Improved Active Power Filter Performance For Renewable Power Generation System

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***Abstract*—A predictive control algorithm specially developed for shunt active power filters aimed to compensate reactive power and current harmonics components is presented and analyzed. The proposed predictive control algorithm is implemented in a three-phase four-leg voltagesource inverter (4L-VSI). The use of a 4L-VSI allows the compensation of current harmonics, reactive power and neutral current harmonics generated by single-phase non-linear loads. A detailed mathematical model of the filter, including the effect of the power system equivalent impedance is derived and used to design the proposed predictive control algorithm. The proposed active power filter and associated control scheme performance and compensation effectiveness are demonstrated by simulation and with experimental results.**

Index Terms*—*Active power filter, current control, four-leg converters, predictive control.

NOMENCLATURE

AC	Alternating current.
dc	Direct current.
PWM	Pulse width modulation.
PC	Predictive controller.
PLL	Phase-locked-loop.
v_{dc}	dc-voltage.
$\mathbf{v_s}$	System voltage vector $[v_{su}\ v_{sv}\ v_{sw}]^T$.
$\mathbf{i_s}$	System current vector $[i_{su}\ i_{sv}\ i_{sw}]^T$.
$\mathbf{i_L}$	Load current vector $[i_{Lu}\ i_{Lv}\ i_{Lw}]^T$.
$\mathbf{v_o}$	VSI output voltage vector $[v_{ou}\ v_{ov}\ v_{ow}]^T$
$\mathbf{i_o}$	VSI output current vector $[i_{ou}\ i_{ov}\ i_{ow}]^T$.
$\mathbf{i_o^*}$	Reference current vector $[i_{ou}^*\ i_{ov}^*\ i_{ow}^*]^T$.
i_n	Neutral current.
L_f	Filter inductance.
R_f	Filter resistance.

I. INTRODUCTION

Renewable generation affects power quality due to its nonlinearity, since solar generation plants and wind power generators must be connected to the grid through high-power static PWM converters [1]. The non uniform nature of power generation directly affects voltage regulation and creates voltage distortion in power systems. This new scenario in power distribution systems will require more sophisticated compensation techniques. Although active power filters implemented with three-phase four-leg voltage-source inverters (4L-VSI) have already been presented in the technical literature [2], the primary contribution of this paper is a predictive control algorithm designed and implemented specifically for this application. Traditionally, active power filters have been controlled using pre tuned controllers, such as PI-type or adaptive, for the current as well as for the dc-voltage loops , . PI controllers must be designed based on the equivalent linear model, while predictive controllers use the nonlinear model, which is closer to real operating conditions. An accurate model obtained using predictive controllers improves the performance of the active power filter, especially during transient operating conditions, because it can quickly follow the current-reference signal while maintaining a constant dc-voltage. So far, implementations of predictive control in power converters have been used mainly in induction motor drives . In the case of motor drive applications, predictive control represents a very intuitive control scheme that handles multivariable characteristics, simplifies the treatment of dead-time compensations, and permits pulse-width modulator replacement. However, these kinds of applications present disadvantages related to oscillations and instability created from unknown load parameters. One advantage of the proposed algorithm is that it fits well in active power filter applications, since the power converter output parameters are well known . These output parameters are obtained from the converter output ripple filter and the power system equivalent impedance. The converter output ripple filter is part of the active power filter design and the power system impedance is obtained from well-known standard procedures . In the case of unknown system impedance parameters, an estimation method can be used to derive an accurate *R*–*L* equivalent impedance model of the system .This paper presents the mathematical model of the 4L-VSI and the principles of operation of the proposed predictive control scheme, including the design procedure. The complete description of the selected current reference generator implemented in the active power filter is also presented. Finally, the proposed active power filter and the effectiveness of the associated control scheme compensation are demonstrated through simulation

II. LITERATURE REVIEW

[1] In the paper, A predictive control algorithm specially developed for shunt active power filters aimed to compensate reactive power and current harmonics components is presented and analyzed. The proposed predictive control algorithm is implemented in a three-phase four-leg voltagesource inverter (4L-VSI). The use of a 4L-VSI allows the compensation of current harmonics, reactive power and neutral current harmonics generated by single-phase non-linear loads. A detailed mathematical model of the filter,

including the effect of the power system equivalent impedance is derived and used to design the proposed predictive control algorithm. The proposed active power filter and associated control scheme performance and compensation effectiveness are demonstrated by simulation and with experimental results.

[2] In the paper Described, Active filtering of electric power has now become a mature technology for harmonic and reactive power compensation in ac networks. In this project, a bidirectional control technique of active tuned hybrid power filter (ATHPF) based on the active reactor using active techniques is proposed to solve the problem of harmonic over-current in ATHPF. The proposed control is to continuously adjust the filter inductance of the active reactor by regulating active power filter (APF) output current in terms of its magnitude and direction. Therefore, the ATHPF using the bidirectional control principle can simultaneously supply different impedances at different selective suppressed harmonic frequencies. The bidirectional control principle can perform both the normal active tuning function and the abnormal active detuning function. Experimental results verify the effectiveness of the ATHPF with the bidirectional control principle in selective harmonic elimination and flexible protection against harmonic over-current.

[3] This paper describes a three-phase four-wire shunt active power filter using a conventional three-leg converter, without the need of power supply at DC bus. Two approaches have been developed to control the active filter. Both control strategies consider harmonics and zero sequence components in the voltage and current simultaneously. The first one provides constant power and the second one sinusoidal current to the source, even under unbalanced voltage conditions. Simulation results from a complete model of shunt active filter are presented to validate and compare the control strategies.

[4] This paper explain, The enabling of ac microgrids in distribution networks allows delivering distributed power and providing grid support services during regular operation of the grid, as well as powering isolated islands in case of faults and contingencies, thus increasing the performance and reliability of the electrical system. The high penetration of distributed generators, linked to the grid through highly controllable power processors based on power electronics, together with the incorporation of electrical energy storage systems, communication technologies, and controllable loads, opens new horizons to the effective expansion of micro grid applications integrated into electrical power systems. This paper carries out an overview about micro grid structures and control techniques at different hierarchical levels. At the power converter level, a detailed analysis of the main operation modes and control structures for power converters belonging to micro grids is carried out, focusing mainly on grid-forming, grid-feeding, and grid-supporting configurations. This analysis is extended as well toward the hierarchical control scheme of micro grids, which, based on the primary, secondary, and tertiary control layer division, is devoted to minimize the operation cost, coordinating support services, meanwhile maximizing the reliability and the controllability of micro grids. Finally, the main grid services that micro grids can offer to the main network, as well as the future trends in the development of their operation and control for the next future, are presented and discussed.

[5] This paper presents a predictive current control method and its application to a voltage source inverter. The method uses a discrete-time model of the system to predict the future value of the load current for all possible voltage vectors generated by the inverter The voltage vector which minimizes a quality function is selected. The quality function used in this work evaluates the current error at the next sampling time. The performance of the proposed predictive control method is compared with hysteresis and pulse width modulation control. The results show that the predictive method controls very effectively the load current and performs very well compared with the classical solutions.

[6] In this paper, A new predictive strategy for current control of a three-phase neutral point clamped inverter is presented. It is based on a discrete-time model of the system, used to predict future values of the load current and voltage of the capacitors in the DC-link, for each possible switching state generated by the inverter. The state that minimizes a given quality function "g" is selected to be applied during the next sampling interval. Several compositions of g are proposed, including terms dedicated to achieve reference tracking, balance in the DC-link and reduction of the switching frequency. The algorithm uses the redundancy of switching states, typical of a three-level inverter, by means of a simple strategy. In comparison with classic PWM current control, the strategy presents a remarkable performance. The proposed method achieves comparable reference tracking with lower switching frequency per semiconductor and a slightly improved transitory behavior. It requires a greater sampling frequency, which should not be a problem, considering the present technologies available in digital signal processors. The main advantage of the method is that it does not require any kind of linear controller or modulation technique, achieving a different approach to control a power converter

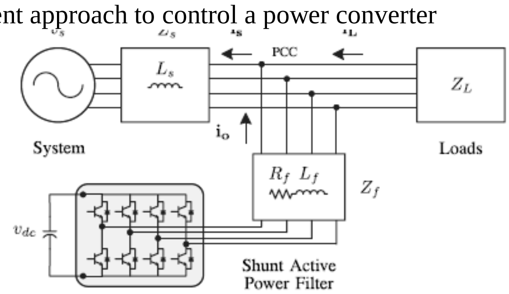

Fig 1. . Three-phase equivalent circuit of the proposed shunt active power filter.

III. FOUR-LEG CONVERTER MODEL

Fig. 2. shows the configuration of a typical power distribution system with renewable power generation. It consists of various types of power generation units and different types of loads. Renewable sources, such as wind and sunlight, are typically used to generate electricity for residential users and

small industries. Both types of power generation use ac/ac and dc/ac static PWM converters for voltage conversion and battery banks for long term energy storage. These converters perform maximum power point tracking to extract the maximum energy possible from wind and sun. The electrical energy consumption behavior is random and unpredictable, and therefore, it may be single- or three-phase, balanced or unbalanced, and linear or nonlinear. An active power filter is connected in parallel at the point of common coupling to compensate current harmonics, current unbalance, and reactive power. It is composed by an electrolytic capacitor, a four-leg PWM converter, and a first-order output ripple filter, as shown in Fig. 1. This circuit considers the power system equivalent impedance Zs , the converter output ripple filter impedance Zf , and the load impedance ZL . The four-leg PWM converter topology is shown in Fig. 2. This converter topology is similar to the conventional three-phase converter with the fourth leg connected to the neutral bus of the system. The fourth leg increases switching states from 8 (23) to 16 (24), improving control flexibility and output voltage quality [21], and is suitable for current unbalanced compensation.

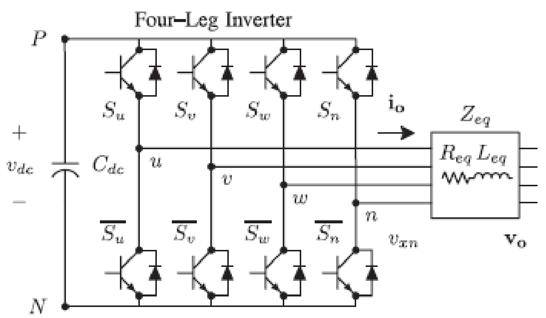

Fig. 2. Two-level four-leg PWM-VSI topology.

The voltage in any leg x of the converter, measured from the neutral point (n), can be expressed in terms of switching states,
as follows:

$$v_{xn} = S_x - S_n\, v_{dc}, \quad x = u,\ v,\ w,\ n. \tag{1}$$

The mathematical model of the filter derived from the equivalent circuit shown in Fig. 1 is

$$\mathbf{v_o} = v_{xn} - R_{eq}\,\mathbf{i_o} - L_{eq}\,\frac{d\,\mathbf{i_o}}{dt} \tag{2}$$

where Req and Leq are the 4L-VSI output parameters expressed as Thevenin impedances at the converter output terminals Zeq .Therefore, the Thevenin equivalent impedance is determined by a series connection of the ripple filter impedance Zf and a parallel arrangement between the system equivalent impedance Zs and the load impedance ZL

$$Z_{eq} = \frac{Z_s Z_L}{Z_s + Z_L} + Z_f \approx Z_s + Z_f. \tag{3}$$

predictive current control scheme is shown in Fig. 3. This control scheme is basically an optimization algorithm and, therefore, it has to be implemented in microprocessor. Consequently, the analysis has to be developed using discrete mathematics in order to consider additional restrictions such as time delays and approximations.

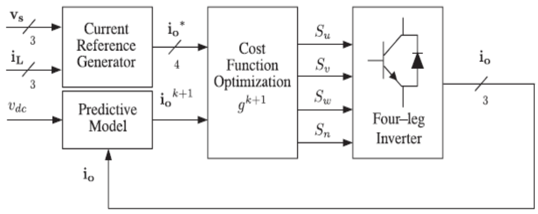

Fig. 3. Proposed predictive digital current control block diagram.

IV. DIGITAL PREDICTIVE CURRENT CONTROL

The main characteristic of predictive control is the use of the system model to predict the future behavior of the variables to be controlled. The controller uses this information to select the optimum switching state that will be applied to the power converter, according to predefined optimization criteria. The predictive control algorithm is easy to implement and to understand, and it can be implemented with three main blocks, as shown in Fig. 3.

1)Current Reference Generator: This unit is designed to generate the required current reference that is used to compensate the undesirable load current components. In this case, the system voltages, the load currents, and the dc-voltage converter are measured, while the neutral output current and neutral load current are generated directly from these signals (IV).

2) Prediction Model: The converter model is used to predict the output converter current. Since the controller operates in discrete time, both the controller and the system model must be represented in a discrete time domain [22]. The discrete time model consists of a recursive matrix equation that represents this prediction system. This means that for a given sampling time Ts , knowing the converter switching states and control variables at instant kTs , it is possible to predict the next states at any instant [k + 1]Ts. Due to the first-order nature of the equations that describe the model in (1)–(2), a sufficiently accurate first-order approximation of the derivative is considered in this paper

$$\frac{dx}{dt} \approx \frac{x[k+1] - x[k]}{T_s}. \tag{4}$$

The 16 possible output current predicted values can be obtained from (2) and (4) as

$$\mathbf{i_o}[k+1] = \frac{T_s}{L_{eq}}(v_{xn}[k] - \mathbf{v_o}[k]) + \left(1 - \frac{R_{eq}\,T_s}{L_{eq}}\right)\mathbf{i_o}[k]. \tag{5}$$

As shown in (5), in order to predict the output current io at the instant (k + 1), the input voltage value vo and the converter output voltage vxN , are required. The algorithm calculates all 16 values associated with the possible combinations that the state variables can achieve.

3) Cost Function Optimization: In order to select the optimal switching state that must be applied to the power converter, the 16 predicted values obtained for io [k + 1] are compared with the reference using a cost function g, as follows:

$$g[k+1] = (i^*_{ou}[k+1] - i_{ou}[k+1])^2 + (i^*_{ov}[k+1] - i_{ov}[k+1])^2$$

$$+ (i^*_{ow}[k+1] - i_{ow}[k+1])^2 + (i^*_{on}[k+1] - i_{on}[k+1])^2 . \qquad (6)$$

The output current (io) is equal to the reference (i∗o) when g = 0. Therefore, the optimization goal of the cost function is to achieve a g value close to zero. The voltage vector vxN that minimizes the cost function is chosen and then applied at the next sampling state. During each sampling state, the switching state that generates the minimum value of g is selected from the 16 possible function values. The algorithm selects the switching state that produces this minimal value and applies it to the converter during the k + 1 state.

V. CURRENT REFERENCE GENERATION

A dq-based current reference generator scheme is used to obtain the active power filter current reference signals. This scheme presents a fast and accurate signal tracking capability. This characteristic avoids voltage fluctuations that deteriorate the current reference signal affecting compensation performance [28]. The current reference signals are obtained from the corresponding load currents as shown in Fig. 4. This module calculates the reference signal currents required by the converter to compensate reactive power, current harmonic, and current imbalance. The displacement power factor (sin φ(L)) and the maximum total harmoni distortion of the load (THD(L)) defines the relationships between the apparent power required by the active power filter, with respect to the load, as shown

$$\frac{S_{\text{APF}}}{S_L} = \frac{\sqrt{\sin\phi_{(L)} + \text{THD}_{(L)}{}^2}}{\sqrt{1 + \text{THD}_{(L)}{}^2}} \qquad (7)$$

where the value of THD(L) includes the maximum compensable harmonic current, defined as double the sampling frequency fs. The frequency of the maximum current harmonic component that can be compensated is equal to one half of the converter switching frequency. The dq-based scheme operates in a rotating reference frame; therefore, the measured currents must be multiplied by the sin(wt) and cos(wt) signals. By using dq-transformation, the d current component is synchronized with the corresponding phase-to-neutral system voltage, and the q current component is phase-shifted by 90◦. The sin(wt) and cos(wt) synchronized reference signals are obtained from a synchronous reference frame (SRF) PLL [29]. The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is

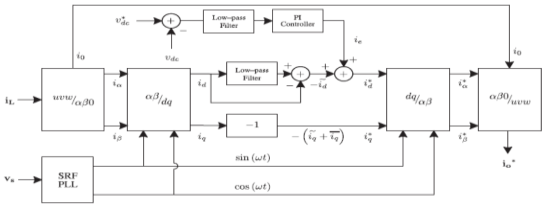

Fig. 4. dq-based current reference generator block diagram.

severely distorted. Tracking errors are eliminated, since SRF-PLLs are designed to avoid phase voltage unbalancing, harmonics (i.e., less than 5% and 3% in fifth and seventh, respectively), and offset caused by the nonlinear load conditions and measurement errors [30]. Equation (8) shows the relationship between the real currents iLx (t) (x = u, v,w) and the associated dq components (id and iq)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix}. \qquad (8)$$

A low-pass filter (LFP) extracts the dc component of the phase currents id to generate the harmonic reference components id . The reactive reference components of the phase-currents are obtained by phase-shifting the corresponding ac and dc components of iq by 180◦. In order to keep the dc-voltage constant, the amplitude of the converter reference current must be modified by adding an active power reference signal ie with the d-component. The resulting signals i∗d and i∗q are transformed back to a three-phase system by applying the inverse Park and Clark transformation. The cutoff frequency of the LPF used in this paper is 20 Hz

$$\begin{bmatrix} i^*_{ou} \\ i^*_{ov} \\ i^*_{ow} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\omega t & -\cos\omega t \\ 0 & \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} i_0 \\ i^*_d \\ i^*_q \end{bmatrix}. \qquad (9)$$

The current that flows through the neutral of the load is compensated by injecting the same instantaneous value obtained from the phase-currents, phase-shifted by 180◦, as shown next

$$i^*_{on} = -(i_{Lu} + i_{Lv} + i_{Lw}) . \qquad (10)$$

One of the major advantages of the dq-based current reference generator scheme is that it allows the implementation of a linear controller in the dc-voltage control loop. However, one important disadvantage of the dq-based current reference frame algorithm used to generate the current reference is that a second dorder harmonic component is generated in id and iq under unbalanced operating conditions. The amplitude of this harmonic depends on the percent of unbalanced load current (expressed as the relationship between the negative sequence current iL,2 and the positive sequence current iL,1). The second-order harmonic cannot be removed from id and iq , and therefore generates a third harmonic in the reference current when it is converted back to abc frame the percent of system current imbalance and the percent of third harmonic system current, in function of the percent of load current imbalance. Since the load current does not have a third harmonic, the one generated by the active power filter flows to the power system.

TABLE I
SPECIFICATION PARAMETERS

Variable	Description	Value [a]
$\mathbf{v_s}$	Source voltage	55 $[V]$
f	System frequency	50 $[Hz]$
v_{dc}	dc-voltage	162 $[V]$
C_{dc}	dc capacitor	2200 $[\mu F]$ (2.0 pu)
L_f	Filter inductor	5.0 $[mH]$ (0.5 pu)
R_f	Internal resistance within L_f	0.6 $[\Omega]$
T_s	Sampling time	20 $[\mu s]$
T_e	Execution time	16 $[\mu s]$

[a]Note: V_{base} = 55 V and S_{base} = 1 kVA.

VI SIMULATION MODEL AND RESULTS

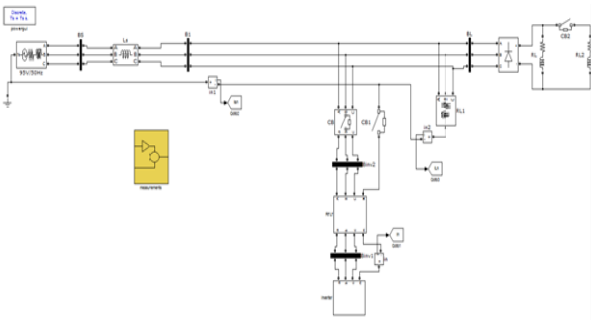

Fig 6: simulation model

A simulation model for the three-phase four-leg PWM converter with the parameters shown in Table I has been developed using MATLAB Simulink. The objective is to verify the current harmonic compensation effectiveness of the proposed control
scheme under different operating conditions. A six-pulse rectifier was used as a nonlinear load. The proposed predictive control algorithm was programmed using an S-function block that allows simulation of a discrete model that can be easily implemented in a real-time interface (RTI) on the R&D control board. Simulations were performed considering a 20 $[\mu s]$ of sample time. In the simulated results shown in Fig. 8, the active filter starts to compensate at $t = t_1$. At this time, the active power filter injects an output current i_{ou} to compensate current harmonic components, current unbalanced, and neutral current simultaneously. During compensation, the system currents **is** show sinusoidal waveform, with low total harmonic distortion (THD = 3.93%). At $t = t_2$, a three-phase balanced load step change is generated from 0.6 to 1.0 p.u. The compensated system currents remain sinusoidal despite the change in the load current magnitude. Finally, at $t = t_3$, a single-phase load step change is introduced in phase u from 1.0 to 1.3 p.u., which is equivalent to an 11% current imbalance. As expected on the load side, a neutral current flows through the neutral conductor (i_{Ln}), but on the source side,
no neutral current is observed (i_{sn}). Simulated results show that the proposed control scheme effectively eliminates unbalanced currents. Additionally, Fig. 8 shows that the dc-voltage remains stable throughout the whole active power filter operation.

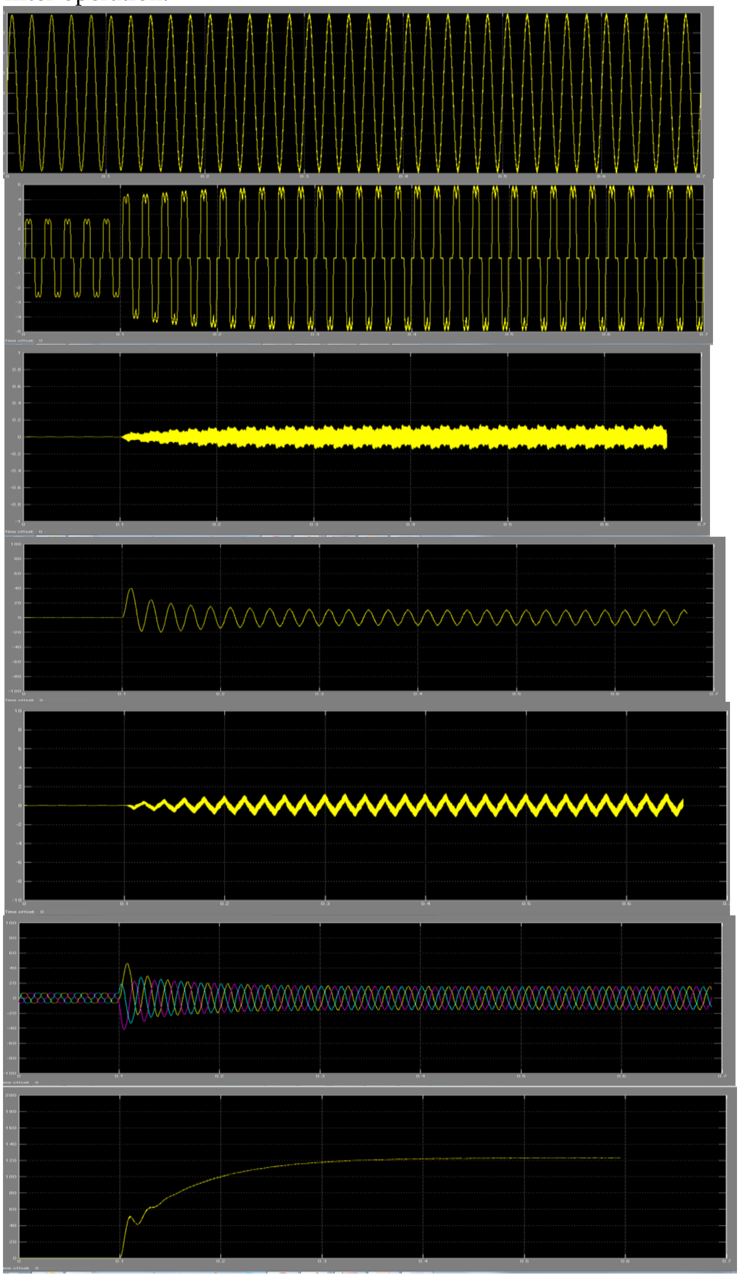

Fig. 7. Simulated waveforms of the proposed control scheme. (a) Phase to neutral source voltage. (b) Load Current. (c) Active power filter output current. (d) Load neutral current. (e) System neutral current. (f) System currents. (g) DC voltage converter.

VII. CONCLUSION

Improved dynamic current harmonics and a reactive power compensation scheme for power distribution systems with generation from renewable sources has been proposed to improve the current quality of the distribution system. Advantages of the proposed scheme are related to its simplicity, modeling, and implementation. The use of a predictive control algorithm for the converter current loop proved to be an effective solution for active power filter applications, improving current tracking capability, and transient response. Simulated and experimental results have proved that the proposed predictive control algorithm is a good alternative to classical linear control methods. The predictive current control algorithm is a stable and robust solution. Simulated and experimental results have shown the compensation effectiveness of the proposed active power filter.

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