Grid-Tie Converters Aided Rapid Grid Voltage Fluctuation Compensation with Power Hardware-in-the-Loop Experimental Validation

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Abstract

The majority of photovoltaic systems, small wind turbines and approximately half of large wind turbines are connected to power grids via electronic converters, which regulate both active and reactive power. Such converters are capable of rapid adjustment of reactive power, thereby assisting in the stabilisation of grid voltage. This capability is of paramount importance in the context of grids with distributed generation. The presented method in the article employs the reactive power generated by converters to compensate for voltage fluctuations in a dynamic manner, obviating the necessity for additional, costly equipment such as dynamic voltage restorers. By regulating the flow of reactive power, voltage fluctuations can be mitigated in real-time. Simulations in Matlab-Simulink and tests in a laboratory power hardware-in-the-loop system demonstrated the efficacy of the method, exhibiting rapid compensation with response times of approximately 100 ms. Despite constraints associated with the converter's power capacity, the approach is promising due to the pervasive availability of converters in power networks.

Keywords: Power Converter, Power Hardware-in-the-Loop, Power Quality, Voltage Disturbance Compensation

1 Introduction

The classic power system consisted of voltage sources in the form of synchronous generators operating in large power plants, as well as consumers connected to the system. In addition to generating active power, synchronous generators also cover the demand for reactive power in the system, thereby stabilising the voltage in the grid. This classical situation changed with the emergence of prosumers in the network, that is, energy consumers who also have the ability to generate energy through photovoltaic installations or small wind farms. A characteristic feature of generation based on renewable energy sources is their variability and unpredictability, which in turn leads to voltage fluctuations. With the current level of development and prevalence of photovoltaic installations, a serious problem faced by power system operators is changes, especially increases, in voltage values in the grid caused by changes in the energy introduced into the system by distributed generation.

Photovoltaic installations, small residential wind turbines, and approximately 50% of large wind turbines are connected to the power system through electronic power converters. The main task of the grid inverter, which serves as the interface for the aforementioned installations, is to control the active power that is fed into the grid. The power factor, which can also be controlled by the inverter, is usually set at a value of 1 or is statically adjusted within the range of $cos\phi \pm 0.9$ depending on the voltage changes in the grid [1]. A distinguishing feature of power electronic converters compared to electromagnetic energy converters is their ability to almost immediately change reactive power, both capacitive and inductive. However, the capability to generate reactive power is naturally limited by the current parameters of the converter and decreases with the increase in processed active power. Considering the volume of power installed in distributed generation currently, the ability to generate reactive power, which can prevent voltage fluctuations, seems to be significant. Another distinguishing feature of the reactive power generation capabilities of converters compared to synchronous machines is the ability to generate inductive reactive power over a much wider range. In the case of synchronous machines, generating inductive reactive power is associated with machine excitation reduction, which in turn can lead to instability and, in extreme cases, machine desynchronisation, which is unacceptable. Such limitations do not apply to converters. The ability to generate inductive reactive power is particularly desirable for system operators because it can be used to compensate for voltage increases occurring locally in the power grid with a large number of distributed generation sources.

In works on the compensation of voltage changes using reactive power generated by voltage inverters, results are presented for a system operating statically or to a limited extent [2]. Several articles are devoted to dynamic voltage restorers (DVR), systems that dynamically prevent voltage dropouts, and a comprehensive review of these solutions is presented in the paper [3]. DVR filters are currently used solutions in the energy industry [4, 5], however, they are devices that require additional relatively large financial outlays, which makes this solution not widely used. The advantage of the proposed solution is the use of converters commonly found in the system, without the need to install new devices.

2 Principle of Compensation for Voltage Changes using Reactive Power

Compensation of voltage variations in the grid by means of reactive power flow control involves inducing a voltage drop across the reactive component of the supplying line with the appropriate phase [6]. Generally, in the case of lines with an inductive characteristic, which is typically encountered, the voltage drop can be compensated by forcing capacitive reactive power flow (injecting reactive power into the grid) [7, 8]. The flow of capacitive reactive current induces a voltage drop across the reactance, resulting in an increase in voltage at the terminals. Conversely, an increase in voltage on the grid can be compensated by the absorption of reactive power (inductive reactive power), resulting in a voltage drop across the line reactance, which reduces the voltage value at the converter terminals [9]. The diagram of the described voltage fluctuation compensation method is presented in Figure 1.

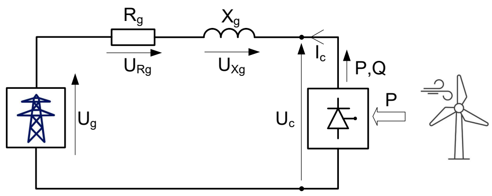

Fig. 1 Power flow and voltage drops to compensate for voltage fluctuations and reactive power.

Figure 2 and Figure 3 depicts the principle of voltage variation compensation using phasor diagrams. Figure 2 pertains to the case where the converter generates active power while simultaneously absorbing inductive reactive power. In such a scenario, the voltage at the terminals U_c is lower than the grid voltage U_g. When the converter, while generating active power, generates simultaneously inductive reactive power (capacitive character), the voltage at its terminals is higher than the grid voltage, as depicted in the graph in Figure 3.

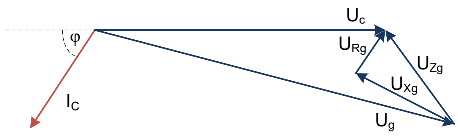

Fig. 2 Active power generation with simultaneous reactive power consumption.

Of course, the feasibility of voltage fluctuation compensation using this method is limited and closely dependent on the grid parameters and the current capabilities of the converter. Based on the phasor diagrams (Figure 2 and Figure 3) voltage at the converter terminals is:

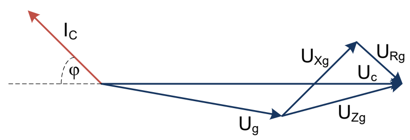

Fig. 3 Active power generation with simultaneous reactive power injection.

$$U_c = U_g + U_{Z_g} \tag{1}$$

where,

$$U_{Z_g} = U_{R_g} \pm U_{X_g} \tag{2}$$

The sign of the voltage drop Uxg depends on the character of the reactive power and is negative for inductive and positive for capacitive. On the other hand, the voltage drop value Uxg depends on the network reactance as well as the current magnitude I_c and its character. In cases where the converter delivers only active power to the grid, the voltage drop U_{Z_g} is also added to the grid voltage U_g causing an increase in voltage at the converter terminals U_c. This phenomenon is commonly observed in networks with a large number of distributed generations (prosumers), this scenario is illustrated by the phasor diagram in Figure 3.

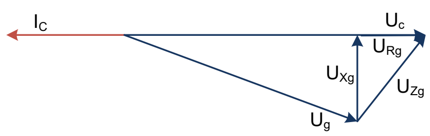

Fig. 4 Active power generation.

In this case, the difference between the voltage at the converter terminals and the network voltage depends solely on the generated active power, which varies stochastically. From the above considerations, it follows that there is no simple translation between voltage drop U_{Z_g} and the value of reactive power, as it depends on the values and characteristics of both power components, of which only reactive power can be controlled depending on the voltage at the terminals.

The limitation of this voltage fluctuation compensation method due to the converter's current efficiency also depends on its current operating point [10]. The limitations of reactive power generation can be represented on a polar plot (Figure 5). When the converter operates at maximum active power, it cannot generate active power. When the amount of generated active power is less than the rated value, the possibility of generating capacitive or inductive reactive power increases. In the case of converters with greater apparent power than active power capability, the range of reactive power generation capabilities is evidently broader.

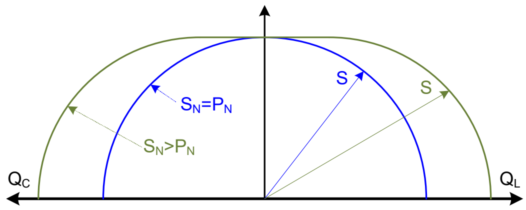

Fig. 5 Reactive power limitations due to the operating point.

3 Simulation Studies of the Dynamic Voltage Fluctuation Compensation System

Taking into account the nature of voltage changes and the relationship between reactive power flow and voltage drop in the network, dynamic compensation was proposed. In this method, the set value of the converter's reactive power depends on the instantaneous value of the voltage deviation in the grid. In order to evaluate the dynamics achievable in the proposed method, simulation studies of the system were carried out in the Matlab-Simulink environment. Figure 6 shows the equivalent system diagram in which the tests were carried out.

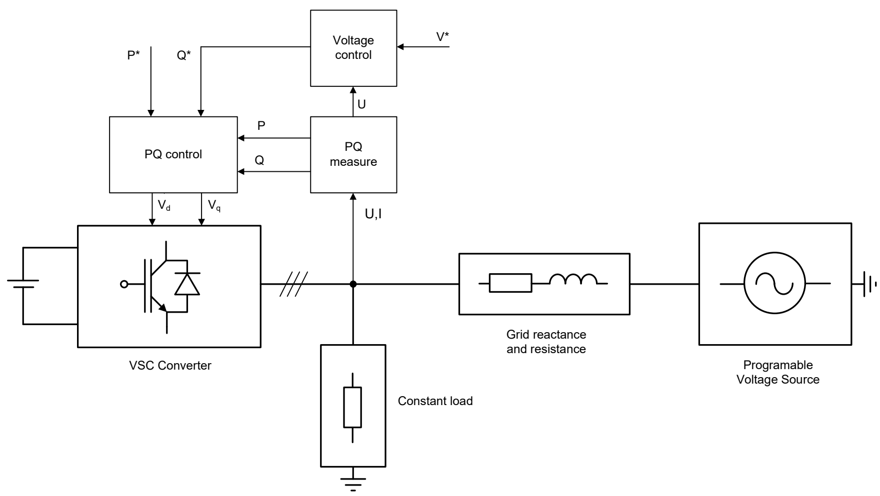

Fig. 6 Model of the system for rapid compensation of voltage fluctuations.

The individual elements of the model, including reactance and resistance, have been assumed to correspond to the actual values of these elements in the laboratory system. The PI controllers were employed in the active and reactive power control system and in the voltage control system. The regulator settings were selected with the objective of achieving the fastest possible voltage regulation at the terminals of the converter. The simulations conducted on the presented model included a series of extreme cases of voltage deviations, which were subsequently compensated in the laboratory system. The results of these simulations are shown in Figure 7 and Figure 8.

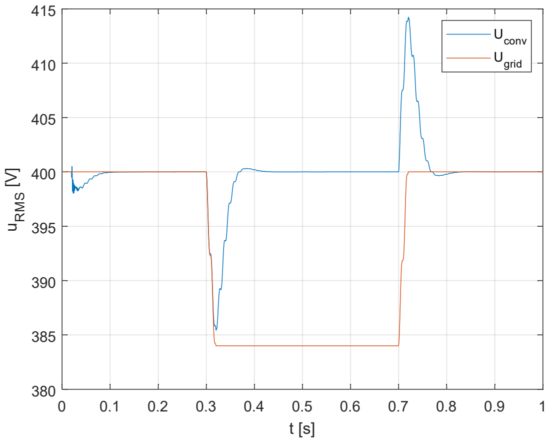

Fig. 7 Voltage waveforms in the grid and at the converter terminals -4% voltage drop.

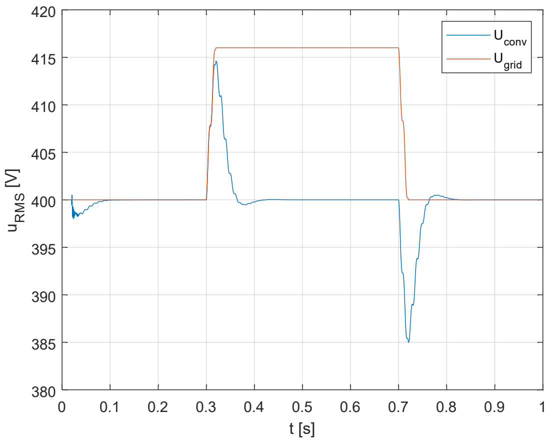

Fig. 8 Voltage waveforms in the network and at the terminals of the converter -4% voltage surge.

The adjustment time for both voltage surge and drop was approximately 100 ms. The regulation is executed with minimal fluctuations, and the voltage waveform remains stable, which indicates that the regulator settings have been correctly selected.

4 Power Hardware-in-the-Loop Experimental Validation

A laboratory system was prepared based on the simulation model, in which the planned tests were carried out. The objective of the tests conducted was to ascertain the extent of voltage variation that could be compensated for within the constraints of the network and converter parameters. The second key objective was to validate the compensation time for voltage drops and surges. All studies were conducted at the Dynamic Power Systems Laboratory (DPSL), University of Strathclyde. The laboratory system in which the tests were conducted was configured as a power hardware-in-the-loop (PHIL) system. PHIL represents a robust testing solution, enabling a real-time simulated power system to be interfaced with hardware devices such as inverters to investigate the interactions between them and the grid or microgrids[11–13].

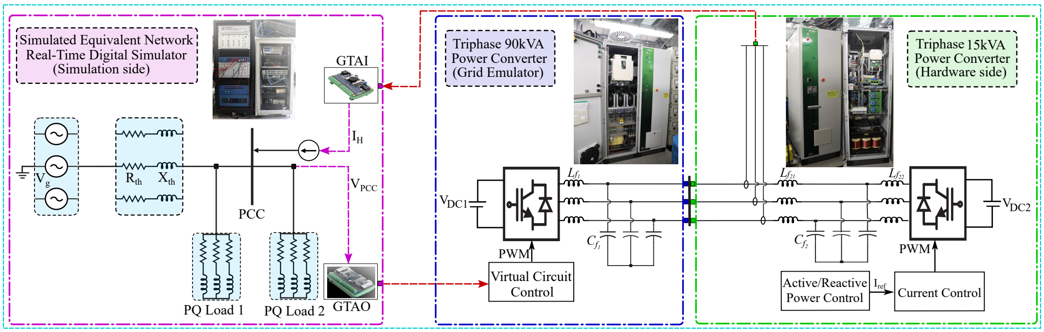

Fig. 9 A representation of the PHIL experimental setup.

A schematic of the PHIL experimental setup is shown in Figure 9. The PHIL setup is configured by a Triphase 90kVA (TP 90kVA) power converter that acts as a grid emulator to interface the real-time emulated power network hosted in the real-time digital simulator (RTDS) with the Triphase 15kVA (TP 15kVA) power converter serving as the converter utilized to compensate for voltage fluctuations in the grid. The configuration of this PHIL setup is defined by employing the ideal transformer model interface as depicted in [14, 15] and the stability and accuracy issues of this PHIL setup arising from the time delay and system impedance variation were addressed by leveraging the methods proposed in [12, 14, 16]. The topology and configuration of the real-time emulated power network are illustrated in Figure 9 with its components parameters tabulated in Table 1. The voltage at the point of common coupling (PCC) was sent to the grid emulator as its voltage command to allow it to replicate the PCC dynamics of the real-time simulated network to the physical TP 15kVA power converter. Furthermore, the current response of the physical TP 15kVA power converter was sent to the RTDS and injected into the real-time emulated power network at PCC, thus enabling the closed-loop PHIL configuration.

The converter utilized for voltage fluctuation compensation was controlled through the Matlab/Simulink environment, within which the converter's PQ power control and voltage fluctuation compensation system were implemented. A schematic of the converter control system is shown in Figure 10.

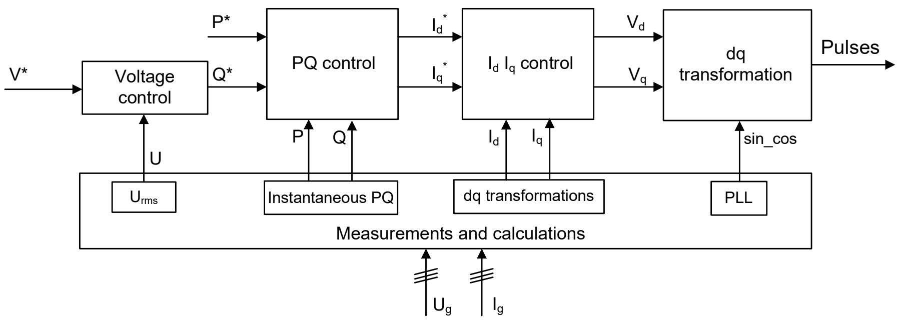

Fig. 10 Converter control system.

The test plan assumed three voltage fluctuation compensation scenarios, which differ in the state of the active power processed by the converter:

1. Generating active power of -2 kW
2. Absorbing active power of 2 kW
3. No active power 0 kW

The grid parameters were set to 0.3 Ω resistance and 0.5 Ω reactance for both the simulation and laboratory tests. This is consistent with the parameters of a 10-kilometer overhead low-voltage line.

For each of the cases mentioned above, three tests were carried out for voltage dip compensation and three tests for voltage rise of different values of change. A total of eighteen tests were thus conducted and are summarized in Table 1.

The most representative waveforms were selected from all those recorded in order to assess the quality and extent of the effectiveness of voltage fluctuations compensation through converter reactive power control. The voltage waveforms are presented in Figures 11-16.

The results of the conducted tests can be deemed satisfactory. The measurement system in the laboratory, constructed on the basis of the simulation system, demonstrated the efficacy of the proposed method in compensating for rapid voltage fluctuations. The results of the analysis indicated that the Hardwer-In-the-loop system exhibited satisfactory performance dynamics. The time required for the compensation of the simulated voltage drop did not exceed 250 ms. The compensation time observed in the simulation was considerably shorter, at approximately 100 ms. However, this discrepancy can be attributed to the speed of the simulated collapse or voltage rise. In the simulation, the collapse was initiated in a step manner, whereas in the laboratory

Table 1 Rapid voltage fluctuations compensation test table

Test Case	Grid Voltage Change (Rated at 0.4 kV)	R_G (Ω)	X_G (Ω)	Grid side load P(kW), Q(kVar)	Converter side load P(kW), Q(kVar)	TP 15kVA P(kW)
1	-1% (0.396 kV)	0.3	0.5	3, 0	1, 0	+2 kW
2	-2% (0.392 kV)	0.3	0.5	3, 0	1, 0	+2 kW
3	-3% (0.388 kV)	0.3	0.5	3, 0	1, 0	+2 kW
4	+1% (0.404 kV)	0.3	0.5	3, 0	1, 0	+2 kW
5	+2% (0.408 kV)	0.3	0.5	3, 0	1, 0	+2 kW
6	+3% (0.412 kV)	0.3	0.5	3, 0	1, 0	+2 kW
7	-1% (0.396 kV)	0.3	0.5	3, 0	1, 0	-2 kW
8	-2% (0.392 kV)	0.3	0.5	3, 0	1, 0	-2 kW
9	-3% (0.388 kV)	0.3	0.5	3, 0	1, 0	-2 kW
10	+1% (0.404 kV)	0.3	0.5	3, 0	1, 0	-2 kW
11	+2% (0.408 kV)	0.3	0.5	3, 0	1, 0	-2 kW
12	+3% (0.412 kV)	0.3	0.5	3, 0	1, 0	-2 kW
13	-1% (0.396 kV)	0.3	0.5	3, 0	1, 0	0 kW
14	-2% (0.392 kV)	0.3	0.5	3, 0	1, 0	0 kW
15	-3% (0.388 kV)	0.3	0.5	3, 0	1, 0	0 kW
16	+1% (0.404 kV)	0.3	0.5	3, 0	1, 0	0 kW
17	+2% (0.408 kV)	0.3	0.5	3, 0	1, 0	0 kW
18	+3% (0.412 kV)	0.3	0.5	3, 0	1, 0	0 kW

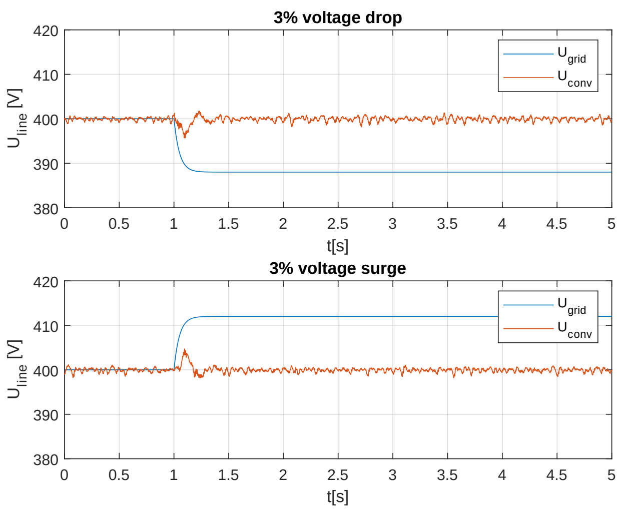

Fig. 11 Voltage waveforms for the case of 2kW active power generation.

tests, the grid simulator permitted a voltage drop of the shortest duration, lasting approximately 200 ms. It can therefore be stated that the compensation time for the voltage change is in alignment with the time of the change itself, with a minimum value of 100 ms.

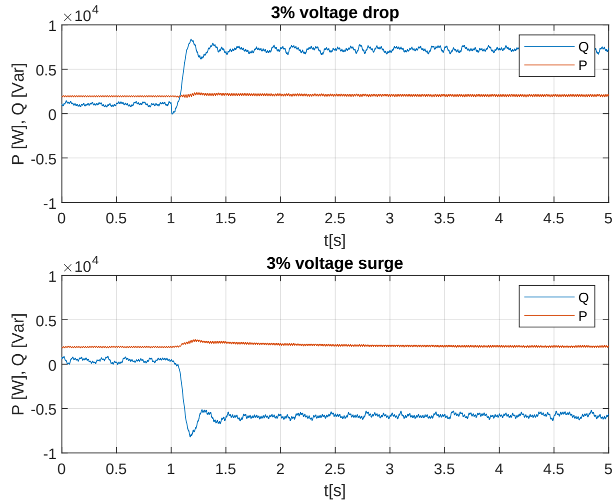

Fig. 12 Active and reactive power waveforms for the case of 2kW active power generation.

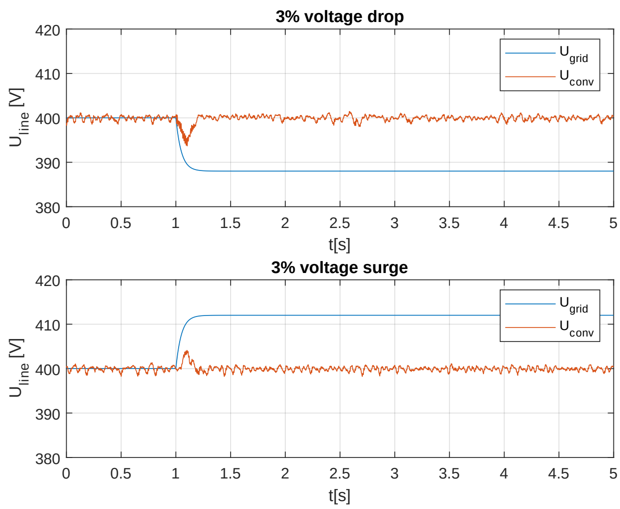

Fig. 13 Voltage waveforms for the case of 2kW active power consumption.

The post-compensation voltage waveform exhibits an oscillatory character that is not visible in the simulation synastry. This is due to the fact that PI controllers were used in the simulation circuit for the regulation of PQ power. In the laboratory system, linear regulators were used due to the specific nature of the PHIL used.

One limitation of this compensation method is the current capacity of the converter. The ratio of rated apparent power to active power provides the most

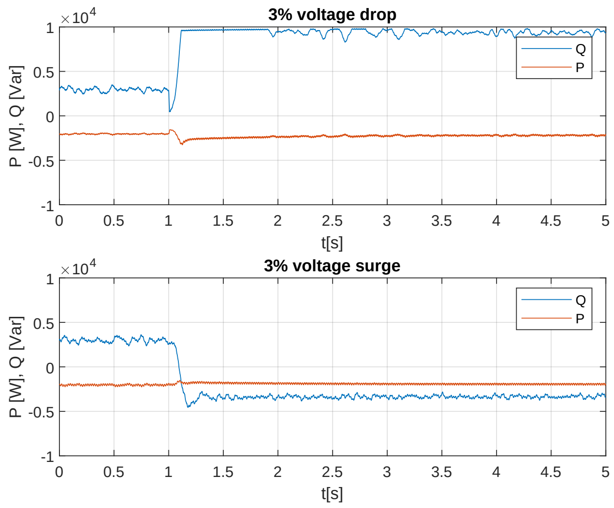

Fig. 14 Active and reactive power waveforms for the case of 2kW active power consumption.

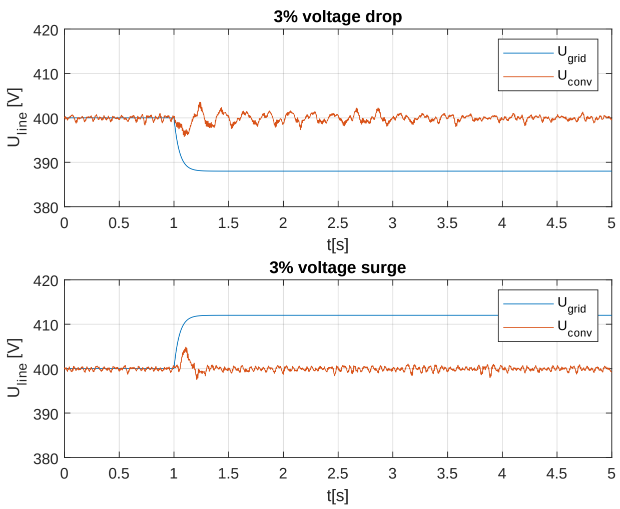

Fig. 15 Voltage waveforms for the case of zero active power.

straightforward description of this phenomenon. The greater the value, the greater the range of compensation for voltage fluctuations that can be achieved. This is a direct consequence of the reactive power that can be generated at a given point of operation of the converter.

A comparison of Figures 12,14,16 reveals that the reactive power required to compensate for voltage variations is lower in the first case. This is due to the fact that,

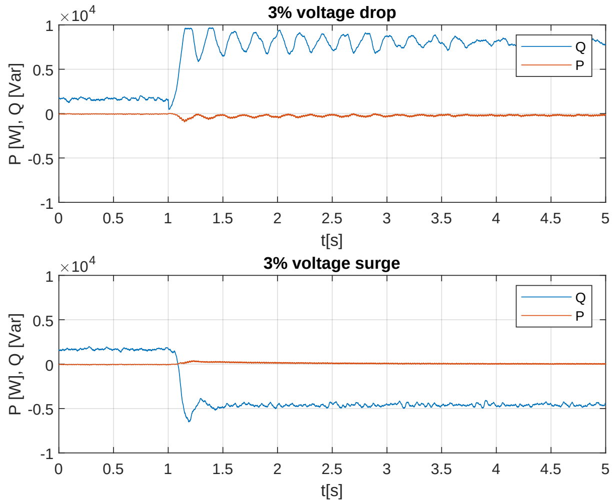

Fig. 16 Active and reactive power waveforms for the case of zero active power.

in the case of active power generation (Figure 12), the voltage variation is partially offset by the voltage increase caused by the active current flowing through the line resistances (see Figure 2 and Figure 3).

5 Conclusions

In conclusion, the research results obtained are promising. The proposed method has been verified in a positive manner. It is acknowledged that the range of compensated voltage variations is limited, however, given the number of converters operating simultaneously in the network, this effect may be sufficient. The compensation rate achieved is entirely satisfactory, and the voltage quality, when PI regulators are employed, is indistinguishable from the main voltage. The most attractive advantage of the proposed method of voltage fluctuation compensation is the fact that the converters required for its application are massively networked, and a change in their software is sufficient to implement it.

6 Acknowledgment

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