Research Article

A Predictive Negative Sequence Current Control Algorithm for Voltage Imbalance Compensation and Power Oscillation Minimization under Unbalanced Conditions

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Abstract
The predictive-based strategy employed in this paper allows an inverter to simultaneously inject positive and negative sequence reactive current to compensate for voltage imbalance, taking into account imbalance adverse effects on power oscillations. A suggested optimization cost function of a predictive-based controller is formulated to solve the trade-off problem between grid voltage support and voltage imbalance compensation by determining the optimal negative sequence reactive power to be injected to the reference current of a generator. The proposed predictive-based control strategy is evaluated under various distributed generation operating conditions in terms of injected active to reactive power ratio. Additionally, its performance is compared with the performance of an active power oscillations minimization ($\tilde{p}$-minimization) control strategy, where the active power oscillations due to reactive power disappear. In contrast with $\tilde{p}$-minimization control strategy, the proposed predictive-based strategy managed to reduce the active power oscillation. The adequacy of the proposed strategy is verified via simulations of a distributed energy resource (DER) grid-connected inverter under voltage imbalance caused by an unbalanced load. The simulation work presented in this paper was conducted using MATLAB/Simulink software. As a part of a smart inverter functions to preserve the energy supply under unbalanced conditions, this research would serve as a platform for studying the inverter optimal control of negative sequence component.

Keywords: Distribution Generation (DG), Model predictive control (MPC), Negative sequence reactive power injection, Power oscillations, Unbalance compensation

1 Introduction

High integration of DGs, including wind and photovoltaic, raises more challenges to improve power system reliability, grid connectivity and resolve power quality problems [1]–[3]. Among these power quality problems comes the problems of voltage imbalance due to unbalanced loads, nonlinear loads, etc. [4]–[6]. Various control strategies have been developed to compensate for voltage imbalance under unbalanced voltage conditions [7]–[11]. More studies were developed to overcome technical problems due to previously developed strategies [12], [13]. Unbalanced conditions result in a negative sequence current and double the fundamental frequency of a converter output power, which may lead to system instability. In general, various kinds of compensators can be employed to compensate for voltage imbalance by injecting reactive power. However, installing such a compensator will increase system cost burden. There comes the need for finding a more cost-effective way to manage imbalance compensation adverse effect problems. Usually, DGs are not running at the designated rated power. Therefore, reactive power can be produced with the remaining capacity. In other words, given that there is an unused power capacity, the inverter can put it to use for reactive power production. Injecting reactive power can help to support ancillary services, such as grid voltage support services and riding through low voltage under unbalanced voltage conditions [14]. Using DGs to provide such services was the main focus of the strategies presented in [14],

[15]. The provision of ancillary services to the grid has been discussed as a way to avoid exceeding voltage limits during unbalanced conditions. Additionally, other strategies investigated grid voltage support, $\tilde{p}$-minimization and voltage imbalance compensation due to unbalance loads or grid faults.

Apparently, most of previous studies focused on dividing sequence components and controlling unbalanced phase voltages, however they paid little attention to optimal compensation of negative sequence currents, which should be taken into consideration as a sufficient way to maintain voltage and power quality under unbalanced conditions. Along with that, using a predictive-based control strategy could help avoiding over-voltage and disconnection due to conventional strategies and improve the controllability of active power and reactive power along with the increase of DGs penetration level.

Given this context, this paper has employed predictive control techniques subjected to unbalanced conditions differently from the way found in literature, which focuses mostly on converter current control [16]–[22]. MPC can contribute to grid reliability through the optimal control of negative sequence reactive power injected into the grid under unbalanced voltage conditions due to an unbalanced load; however, this is hardly addressed in the current literature. Moreover, it opens the way for expanding the ancillary services provided by DGs.

In light of the aforementioned issues, this paper proposes a predictive-based negative sequence reactive power injection control strategy during unbalanced conditions. The voltage imbalance arises from an unbalanced load. The proposed strategy aims to compensate for the voltage imbalance while reducing the adverse effect due to compensation. In other words, the strategy compensates for the voltage imbalance as well as minimizing the active power oscillations' adverse effect due to unbalance conditions. The proposed strategy is compared with a $\tilde{p}$-minimization strategy to investigate the inverter capability of supporting grid voltage and evaluate the proposed strategy performance.

2 Problem Formulation

2.1 *Configuration*

Figure 1 shows the configuration of the grid connected to a three-phase DG inverter. The inverter is connected to the grid via an LCL filter at the point of common coupling (PCC) as shown in Figure 2.

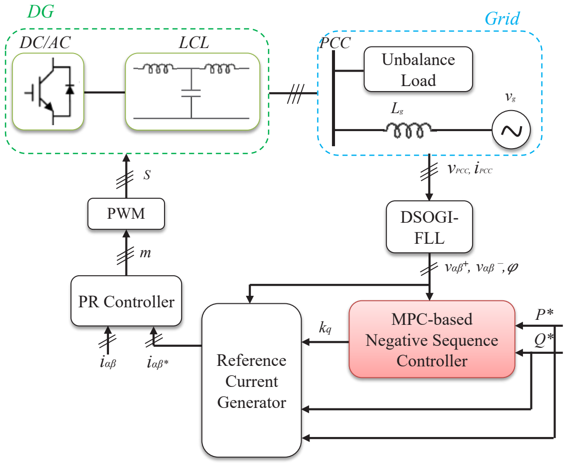


Figure 1: Layout of the proposed control strategy during unbalanced conditions due to unbalanced load.

At normal conditions inverter injects active power to the grid. Equation (1) represents the transfer function of the LCL connected inverter,

$$\frac{I_f(s)}{V_g(s)} = \frac{R_d Cs + 1}{L_1 L_2 Cs^3 + R_d(L_1 + L_2)Cs^2 + (L_1 + L_2)s} \quad (1)$$

where I_f is the inverter output current, V_g is the grid voltage, R_d is the damping resistor, C is the filter capacitance, L_1 is the inverter side inductance, and L_2 is the grid side inductance [23].

The grid is exposed to a voltage imbalance due to a three-phase unbalanced load connected to PCC. The three-phase unbalanced load is represented by a three-phase resistive load 18Ω, 5Ω, 3Ω based on the system parameters in Table 1 [14].

Table 1: System parameters

Symbol	Quantity	Value
S_b	Nominal rated Power	20.61 kVA
$P*$	Reference active power	20 → 5 kW
$Q*$	Reference reactive power	5 → 20 kVAr
v_g	Nominal grid voltage	240 V
R_{Load}	Three phase unbalanced load	18Ω, 5Ω, 3Ω
L_g	Grid Inductance	10 mH

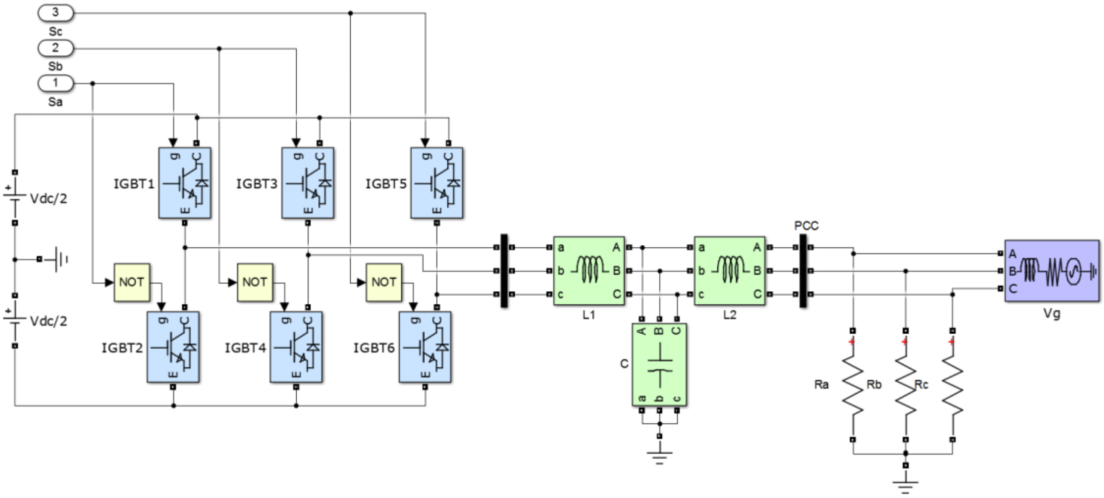


Figure 2: Simulink model of a grid-connected inverter.

L_g is used to model the connection between the grid and the DG inverter with an apparent power S = 20.61 kVA. Grid voltage v_g is affected by the unbalance conditions occurring at the PCC due to the unbalanced resistive load R_{Load}.

In the proposed strategy, once the load becomes unbalanced and the unbalanced conditions are detected, the predictive-based control is activated. Based on previous investigations on the performance of an inductive grid connected to a DG inverter, changing the ratio P/Q of injected active to reactive power affects the performance of voltage imbalance compensation and $\tilde{p}$-minimization in accordance with the control strategy used for power injection [14]. Therefore, and for the aim of evaluating the proposed strategy, a sequence of active to reactive power ratios is injected. The double second-order generalized integrator frequency-locked loop (DSOGI-FLL) synchronization block generates positive and negative α-β reference frame voltage sequence components that assist the generation of current reference under unbalanced conditions. It also contributes to the implementation of the MPC-based control strategy shown in the red block in Figure 1 that intends to trace the optimal operating conditions by minimizing a multivariable optimization cost function and regulating each voltage sequence.

2.2 *MPC control concept*

During unbalanced conditions, it is desirable to be able to raise and equalize the voltage not to violate the lower and upper limits of phase voltages, however, using conventional control strategies may lead to inverter disconnection. The current control strategy based on predictive control can be used to avoid inverter disconnection due to conventional strategies. It can manage the nonlinear nature of a converter, as well as easily consider many constrains and restrictions with less complexity during implementation [5], [19].

The MPC-based control strategy presented in this paper is implemented by modeling all possible control actions, each control action $C_{Si}(t_k + 1)$ corresponds to a control variable $k_{qi}(t_k + 1)$, based on a prediction function. To determine which control action to be selected, the cost function $g_i(_k + 1)$ is designed as a function in both the reference and the predicted-based voltage sequence amplitudes, and then, evaluated for each control action, for $i = 1,\ldots,n$. Finally, the control action which minimizes that cost function is selected. To select the optimal operation point, the cost function is evaluated for all the regions based on the minimum distance, as shown in Figure 3 the optimal control gain corresponding to that region is then selected and stored to be used next.

3 Grid-connected DG Inverter under Unbalance Conditions

In this section, a detailed study of the proposed control strategy is presented, where the ratio P/Q plays a key

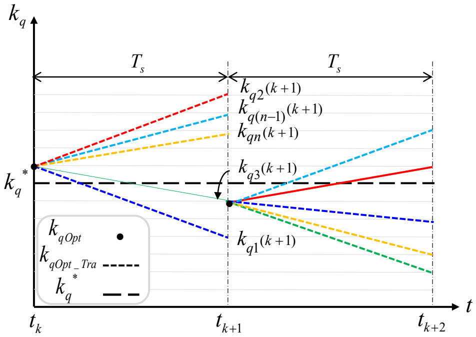


Figure 3: Layout of the proposed control strategy during unbalanced voltage conditions.

role in how much the imbalance can be compensated and the power oscillations can be minimized.

3.1 *Theory*

Controlling the inverter current with a proportional-resonant (PR) controller eliminates steady-state error while controlling the sinusoidal α-β reference current input signals to the controller. The proportional PR controller transfer function in Equation (2), can be designed from a synchronous control based on PI [24]–[26].

$$G_{PR}(t) = K_p + \frac{2K_r\omega_c s}{s^2 + 2\omega_c s + \omega^2} \tag{2}$$

where G_{PR} is the transfer function of a proportional resonant controller, K_p is the proportional gain, K_r is the resonant gain, ω is the fundamental frequency and ω_c is the resonant controller bandwidth.

The grid-PCC voltage imbalance compensation and $\tilde{p}$-minimization relations implemented in the MPC-based negative sequence controller block are based on Equations (3) and (4).

$$v_\alpha = v_{g\alpha} + L_g\frac{di_\alpha}{dt} \tag{3}$$

$$v_\beta = v_{g\beta} + L_g\frac{di_\beta}{dt} \tag{4}$$

where $v_{g\alpha}$ and $v_{g\beta}$ are the α-β reference frame grid voltages, L_g is the grid inductance, and i_α and i_β are the current components in the α-β reference frame [12].

The PCC α-β reference frame voltages v_α and v_β are expressed in terms of positive and negative voltage sequence components as indicated in Equations (5) and (6), [12]

$$v_\alpha = v_\alpha^+ + v_\alpha^- \tag{5}$$

$$v_\beta = v_\beta^+ + v_\beta^- \tag{6}$$

where v_α^+ and v_α^- are positive and negative voltage sequences in the α reference frame, respectively, and v_β^+ and v_β^- are positive and negative voltage sequences in the β reference frame, respectively, given by Equations from (7) to (10), [12]

$$v_\alpha^+ = V^+\cos(\omega t + \varphi^+) \tag{7}$$

$$v_\beta^+ = V^+\sin(\omega t + \varphi^+) \tag{8}$$

$$v_\alpha^- = V^-\cos(\omega t - \varphi^-) \tag{9}$$

$$v_\beta^- = -V^-\sin(\omega t - \varphi^-) \tag{10}$$

where V^+ and V^- are the amplitudes of positive and negative sequences, respectively, and φ^+ and φ^- are the initial phase angles of positive and negative sequences, respectively.

According to the definition of flexible positive and negative sequence control (FPNSC), the injected reference current components in α-β reference frame i^*_α and i^*_β during unbalanced conditions can be obtained in terms of positive and negative voltage sequence components.

k_q is the control gain controlling the proportion between positive and negative sequence voltages; it controls the amount of injected negative reactive power sequence to the grid experiencing unbalanced conditions. Although the control gain k_q can take any values in the range of [0, 1], selecting certain values allows providing different kind of services to grid. Selecting k_q = 1 allows supporting the grid by injecting positive reactive power sequence but it does not contribute to imbalance compensation. Selecting k_q = 0 allows grid voltage imbalance compensation by injecting negative reactive power sequence but it does not contribute to voltage support services. Selecting k_q between 0 and 1 will contribute to $\tilde{p}$-minimization.

To evaluate the performance of the proposed predictive-based control strategy, a comparison was made with $\tilde{p}$-minimization control strategy where $k_q = 0.5$. According to previous studies, the active power oscillation is minimized when $k_q = 0.5$, because the oscillations in active power due to reactive power will disappear. Therefore, the comparison was made with $\tilde{p}$-minimization strategy where $k_q = 0.5$.

Grid codes prescribe strict limits for remaining connected under unbalanced conditions due to grid faults [27]–[29]. However, those limits are subjected to national grid codes and can vary by jurisdiction. For the proposed control strategy, the optimization target to inject the optimal amount of negative sequence reactive power during unbalanced voltage conditions to not violate the upper and lower limits of phase voltages according to grid regulations as in Equations (11) and (12), [13]

$$V_h \leq 1.1\ V_{nom} \tag{11}$$

$$V_l \geq 0.9\ V_{nom} \tag{12}$$

where V_h is the maximum phase voltage limit, V_l is the minimum phase voltage limit, and V_{nom} is the nominal grid voltage.

To investigate the optimal injected reactive power, the possible range for k_q is divided into a number of regions, each with 0.01 wide. For all these regions, the reference reactive power sequences are obtained from Equations (13) and (14), [12]

$$Q^{+}_{k+1} = \frac{k_q (V^{+})^{*2}}{k_q (V^{+})^{*2} + (1-k_q)(V^{-})^{*2}} Q^{*} \tag{13}$$

$$Q^{-}_{k+1} = \frac{(1-k_q)(V^{-})^{*2}}{k_q (V^{+})^{*2} + (1-k_q)(V^{-})^{*2}} Q^{*} \tag{14}$$

where Q^{+}_{k+1} and Q^{-}_{k+1} are the predicted positive and negative reactive power sequences, respectively, and $k + 1$ refers to the next sampling time, $(V^{+})^{*}$ and $(V^{-})^{*}$ are the reference amplitudes of the voltage sequences, and k_q is the control gain.

The predicted sequence current component at the next sampling time $k + 1$ is then calculated based on the previously obtained reactive power sequences as in Equation from (15) to (18), [12]

$$i_{\alpha}{}^{+}{}_{k+1} = \frac{2}{3}\frac{v_{\alpha}{}^{+*}}{(V^{+})^{*2}} P^{*}{}_{k+1} + \frac{2}{3}\frac{v_{\beta}{}^{+*}}{(V^{+})^{*2}} Q^{+}{}_{k+1} \tag{15}$$

$$i_{\alpha}{}^{-}{}_{k+1} = \frac{2}{3}\frac{v_{\beta}{}^{-*}}{(V^{-})^{*2}} Q^{-}{}_{k+1} \tag{16}$$

$$i_{\beta}{}^{+}{}_{k+1} = \frac{2}{3}\frac{v_{\beta}{}^{+*}}{(V^{+})^{*2}} P^{*}{}_{k+1} - \frac{2}{3}\frac{v_{\alpha}{}^{+*}}{(V^{+})^{*2}} Q^{+}{}_{k+1} \tag{17}$$

$$i_{\beta}{}^{-}{}_{k+1} = -\frac{2}{3}\frac{v_{\alpha}{}^{-*}}{(V^{-})^{*2}} Q^{-}{}_{k+1} \tag{18}$$

where $i_{\alpha}{}^{+}{}_{k+1}$, $i_{\alpha}{}^{-}{}_{k+1}$, $i_{\beta}{}^{+}{}_{k+1}$, and $i_{\beta}{}^{-}{}_{k+1}$ are the α-β reference frame predicted sequence current components, $v_{\alpha}{}^{+*}$, $v_{\alpha}{}^{-*}$, $v_{\beta}{}^{+*}$, and $v_{\beta}{}^{-*}$ are the approximated voltage sequence references in the stationary α-β reference frame, and $P^{*}{}_{k+1}$ is the injected active power at $k + 1$.

Accordingly, the predicted-based voltage sequence amplitude is obtained through the corresponding relation between the PCC voltage sequences at k, the grid voltage sequences amplitude at k, the predicted current sequences at $k + 1$ and current sequences at k as in Equations (19) and (20),

$$(V^{+})^{PB} = \sqrt{(v_{\alpha}{}^{+}{}_{k})^{2} + (v_{\beta}{}^{+}{}_{k})^{2}} \tag{19}$$

$$(V^{-})^{PB} = \sqrt{(v_{\alpha}{}^{-}{}_{k})^{2} + (v_{\beta}{}^{-}{}_{k})^{2}} \tag{20}$$

where $i_{\alpha}{}^{+}{}_{k+1}$, $i_{\alpha}{}^{-}{}_{k+1}$, $i_{\beta}{}^{+}{}_{k+1}$, and $i_{\beta}{}^{-}{}_{k+1}$ are the α-β reference frame predicted sequence current components, $v_{\alpha}{}^{+*}$, $v_{\alpha}{}^{-*}$, $v_{\beta}{}^{+*}$, and $v_{\beta}{}^{-*}$ are the approximated voltage sequence references in the stationary α-β reference frame, and $P^{*}{}_{k+1}$ and $Q^{+}{}_{k+1}$ are the injected active power and reactive power at $k + 1$ [15].

According to the design requirements, the cost function representing a predictive-based control strategy is a combination of two terms; reflecting the regulation of positive and negative sequence voltage. The designed cost [Equation (21)]

$$g = |(V^{+})^{*} - (V^{+})^{PB}| + |(V^{-})^{*} - (V^{-})^{PB}| \tag{21}$$

where g is cost function.

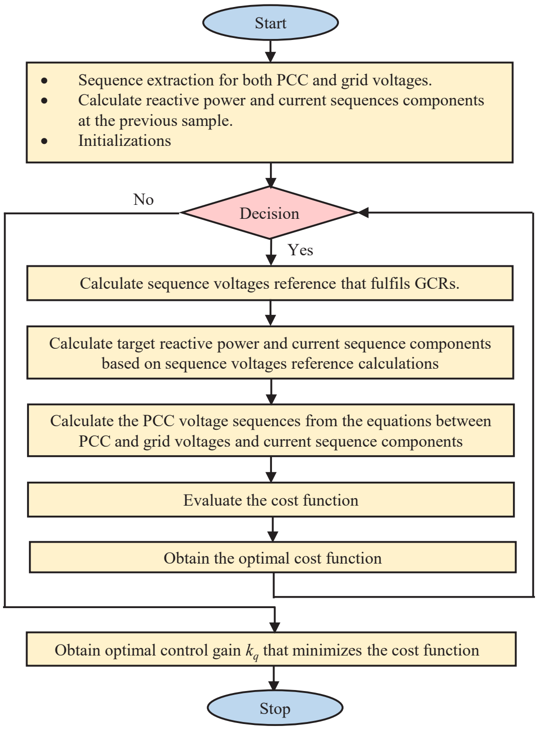


Figure 4: Proposed control strategy flowchart.

3.2 *Algorithm*

A detailed implementation of this control strategy is shown in Figure 4 illustrates how the proposed control works. The proposed strategy can be implemented by allowing the DG inverter to inject both active and reactive power once the voltage imbalance is detected.

Following that, the predictive control operation mode of the inverter is activated, active and reactive power to be injected are obtained, then the needed initialization is performed; voltage sequence extraction, reactive power, and current sequence components calculations, defining the range of operation, region wide and setting the initial value of the cost function to infinity. After that the voltage sequence amplitude references that fulfil grid requirements under unbalanced voltage conditions, target reactive power and current sequence components at $k + 1$ sampling time are determined.

Therefore, based on the grid-PCC voltage relation, the PCC voltage sequence components at k sampling time are obtained and the cost function for each region is computed. Finally, the k_q corresponding to the minimum cost function is selected and the optimal injected negative sequence reactive power to the reference current generator is computed.

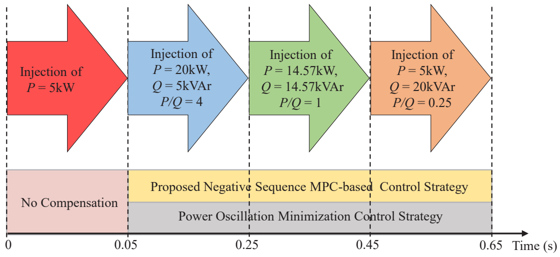


Figure 5: Control sequence of the power inverter.

4 Simulation Results

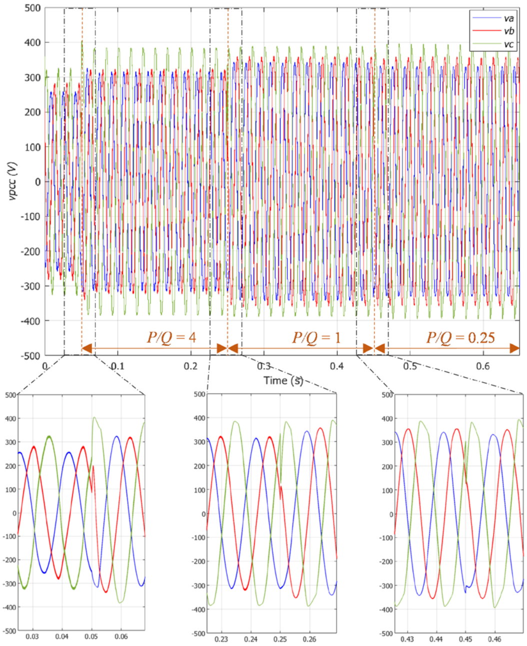
The simulation results for the proposed strategy using MATLAB/Simulink are presented in this section. For the aim of evaluating the performance of the proposed predictive negative sequence control strategy, the proposed control strategy is applied under unbalanced load condition with a sequence of injected P/Q ratios, and the results are compared with the simulation results of a $\tilde{p}$-minimization control strategy for more effective demonstration.

The performance of the proposed work is analyzed under various P/Q injected ratios to the grid using the control sequence presented in Figure 5. At normal conditions, the grid load is fed with a 5kw. Between t = 0s and t = 0.05s, the unbalanced load condition is analyzed without injecting the P/Q ratio. To evaluate the proposed strategies under unbalanced load condition, the power inverter delivers both active power and reactive power with a ratio P/Q = 4 to the grid between t = 0.05 s and t = 0.25 s, a ratio P/Q = 1 until t = 0.45 s, and a ratio P/Q = 0.25 until t = 0.65 s.

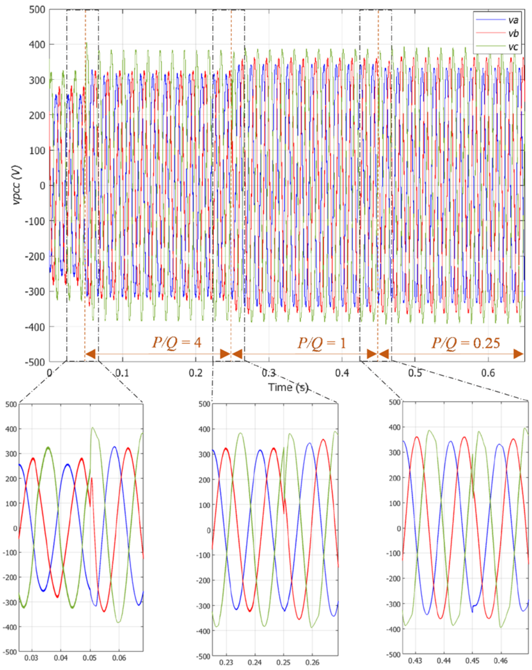
Figure 6(a), b compares the transient behavior of PCC phase voltages under unbalanced voltage condition due to unbalanced load by injecting a sequence of P/Q ratios as previously illustrated in Figure 5.

As can be seen from Figure 6(b), the lower the injected P/Q ratio is, the more improved the grid voltage support. Similar results can also be seen in Figure 6(a) when the $\tilde{p}$-minimization strategy is employed.

There is not much performance improvement observed from the MPC-based strategy with reference to the $\tilde{p}$-minimization strategy, however, there will be

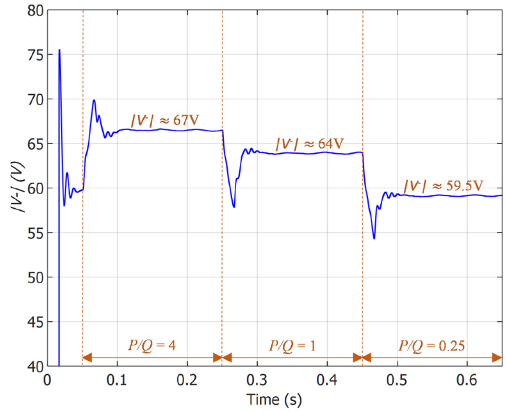


(a)

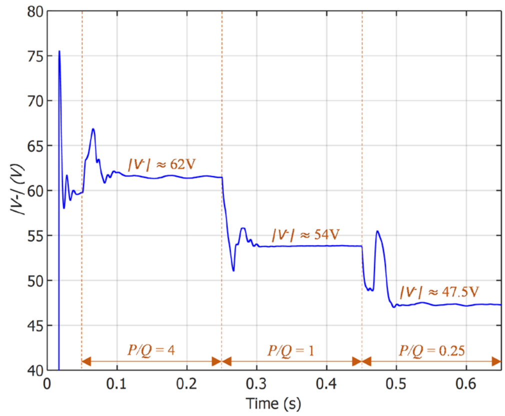


(b)

Figure 6: Simulation of the transient behavior of the PCC phase voltages *va*, *vb*, *vc* for presented control sequence: (a) $\tilde{p}$-minimization strategy; (b) proposed MPC-based strategy.



(a)



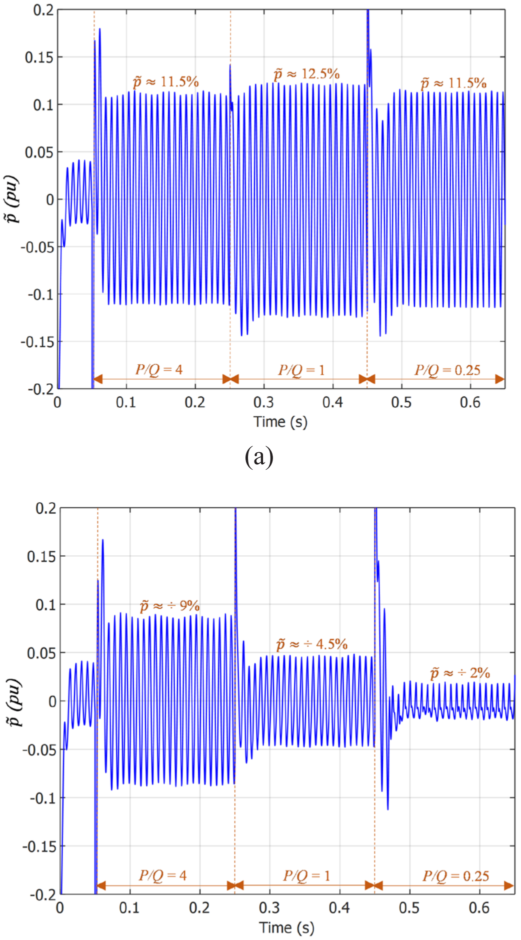
(b)

Figure 7: Simulation of the negative voltage sequence components $V-$ for presented control sequence: (a) $\tilde{p}$-minimization strategy; (b) proposed MPC-based strategy.

a marked performance improvement between the two control strategies, considering active power oscillation and negative sequence voltage reduction.

Due to the injection of negative reactive power sequence at PCC with accordance to the optimal control gain, the positive sequence voltage is boosted, improving the voltage support performance for both control strategies showing similar performance with the $\tilde{p}$-minimization strategy no matter how much the *P/Q* ratio is injected.

As indicated from Figure 7(a) and (b) the negative-sequence voltage drops more as we inject more reactive power and lower *P/Q* ratio; when the injected *P/Q* ratios are 4, 1, and 0.25, the negative



(b)

Figure 8: Simulation of the active power oscillations for presented control sequence: (a) $\tilde{p}$-minimization strategy; (b) proposed MPC-based strategy.

voltage sequence drops the most in case the ratio of $P/Q \leq 0.25$ in case of employing the $\tilde{p}$-minimization strategy and drops to 54V when the ratio of $P/Q \leq 1$, and drops to 47.5V when the ratio of $P/Q \leq 0.25$, in case of employing the MPC-based strategy. As noted, the MPC-based strategy reduces the negative sequence voltage compared to the $\tilde{p}$-minimization strategy when the ratio of $P/Q \leq 1$.

Figure 8(a) and (b) demonstrate that, during unbalanced conditions providing both active and reactive power with 2ω oscillations will fulfill grid requirements, however, it will have an adverse effect on the power oscillations as previously explained.

As noticed in Figure 8(a), for the $\tilde{p}$-minimization strategy the active power oscillation is nearly the same no matter how much P/Q ratio is injected. In other words, when the injected P/Q ratios are 4, 1, and 0.25, the active power oscillation equals ±11%, ±12.5%, and ±11%, respectively, in case of employing the $\tilde{p}$-minimization strategy and equals ±9%, ±4.5%, and ±2%, respectively, in case of employing the MPC-based strategy as seen in Figure 8(b). As indicated in Figure 8(a) and (b), for the MPC-based proposed strategy, the higher the injected reactive power compared to active power and the lower the P/Q ratio is, the more the power oscillation decreases. This happened due to the control gain k_q used in the MPC-based strategy that affects the amount of the negative sequence reactive power injected to the grid.

5 Conclusions

The paper proposed a voltage support control strategy to regulate the injected reactive power during unbalanced conditions due to an unbalanced load. From an optimization perspective, the predictive control is employed to regulate the voltage sequence components. Controlling those components will contribute to ensuring a proper reactive power injection under unbalanced conditions. This paper expanded on the predictive control for optimally controlling negative sequence reactive power injected to the grid under unbalanced conditions due to an unbalanced load. The proposed strategy selects optimal operating conditions that minimize a multi-objective cost function to keep the phase voltage within safety limits according to the GCRs, compensate voltage imbalance and minimize power oscillations by delivering negative sequence reactive power. The high integration of DGs can be invested in providing grid ancillary services by adding this control strategy to the functions provided by smart inverters in case of grid contingencies. As ascertained from the presented simulation results, without such a voltage control strategy, the power coming from the DGs is not sufficient for usage because the voltage imbalance will proceed, and other loads are quite sensitive to voltage variations.

Author Contributions

N.H.: conceptualization, investigation, research design, methodology, data analysis, writing and editing. The author has read and agreed to the published version of the manuscript.

Conflicts of Interest

The author declares no conflict of interest.

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