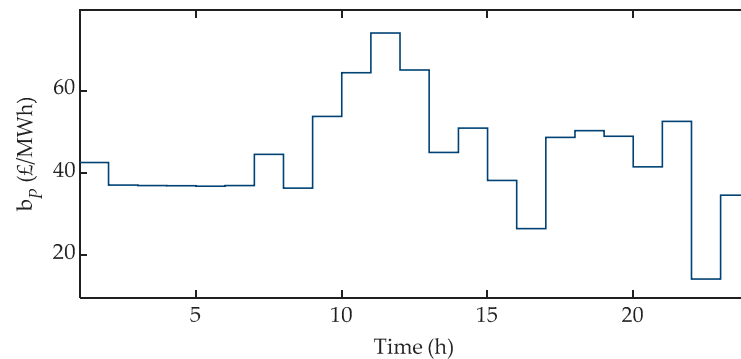


Figure 8. Active power price curve over 24 h of 19 August 2020.

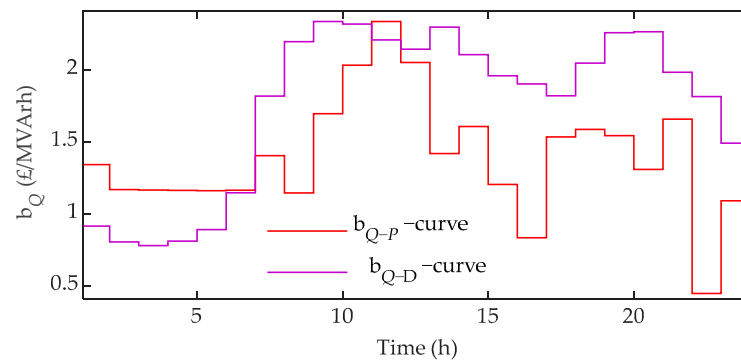


Figure 9. Reactive power price curve based on b_p -curve (b_{Q-p} -curve) and reactive power curve price base on the demand curve (b_{Q-D} -curve).

The day-ahead cost of reactive power production of the smart converters measured at the PCC is computed considering three main scenarios:

- Scenario I: using a fixed reactive power price, $b_{Q-fixed}$.
- Scenario II: using a variable costs curve based on the b_p -curve, b_{Q-p} -curve.
- Scenario III: using a variable costs curve based on the reactive power demand curve, b_{Q-D} -curve.

The day-ahead steady-state of the European MV distribution Benchmark network is performed to evaluate the seven local-reactive power management types and the optimal-centralised reactive power management in Table 3. The overall voltage index computed using (15) and (17); the active power losses, calculated using (7), of the microgrid and the reactive power production coming from the DER (eight solar photovoltaic and the wind technologies), measured at the PCC, are presented in Figure 10.

From Figure 10a, it can be easily seen all reactive power management strategies were able to maintain the voltage profile within its permissible limits, i.e., $0.95 \text{ pu} \leq V_{OI} \leq 1.05 \text{ pu}$, and therefore the overall voltage index (V_{OI}) of the microgrid is less than one ($V_{OI} < 1$) indicating there were not voltage violations in the day-ahead steady-state operation as it is defined in (16). Figure 10b demonstrates the OQM maintains a minimum active power loss over the 24 h. Moreover, from Figure 10c, it can be observed the constant voltage control (CVC) strategy produced the DERs operating at Q_{max} from 6:00 to 21:45 h.

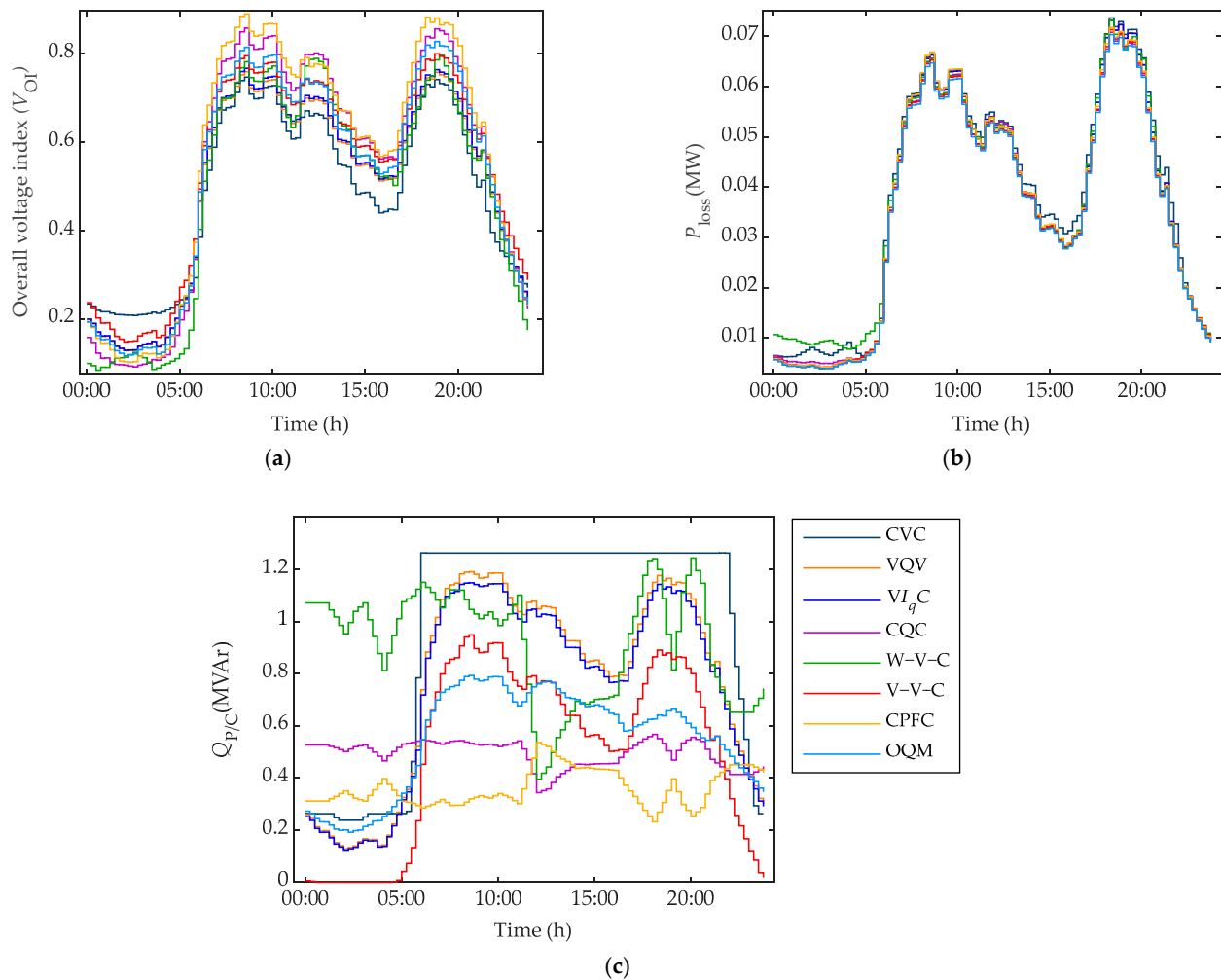


Figure 10. Day-ahead steady-state performance of microgrid by enabling the local and the optimal-centralised reactive power management at the smart converters using 15-min resolution: (a) Overall voltage index (V_{OI}) (b) Active power losses (P_{loss}); (c) reactive power produced by the DER.

Table 4 describes the total energy losses produced by the seven local-reactive power management and OQM strategies evaluated in this paper. Moreover, the maximum overall voltage index is presented for each reactive power control strategy. From these results, it is essential to highlight the OQM strategy produced minimum energy losses. It achieved the purpose for which it was formulated and reduced the energy losses 0.0607 MWh/day, representing a 6.7% difference compared with the CVC strategy, which produced the maximum energy losses.

Table 4. Total energy losses and maximum overall voltage index of the day-ahead steady-state microgrid operation of the seven local-reactive power management and OQM strategies enabled in the smart converters.

Reactive Power Management Strategies	E_{loss} (MWh/day)	max (V_{OI}) in pu
CVC	0.9017	0.7474
VQC	0.8648	0.7599
$V I_q C$	0.8645	0.7675
CQC	0.8569	0.8586
W-V-C	0.8882	0.7969
V-V-C	0.8522	0.8003
CPFC	0.8627	0.8905
OQM	0.8411	0.8283

The primary purpose of this assessment was to determinate the most suitable reactive power control strategy, which produced the best techno-economic profit. Therefore, it was computed the day-ahead costs of energy losses and reactive power provided by the DER using (14). It was assumed only the reactive power supplied by the DER was economically compensated, i.e., when the DER are operating in an inductive power factor. The cost of energy losses was computed using the b_P -curve shown in Figure 8. Meanwhile, the cost of reactive power delivered by the DER is calculated by using Scenario I, Scenario II, and Scenario III, which are using the reactive power prices curves presented in Figure 9.

The results of computing the costs of energy losses and the cost of reactive power provided by the DER are depicted in Table 5.

Table 5. Day-ahead cost of the energy losses and the reactive power injected by the DER at the PCC.

Reactive Power Management Strategies	$E_{\text{loss, cost}}$ (£/day)	Q_{cost} (£/day)		
		Scenario I: $b_{Q-\text{Fixed}}$	Scenario II: $b_{Q-P-\text{Curve}}$	Scenario III: $b_{Q-D-\text{Curve}}$
CVC	42.9569	53.7635	33.3339	43.6889
VQC	41.4771	42.8143	27.1646	35.2430
$V I_q C$	41.4608	41.5715	26.3735	34.2217
CQC	41.0370	27.6545	16.5481	19.4450
W-V-C	42.3264	51.5433	31.0555	35.9611
V-V-C	40.8186	28.1199	18.3524	24.3942
CPFC	41.3711	20.2530	11.8580	14.4222
OQM	40.3228	30.8408	19.1577	24.3853

From Table 5, it can be determined that the OQM produced the minimum costs of energy losses. Moreover, the cost of the reactive power delivered by the DER changed depending on the reactive power price. Even though the CPFC strategy produced the minimum costs of the reactive power procurement, this control strategy cannot be considered the best techno-economic solution. It is because it did not have the minimum energy losses and could not regulate the injection/absorption of reactive power since it was designed to maintain constant reactive power. Following the same idea, the CQC strategy neither can be considered as the best techno-economic solution. On the other hand, although CVC, VQC, $V I_q C$, W-V-C, V-V-C and OQM strategies provided adaptability over a day-ahead steady-state operation, only the OQM strategy ensured the minimum reactive power losses.

Another essential aspect that must be analysed is the pricing of the reactive power procurement. Table 5 shows that the day-head cost of reactive power services provided by the microgrid depended on how the price was established. For instance, the reactive power costs in Scenario II Scenario III decreased by 39% and 22% concerning Scenario I. Meanwhile, the reactive power costs in Scenario II were reduced by 20% concerning Scenario III.

4. Discussion

The local-reactive power strategies only regulate the $Q_{P/C}$ to ensure the voltage at the PoC is inside certain limits. Consequently, the local voltage regulation feature makes the local reactive power strategies based on proportional control and characteristic control capable of reducing the overall voltage index profile of the microgrid. However, this feature does not ensure the total energy losses will be the minimum.

On the other hand, the proposed OQM approach seeks the optimal $Q_{P/C}$ of the smart converters to minimise the P_{loss} and enforce all bus voltage of the microgrid be within its allowable limits. This centralised strategy provides outstanding results against the local reactive power management controls since it guarantees the minimum active power losses through the microgrid and maintains the voltage in its steady-state safe operation limits.

Moreover, it incorporates two novel mathematical expressions to determine the voltage profile index, which positively improves the monitoring of the entire microgrid voltage

profile. It avoids masking voltage violation at any bus, and it provides a clear and understandable metric to identify if the voltage is out of the permissible limits of operation.

From the economic point of view, the numerical results evidence that adopting a fixed price (Scenario I) for reactive power pricing in the day-ahead operation is the worst pricing alternative. It suggests adopting a variable price curve, which the best economical alternative is Scenario II, which pricing the reactive power following the active power price curve.

Although the proposed methodology in this paper achieves answering the research question and validates the hypothesis of this paper, the optimal-centralised control can manage the microgrid reactive power by computing an optimal reactive power dispatch of the smart converter, ensure the operational requirements and provide better techno-economic performance than local individual control strategies; further work is required to determinate a mechanism of reactive power pricing when the microgrid is providing reactive power services beyond the obligatory requirements.

5. Conclusions

This paper answers the research question: can a microgrid grid-interactive be used as an enhancement mechanism of reactive power regulation for smart converters based renewable technologies and provide better techno-economic performance using a centralised control approach than a local control strategy? By performing a techno-economic assessment of the optimal microgrid-interactive reactive power management strategy and seven local reactive power control strategies.

The optimal microgrid-interactive reactive power management strategy for a day-ahead operation is formulated based on an optimal-centralised reactive power management control. It adequately determinates the optimal reactive power dispatch of the smart converters, minimises the active power losses and ensures the bus voltage inside the operational limits. Unlike the local reactive power strategies that only regulate the voltage at its PoC and cannot monitor and reach a solution for microgrid global variables energy losses. Moreover, the day-ahead reactive power pricing based on the active power price curve (b_p -curve) proves to be the best economic option, since it produces the minimum cost of reactive power procured from DER.

Although the techno-economic assessment suggests having a variable reactive power price for the day-ahead operation instead of adapting a fixed price, addressing this issue is not as simple as it seems. For instance, from TSO-DSO point of view, this approach suits since they are looking to minimise the cost of energy losses and procurement services (buy reactive power). On the other hand, the prosumers of the microgrid may want to maximise the cost of day-ahead services (sell reactive power) provided by DER. Therefore, the optimal microgrid-interactive reactive power management represents an alternative to address this issue since it can be adapted to solve it depending on the desired approach. However, it still necessary to create reactive power pricing mechanisms and a reactive power market framework to cope with the upcoming changes in the reactive power necessities of the distribution/transmission network and the active participation of the microgrids.

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Abbreviations

CPFC	Constant power factor control
CQC	Constant reactive power control
CVC	Constant voltage control
DER	Distributed energy resources
DSO	Distribution system operator
ERPS	Enhancement reactive power service
K_{droop}	Voltage droop constant
MV	Medium voltage
OQM	Optimal–centralised reactive power management
ORSP	Obligatory reactive power services
PCC	Point of common connection
$P_{\text{DER},k}$	Active power of the k -th DER
PF	Power factor
PF_{setpoint}	Power factor setpoint
$P_{L,j}$	Active power of the j -th load
P_{min}	Minimum active power limit of DER
P_{max}	Maximum active power limit of DER
PoC	Point of connection
Q_{min}	Minimum reactive power limit of DER
Q_{max}	Maximum reactive power limit of DER
$Q_{P/C}$	Reactive power production/consumption
Q_{setpoint}	Reactive power setpoint
S_n	Apparent nominal power of the DER
TSO	Transmission system operator
V_{I_qC}	Voltage I_q –droop control
V_{LI}	local voltage index
V_{min}	Minimum allowable voltage limit
V_{max}	Maximum allowable voltage limit
V_n	Nominal voltage
V_{OI}	Overall voltage index
V_{PoI}	Voltage at the point of connection
VQC	Voltage Q–droop control
V_{setpoint}	Voltage setpoint
V–V–C	Volt–Var–characteristic based control
W–V–C	Watt–Var–characteristic based control

Appendix A

Table A1. Range of values considered in the parameter sensitivity analysis of the local-reactive power management strategies.

Reactive Power Management Strategies	Parameter	Values
CVC	V_{setpoint} (pu)	[0.95, 0.96, 0.97, 0.98, 0.99, 1.00, 1.01, 1.02, 1.03, 1.04, 1.05]
VQC	K_{droop} $0.95 \text{ pu} < V_{\text{setpoint}} < 1.05 \text{ pu}$	[1.5%, 2%, 3%, 3.5%, 4%, 4.5%, 5%, 10%]
V_{I_qC}	K_{droop} $0.95 \text{ pu} < V_{\text{setpoint}} < 1.05 \text{ pu}$	[1.5%, 2%, 3%, 3.5%, 4%, 4.5%, 5%, 10%]
CQC	Q_{setpoint} (pu)	[0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1] Q_{max} @ lagging and leading operation
W–V–C	$(P_{\text{min}}, Q_{\text{min}})$ (pu) $(P_{\text{max}}, Q_{\text{max}})$ (pu)	[(0,1), (1,0)] [(0,−1), (1,0)]
V–V–C	$(V_{\text{min}}, V_{\text{max}})$ $V_{\text{db,min}} = 0.99 \text{ pu}$; and $V_{\text{db,max}} = 1.01 \text{ pu}$	[(0.89, 1.11), (0.94, 1.06), (0.945, 1.055), (0.95, 1.05), (0.955, 1.045), (0.96, 1.04), (0.965, 1.035), (0.97, 1.03), (0.975, 1.025)]
CPEC	PF_{setpoint}	[0.85,0.9,0.95,1] @ lagging and leading operation

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