International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 9, No. 2, June 2018, pp. 668~678
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v9.i2.pp668-678

Predictive Approach for Power Quality Improvement based Direct Power Control

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Article Info

Article history:

Received Sep 24, 2017
Revised Jan 11, 2018
Accepted Jan 25, 2018

Keyword:

Direct power control (DPC)
Harmonics
Non-linear load
Predictive model
Shunt active power filter (SAPF)

ABSTRACT

The extensive use of non-linear loads in industry becomes increasingly a serious problem that affects the quality of energy delivered to customers. Therefore, the shunt active power filter (SAPF) has emerged as an important industrial tool to eliminate induced harmonic currents and compensating of reactive power. This paper proposes an improved control configuration for SAPF based on a modern technique called predictive direct power control (Predictive-DPC). The principle of this control is based on the direct regulation of the instantaneous active and reactive powers to guarantee a good energy quality on the grid side. For this purpose the appropriate average voltage vector which cancels power tracking errors is calculated by a simple predictive model at the bigining of each control period. This type of control includes various features such as the lack of look up table (LUTs) and closed current loops and the constant switching frequency is achieved through the use of PWM modulation. The results of the simulation process show a high performance in the steady and transient state function for predictive-DPC control that might be a reasonable alternative to conventional DPC in the field of active power filtering.

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1. INTRODUCTION

Over the last few decades, the majority of AC electrical systems contain different types of non-linear loads. The non-linear load induces harmonics that affect the sinusoidal waveforms of the supply voltage and current. As a conventional solution passive inductance capacitance (LC) filters have been used used to eliminate line current contamination and to address low power factor. Although this second-order passive filter solution involves many disadvantages such as aging, tuning problems and resonance phenomenon, and it is necessary to design a filter for each a harmonic frequency targeted to be removed [1]. In practice has been found that harmonic suppression via a shunt active power filter (SAPF) is more efficient and more flexible compared to a passive power filter [2–3].

The control of SAPF is experiencing a significant development over time where works in [4-5] represent actual launch of the idea of of SAPF systems. In the literature [6], Akagi et al. proposed a strategy based on an algorithm called "P-Q theory". Since then, the P-Q theory has inspired many works dealing with active filter control strategies [6-17]. As well, control based sliding mode approach [18] and repetitive control [19] have been presented. As an alternative to conventional vector control, the direct power control DPC strategy proposed in [20] has opened a new era in the field of power electronics control. DPC control derives its principles and philosophy from the direct torque control DTC used for adjustable speed drives and it was proposed in [21]. Unlike to DTC, the DPC control adopts active and reactive powers as control variables instead of torque and flux in DTC. In contrast of traditional techniques, DPC introduces important features such as low complexity control system, fast response and ease of implementation. Emergence of conventional DPC usage for SAPF systems is introduced by [22-23]. Furthermore, a modified DPC applied for an SAPF system is proposed by [24-25] in order to remedy adverse effects created by unbalance and distorted grid voltage conditions. As well, multifunctional SAPF system based DPC for a photovoltaic generator is presented by [26]. In the literature [27], a new control strategy called "predictive DPC technique" is used for the control of PWM voltage source inverters (VSI's). The idea was to design a simple mathematic predictive model has capability to estimate the appropriate voltage reference at every sampling time which ultimately leads to the cancellation of active and reactive power tracking errors.

In this paper, an improved control configuration has been proposed that incorporates predictive DPC control featuress in the field of active power filtering. The results and the analysis study which will present and illustrate in this paper exhibit satisfactory performances with high harmonic elimination efficiency.

2. SYSTEM TOPOLOGY DESCRIPTION AND MODELING

2.1. System description

The configuration of the adopted system is shown in Figure3. The system consists mainly of a network, a nonlinear load and shunt active power filter (SAPF) unit. Both grid and SAPF unit supply the non-linear load to provide a pure sine waveform for line current and reactive power compensation in the grid side. We have assumed that the power grid is balanced and sunusoidal connected in series with with line impedance(Z_s). The non-linear load consists of an uncontrolled three-phase rectifier with an inductive load. In In addition, there is impedance between the common coupling point (PCC) and the non-linear load (Z_c). As well there is filter impedance (Z_f) its emplacement between PWM inverter and PCC node and this structure can consider as a controlled current source (as shown in Figure1) which can generate the shape required for the harmonic current.

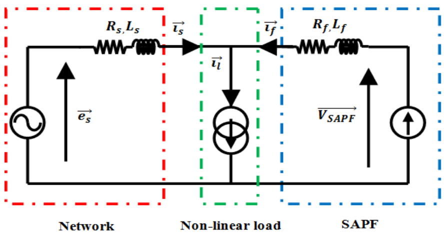

Figure 1. Equivalent circuit of shunt power filtring system.

a. Mathematical model of SAPF

This section presents the detailed mathematical modeling of the different parts of the system presented in Figure3.

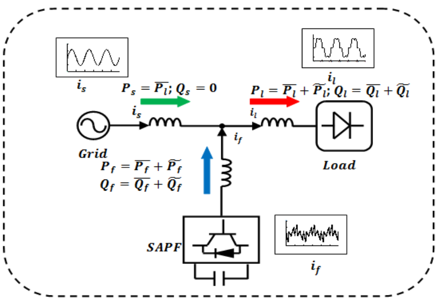

Figure 2. Harmonic elimination system by

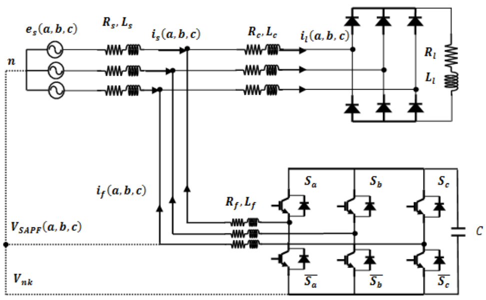

Figure 3. Detailed scheme for shunt active power filter using SAPF

The three phase voltage system can be expressed as follow:

$$\begin{cases} e_{sa}(t) = V_m \sin(\omega t) \\ e_{sb}(t) = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \\ e_{sc}(t) = V_m \sin\left(\omega t - \frac{4\pi}{3}\right) \end{cases} \quad (1)$$

We consider the supply system as symmetrical balanced source:

$$\begin{cases} e_{sa} + e_{sb} + e_{sc} = 0 \\ i_{sa} + i_{sb} + i_{sc} = 0 \\ i_{la} + i_{lb} + i_{lc} = 0 \\ i_{fa} + i_{fb} + i_{fc} = 0 \end{cases} \quad (2)$$

From Figure1 and by neglecting source impedance can find the relationship that links between network and SAPF unit.

$$V_{SAPF} = e_s - L_f \frac{di_f}{dt} - R_f i_f \quad (3)$$

Where: V_{SAPF} is the converter output voltage and e_s is the grid voltage.
The detailled expression of Eq.3 can be written in the following equation pattern:

$$\begin{cases} {V_{SAPF}}^a = e_{sa} - L_f \frac{di_{fa}}{dt} - R_f i_{fa} = S_a V_{dc} - V_{nk} \\ {V_{SAPF}}^b = e_{sb} - L_f \frac{di_{fb}}{dt} - R_f i_{fb} = S_b V_{dc} - V_{nk} \\ {V_{SAPF}}^c = e_{sc} - L_f \frac{di_{fc}}{dt} - R_f i_{fc} = S_c V_{dc} - V_{nk} \\ C \frac{dV_{dc}}{dt} = S_a i_{fa} + S_b i_{fb} + S_c i_{fc} \quad . \end{cases} \quad (4)$$

The sum of the first three equations in Eq.4 leads to:

$$\begin{cases} {V_{SAPF}}^a + {V_{SAPF}}^b + {V_{SAPF}}^c = 0 \\ V_{nk} = \frac{S_a + S_b + S_c}{3} V_{dc} \end{cases} \quad (5)$$

Substituting Eq.5 in Eq.4 yields

$$\begin{cases} \frac{di_{fa}}{dt} = -\frac{R_f}{L_f} i_{fa} - \frac{V_{dc}}{L_f}\left(S_a - \frac{S_a + S_b + S_c}{3}\right) + \frac{1}{L_f} e_{sa} \\ \frac{di_{fb}}{dt} = -\frac{R_f}{L_f} i_{fb} - \frac{V_{dc}}{L_f}\left(S_b - \frac{S_a + S_b + S_c}{3}\right) + \frac{1}{L_f} e_{sb} \\ \frac{di_{fc}}{dt} = -\frac{R_f}{L_f} i_{fc} - \frac{V_{dc}}{L_f}\left(S_c - \frac{S_a + S_b + S_c}{3}\right) + \frac{1}{L_f} e_{sc} \end{cases} \quad (6)$$

Can summarize control signals as follow

$$\begin{cases} q_a = S_a - \frac{S_a + S_b + S_c}{3} \\ q_b = S_b - \frac{S_a + S_b + S_c}{3} \\ q_c = S_c - \frac{S_a + S_b + S_c}{3} \end{cases}$$

$$q_{abc} = K S_{abc} \quad (7)$$

With: $q_{abc} = [q_a \; q_b \; q_c]^T$; $S_{abc} = [S_a \; S_b \; S_c]^T$

And $K = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$

The Shunt Active Power Filter (SAPF) can be regarded as a controlled current source that generates the appropriate filter current that is the same as the harmonic current absorbed by the contaminated networks.

In order to In order to provide a reference system based on power quantities, it is necessary to analyze the instantaneous power balance between the power transmitted by the grid and SAPF unit and power absorbed by load. With the consideration that P_s,Q_s are respectively active and reactive delivered powers by the grid and P_f,Q_f are respectively active and reactive generated powers by the filter and P_l,Q_l are respectively active and reactive consumed powers. The main objective of SAPS is to compensate of the reactive power and the mitigation of the harmonic currents. This target is possible if the active power on the grid side is maintained to be equal to the DC component in the load side $P_s = \overline{P_l}$ and grid side reactive power equal to zero$Q_s = 0$. To ensure this condition, the harmonic power component and the reactive power drawn by load must be fully powered by the SAPF unit. Thus, the power balance of the system can be written in the following form:

$$P_s = \overline{P_l};\, Q_s = 0\,;\, P_f = P_l - P_s = P_l - \overline{P_l} = \widetilde{P_l} \tag{8}$$

$$Q_f = Q_l - Q_s = Q_l \tag{9}$$

3. THE CONTROL DESIGN OF SAPF

3.1. Conventional direct power control

The instantaneous power calculation needs an algebraic transformation (Concordia transformation) of the grid three phase voltages and three phase currents from the (abc) coordinates to the $(\alpha\beta)$ coordinates.

$$\begin{bmatrix} i_s^{\alpha} \\ i_s^{\beta} \end{bmatrix} = T^{2\text{x}3} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix};\, \begin{bmatrix} e_s^{\alpha} \\ e_s^{\beta} \end{bmatrix} = T^{2\text{x}3} \begin{bmatrix} e_{sa} \\ e_{sb} \\ e_{sc} \end{bmatrix} \tag{10}$$

With: $T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$

Thus, the instantaneous active and reactive powers values are expressed as [7]:

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} e_s^{\alpha} & e_s^{\beta} \\ -e_s^{\beta} & e_s^{\alpha} \end{bmatrix} \begin{bmatrix} i_s^{\alpha} \\ i_s^{\beta} \end{bmatrix} \tag{11}$$

Instantaneous power errors expressions:

$$\begin{aligned} \Delta P_s &= {P_s}^* - P_s \\ \Delta Q_s &= {Q_s}^* - Q_s \end{aligned} \tag{12}$$

Digitized power error signals are given as:

$$\begin{cases} S_P = 1 & if \quad {P_s}^* - P_s \geq h_p \\ S_P = 0 & if \quad {P_s}^* - P \leq_s -h_p \end{cases}$$

$$\begin{cases} S_Q = 1 & if \quad {Q_s}^* - Q_s \geq h_q \\ S_Q = 0 & if \quad {Q_s}^* - Q_s \leq_s -h_q \end{cases} \tag{13}$$

Where h_p and h_q are the hysteresis bands.

The DPC controller has three main inputs: the location of the source voltage vector and digitized power errors S_P and S_Q. The digitized error signals are obtained using hysteresis comparators to instantaneous power errors and the position of the grid voltage vector is determined by dividing the space plane into twelve symmetric sectors. A look up table (LUT) summarizes the appropriate vectors of the voltage source inverter as can be seen in Table.1. The dc link voltage is regulated by closed loop control and it depends on the controlling of the active power in grid side, and the unity power factor operation is achieved by controlling the reactive power to be equal to zero [18].

3.2 Predictive direct power control

The proposed predictive-DPC configuration is based on the direct calculation of the appropriate average voltage vector of shunt active power filter by using a predictive mathematical model as written in Eq.19, which drives the active and reactive powers of the instantaneous line to their reference values at the end of each sampling period which will indirectly force SAPF to generate the required harmonic power component for the load side, therefore generates the shape current compensation wave which will contribute to the removal of the contamination included in the side of the grid. Moreover, instantaneous quantities of active and reactive powers (P_s, Q_s) which considered as controlled variables and desired commands $({Q_s}^* {P_s}^*)$ and grid voltage vector components $e_{s\alpha\beta}$, $e_{s\beta}$ are used as inputs data variables for a predictive controller block as depicted in Figure4. At the outset of each sampling period Ts , SAPF average voltage vector ${V_{SAPF}}^{\alpha\beta}$ is computed, and will cancel instantaneous active and reactive power tracking errors at the end of the sampling period. Finally, PWM modulator is implemented to generate a pattern of switching states, with constant switching frequency.

Based on Eq .3 then derivative expression of source current can be written:

$$\frac{d}{dt}\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \frac{1}{L_s}\begin{bmatrix} e_{s\alpha} \\ e_{s\beta} \end{bmatrix} - \begin{bmatrix} \boldsymbol{V}_{SAPF}^{\alpha} \\ \boldsymbol{V}_{SAPF}^{\beta} \end{bmatrix} - R_s \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (14)$$

The discrete mathematical model of line current can be expressed as:

$$\begin{bmatrix} i_{s\alpha}(k+1) - i_{s\alpha}(k) \\ i_{s\beta}(k+1) - i_{s\beta}(k) \end{bmatrix} = \frac{T_s}{L_s}\left(\begin{bmatrix} e_{s\alpha} \\ e_{s\beta} \end{bmatrix} - \begin{bmatrix} \boldsymbol{V}_{SAPF}^{\alpha} \\ \boldsymbol{V}_{SAPF}^{\beta} \end{bmatrix}\right) \quad (15)$$

If the sampling period Ts is assumed to be small enough then can consider that variation of grid voltage over this short time is ignored then $e_{s\alpha}(k+1) = e_{s\alpha}(k)$.

Based on Eq .11 then instantaneous line power variation over two successive sampling periods can be written as

$$\begin{bmatrix} P_s(k+1) - P_s(k) \\ Q_s(k+1) - Q_s(k) \end{bmatrix} = \begin{bmatrix} e_{s\alpha} & e_{s\beta} \\ e_{s\beta} & -e_{s\alpha} \end{bmatrix}\begin{bmatrix} i_{s\alpha}(k+1) - i_{s\alpha}(k) \\ i_{s\beta}(k+1) - i_{s\beta}(k) \end{bmatrix} \quad (16)$$

Substuting Eq .15 in Eq .16 yields:

$$\begin{bmatrix} P_s(k+1) - P_s(k) \\ Q_s(k+1) - Q_s(k) \end{bmatrix} = \frac{T_s}{L_s}\begin{bmatrix} e_{s\alpha} & e_{s\beta} \\ e_{s\beta} & -e_{s\alpha} \end{bmatrix} \times \left(\begin{bmatrix} e_{s\alpha} \\ e_{s\beta} \end{bmatrix} - \begin{bmatrix} \boldsymbol{V}_{SAPF}^{\alpha} \\ \boldsymbol{V}_{SAPF}^{\beta} \end{bmatrix}\right) \quad (17)$$

Can consider the power at instant $k+1$ as the desired power as the control approach tries to drive the system towards it.

$$\begin{bmatrix} P_s(k+1) \\ Q_s(k+1) \end{bmatrix} = \begin{bmatrix} {P_s}^* \\ {Q_s}^* \end{bmatrix} \quad (18)$$

From Eq .17 and Eq .18 shunt active power filter voltage expression can be extracted as in [25]

$$\begin{bmatrix} \boldsymbol{V}_{SAPF}^{\alpha}(k) \\ \boldsymbol{V}_{SAPF}^{\beta}(k) \end{bmatrix} = \begin{bmatrix} e_{s\alpha}(k) \\ e_{s\beta}(k) \end{bmatrix} + \frac{L_s}{T_s\|{e_s}^{\alpha\beta}\|}\begin{bmatrix} e_{s\alpha}(k) & e_{s\beta}(k) \\ e_{s\beta}(k) & -e_{s\alpha}(k) \end{bmatrix} \times \begin{bmatrix} {P_s}^* - P_s(k) \\ {Q_s}^* - Q_s(k) \end{bmatrix} \quad (19)$$

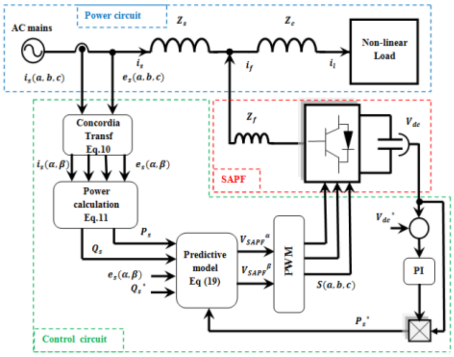

Figure 4. Design of SAPF control based predictive- DPC

Table 1. System parameters

Symbol	Description	Value
e_s	Grid voltage	80 V
R_s	Grid resistance	0.1 Ω
L_s	Grid inductance	1 mH
R_c	Load side filter resistance	0.01 Ω
L_c	Load side filter inductance	0.5 mH
R_F	Filter input resistance	0.01 Ω
L_F	Filter input inductance	2 mH
R_l	Load resistance	10 Ω
L_l	Load inductance	1 mH
C	DC link capacitance	2200 µF
V_{dc}	DC voltage	180 V

4. SIMULATION RESULTS AND DISCUSSION

In order to evaluate the performance of the proposed control configuration of the power filtering system, a numerical simulations of the whole system were carried out by using environement Matlab/SIMULINK. The effectiveness of the control mechanism was evaluated by a comparative study with the conventional control strategy to highlight the positive points and improvements achieved. Simulation parameters are listed in Table.1. All obtained results are sheduled for both control strategies conventional and predictive DPC. The performance and robustness of the proposed strategy are tested using two separate perturbations, which are sudden changes of capacitor voltage and load resistor. The discussion of the results focuses on three main points, steady state and transient state function introduced by the two strategies and finally concluded with a comparative study.

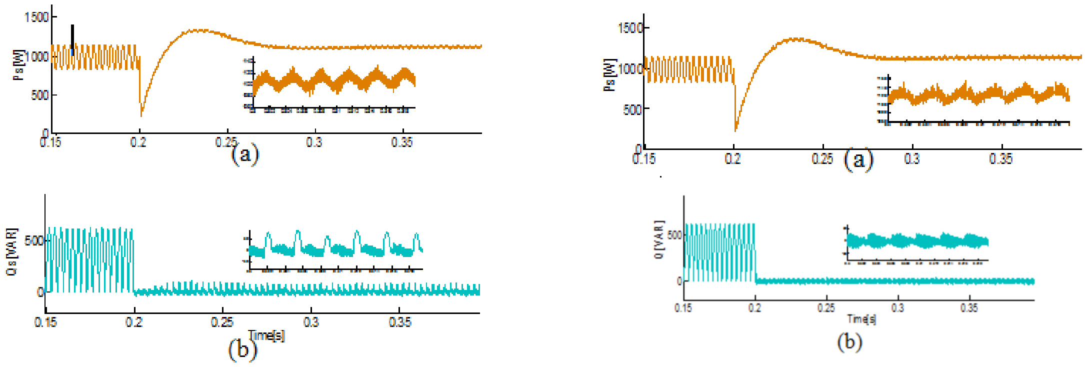

Figure 5. Grid power flow by using conventional DPC (a) Active power [Watt], (b) Reactive power[VAR].

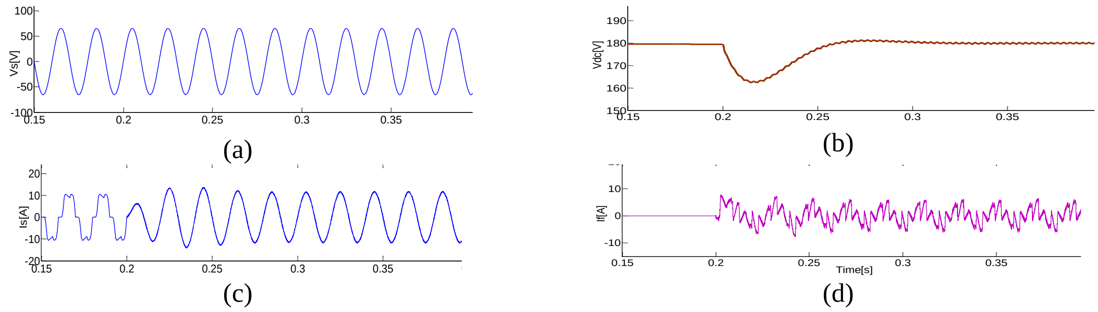

Figure 6. Grid power flow by using predictive DPC (a) Active power [Watt], (b) Reactive power[VAR].

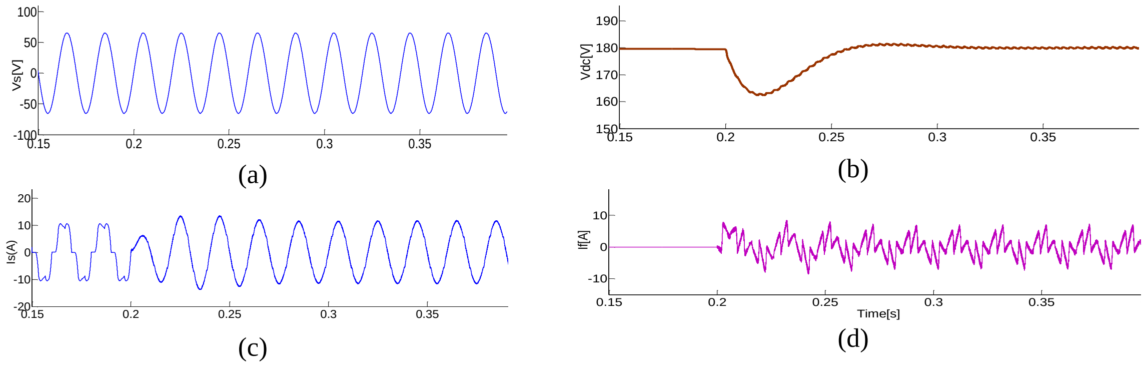

Figure 7. Steady state performance for phase A by using conventional DPC (a) grid voltage (b) Line current [A] (c) capacitor voltage[V], (d) Filter current [A].

Figure 8. Steady state performance for phase A by using predictive DPC (a) grid voltage (b) Line current [A] (c) capacitor voltage[V], (d) Filter current [A].

steady state analysis: Figure 5 and Figure6 display the power flow in the system before and after switching on the SAPF unit (SAPF ON at time t = 0.2 s) in the case of the use of conventional DPC and predictive DPC respectively, and also the steady state behavior and level of power ripples have been clarified. Figure7 and Figure8 represent line voltage, line current, capacitor voltage and filter current in the case of using conventional DPC and predictive DPC respectively. We can observe that active power is achieved its rated value and reactive power regulated at zero level in the aim to ensure unity of power factor. capacitor voltage reaches a steady-state value around Vdc = 180 V within a few mains periods (3 mains cycles). It is necessary to recall that capacitor is pre-charged in the aim to avoid start up divergence of input power and undesired overshot for dc bus voltage.

Transient state analysis: As aforementioned, the system was under the influence of two different disturbances (load resistor and capacitor voltage changes) and were examined to evalute system reaction and response correspending to applied conrol approachs, traditional-DPC and predictive-DPC respectively.

1. **In instant t=0.4 s load resistor is stepped from 10 Ω to 20 Ω**

From Figure 9 and Figure 10 when the load resistor has been stepped , the required power decreased and the grid power flow has been a pretty good dynamic behavior due to the satisfactory performance of conventional and predictive-DPC controls , and as well the reactive power is controlled to be zero in order to maintain operation with unity power factor for the system. Furthermore, fast variation of the active power does not affect the reactive power level which is maintained at its reference value (0 VAR), so that the decoupled control between the active and the reactive powers is successfully achieved. The robustness of the system is reflected by the rapid reduction of the line current from i_s^{mag}= 11 to 6 A due to a decrease in power absorption but retains a sinusoidal waveform, which means that the filtration function has good immunity against sudden load variation.

2. **In instant t=0.4 s capacitor voltage stepped from 180 V to 200 V**

Figure11 and Figure12 present results of a step response against the capacitor voltage disturbance. As can be seen variation of capacitor voltage has no effect on the level of generated power only temporary limited disturbance as transient perturbation. The capacitor voltage reaches its new level within 2 to 3 periods with low overshot which demonstrates satisfactory dynamic performance for dc bus voltage closed loop regulation. The main issue of a SAPF system is achieving a smooth sinusoidal form of the input current, under any disturbances encountered.

Comparative study: In order to prove effectiveness and superiority of the predictive-DPC compared to conventional one which was proposed in [22], a comparative evaluation is done focused on key points such as: Power ripple, THD factor, and transient response.

The level of input power fluctuation in the steady state as shown in previous results demonstrate a clear superiority for predictive DPC over conventional one especially in terms of reactive power ripples. For example the power ripple in conventional DPC case is around 100 VAR whereas for predictive DPC was restricted to about 50 VAR.

Since the validation of control approachs is done only trought simulation process and with slightly hight samling frequency so it was expected that conventional-DPC can guarantee that current THD factor bellow standard threshold. Presented results demonstrate that both control strategies has ability to drive source current below standard harmonic current limits (IEEE-519). The same results prove the superiority of proposed predictive DPC than conventional DPC in terms of THD as depicted in Figure 13 with 1.42 % and 2.70 % respectively. And as well can be note that in case of conventional–DPC baseded LUT generates broadband harmonic spectra whereas predictive-DPC produces deterministic harmonics with dominant harmonics around the switching frequency.

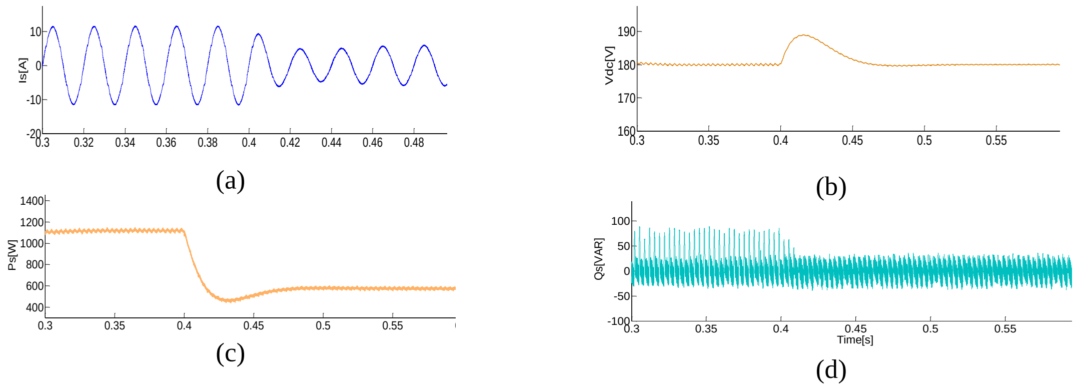

Figure 9. Transient state performance for phase A by using predictive DPC (a) grid current (b) Line active power [W] (c) capacitor voltage[V], (d) Line reactive power [VAR].

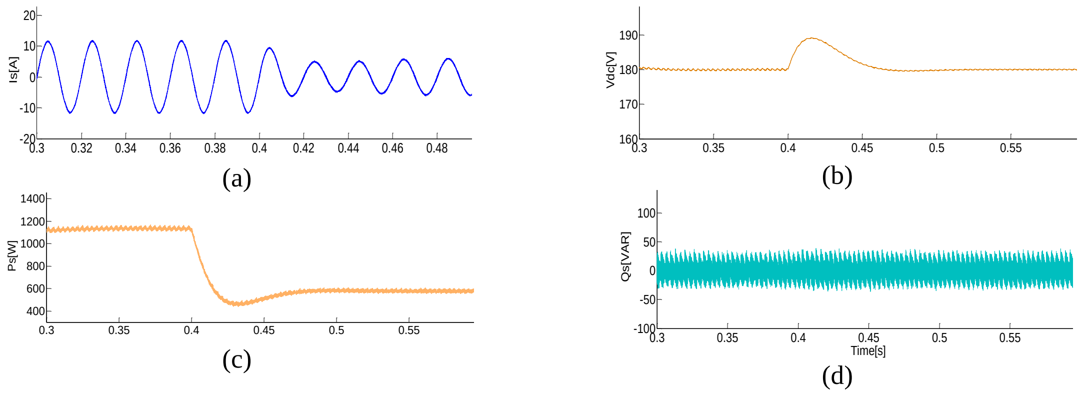

Figure 10. Transient state performance for phase A by using predictive DPC (a) grid current (b) Line active power [W] (c) capacitor voltage[V], (d) Line reactive power [VAR].

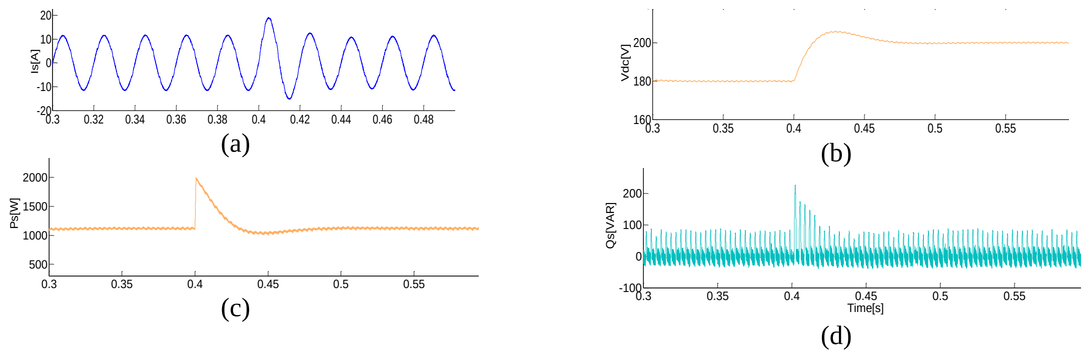

Figure 11. Transient state performance for phase A by using conventional DPC (a) grid current (b) Line active power [W] (c) capacitor voltage[V], (d) Line reactive power [VAR].

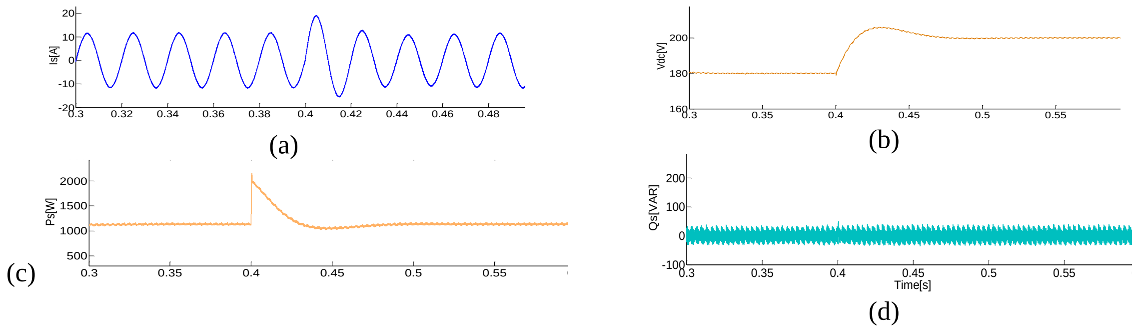

Figure 12. Transient state performance for phase A by using predictive DPC (a) grid current (b) Line active power [W] (c) capacitor voltage[V], (d) Line reactive power [VAR].

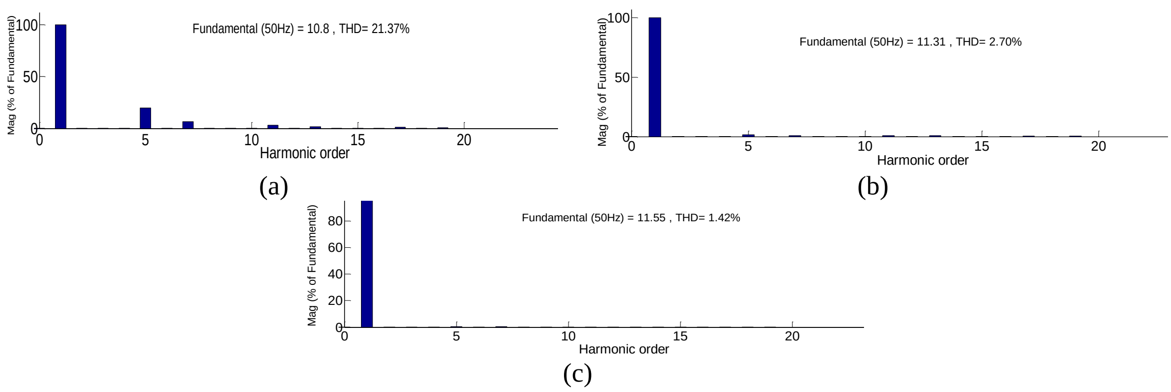

Figure 13. Spectrum harmonic analysis for line current phase-A (a) before filtering (b) filtring using conventional-DPC strategy (c) filtring using predictive-DPC strategy.

As can be seen from previous results, during start up and transient state operation in case of change of load or capacitor voltage the two control strategies converge to similar results, which means similarity of time response (Ts) around 3 cycles of ac mains is achieved. Briefly, predictive-DPC control keeps similar performance as conventional DPC for transient state operation whereas it introduced significant improvement for the steady state operation.

5. CONCLUSION

This paper has been described an improved configuration for the three-phase SAPF system based on a predictive approach. This approach adopts a simple predictive model has the ability to generate the appropriate SAPF voltage reference for the next control cycle according to the data of the current instant. The

accuracy of this algorithm allows the instantaneous elimination of tracking power errors which, in turn, indirectly contribute to the suppression of the harmonic component in the grid side, which will ensure a sinusoidal smooth waveform for the input current and a proper grid power with a satisfactory power factor.
The analysis and comparative study carried out in this work allowed to identify the main drawbacks of the conventional algorithm and key benefits and enhancements offered by the improved control scheme. As wise findings, improvements obtained by predictive-DPC approach can be summarized as follows: lower steady state power ripple, smooth sinusoidal line current, lower THD factor and constant switching frequency with dominant harmonics around basic switching frequency.

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