Design of the Current and the Voltage Observers for Active-Load-Balancer (ALB) in Model Predictive Control System

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ABSTRACT In this paper, two observers for the model predictive control system of the active load balancer (ALB), are proposed. An unbalanced single-phase load in the distributed power system causes significant difficulties. An active load balancer is an efficient approach to tackle these issues. Model predictive control is one of the centralized proper control system for a power electronic converter. The main drawback of this control system is the use of numerous voltage and current sensors. Therefore, using of observers instead of sensors makes the implementation of the model predictive control system more cost effective. These two observers, estimate the load current and PCC voltage, fast and accurate as possible. This paper presents load current observer based on furrier series and voltage observer based on nonlinear newton-raphson method. The experimental results obtained from a 4 kW prototype ALB validate the theoretical analysis. The experimental results reveal that the proposed observers can achieve high accuracy and low costs as well as a high-quality grid side current.

INDEX TERMS Active load balancer, observer, predictive control, reliability.

I. INTRODUCTION
Ever increased the unbalance single-phase and three-phase electric loads in the distributed power grids, cause excessive neutral current at the grid side. The natural current deteriorates the power quality of distributed system, decreases the energy conversion efficiency of power transformers and other accessories [1]–[4].

However, different natural current compensation approaches are proposed as installing zig-zag power transformers in [5], DY transformer [6], passive filters [7], series and shunt active filters in [8] and [9] and hybrid filters [10]. The main shortcomings of passive filters are the risk of resonant and electromagnetic interface (EMI) problems. However, the main advantage of the zig-zag transformer technique is a simple control system and high capacity for compensation. However, in the case of an unbalance voltage, a zig-zag transformer may increase the neutral current. Therefore, four-leg voltage source inverter in [11], presented a more proper solution for unbalanced load compensation.

A new structure of the unified power quality conditioner (UPQC) in [12] successfully compensates the unbalance load current problem. The UPQC suffers from numerous active and passive elements and complicated control system.

The four-leg smart voltage source inverter presented in [13], incorporates photovoltaic systems with traditional inverters to regulate the active and reactive power, as well as load balancing and reducing the electricity costs. However, the unpredictable behavior of photovoltaic generation and the high complexity of the control system, are the main problems of this smart technique. Consequently, the DC link voltage regulating incorporates with a simple control technique for active load balancer (ALB) has been proposed in [14]. However, the use of the classic proportional-integral (PI) control system and delays are affected the performance of the ALB converter. Due to the high development of modern control systems, it seems that the use of a PI controller is not an optimal solution. Furthermore, due to the four-wire ALB system
and the use of multiple voltage sensors and current sensors, increases the cost, complicates the driving and calibration of these sensors. Also, the use of sensors may reduce the system reliability, due to the possibility of sensors improper functioning.

Besides, the control strategy based on active and reactive instantaneous power theory for regulating ALB current, presented in [14]. However, the traditional active and reactive power control theory suffers from a significant number of computation steps and computational burden.

In [15] adaptive neural tracking control for uncertain switched multi-input multi-output (MIMO) presented and the tracking errors converged to small area. A fuzzy peak-to-peak filter designed such that the filtering error system is stochastically stable in [16] and in [17] an observed-based adaptive finite-time tracking control is designed and output can surely track the desired trajectory within a specified bounded error in a finite time. A filter designed such that the filtering error system preserves a prescribed $H\infty$ is stable in [18]. In [19] to investigate the semi-global tracking cooperative control, a multiple saturation levels framework is presented. A distributed resilient control strategy for multiple energy storage systems is presented in [20] and to investigate the semi-global robust tracking consensus problem of multi-agent uncertain systems a metamorphic adaptive low-gain feedback approach is presented in [21].

The model predictive control (MPC) system has been widely used in power electronic converters due to fast, smooth, and optimal selection of the switching states [22]–[26]. The main drawback of the MPC control system is the use of a high number of current and voltage sensors [27].

This paper proposes new load current and point of common coupling (PCC) voltage observers to improve accuracy and cost effective operation of ALB converter controlled by the MPC control system along with improves reliability and reduces the cost of implementing of the control system.

To validate the performance of the proposed ALB system, the foremost necessary tests are carried out by the experimental set-up prototype.

The motivation on the study is reducing the voltage and current sensors which have been used in the predictive control system of active load balancer. Reducing the number of sensors and using estimators and observers instead of sensors, will reduce the cost of implementation of the proposed converter with the proposed controller. Furthermore, reducing sensors improves the reliability and energy conversion efficiency of whole system.

This paper is organized as follows. The operation model and the modulation strategy are presented in section II. Then, the proposed observer algorithms are explained in detail in section III. The main concept of predictive control for ALB presented in section IV. Finally, the experimental results in section IV are presented, followed by the conclusion in section V.

II. ALB SYSTEM MODELING

The ALB converter system consists of a DC-link stage, active switches as a four-leg full-bridge inverter, an LC filter, and linear, nonlinear, or unbalanced loads, which is described in the following subsections.

A. FULL-BRIDGE ALB INVERTER

The ALB four-leg inverter, along with the LC filter shows in Fig. 1 based on [14]. All the switching-states of the ALB four-leg inverter for the legs $a$, $b$, $c$, and $n$ are distinct by four switching functions $S_a$, $S_b$, $S_c$, and $S_n$ as follows [28]–[30]:

$$S_a = \begin{cases} 
1 & \text{if } S_1 = \text{on and } S_2 = \text{off} \\
0 & \text{if } S_2 = \text{on and } S_1 = \text{off} 
\end{cases}$$

$$S_b = \begin{cases} 
1 & \text{if } S_3 = \text{on and } S_4 = \text{off} \\
0 & \text{if } S_4 = \text{on and } S_3 = \text{off} 
\end{cases}$$

$$S_c = \begin{cases} 
1 & \text{if } S_5 = \text{on and } S_6 = \text{off} \\
0 & \text{if } S_6 = \text{on and } S_5 = \text{off} 
\end{cases}$$

$$S_n = \begin{cases} 
1 & \text{if } S_7 = \text{on and } S_8 = \text{off} \\
0 & \text{if } S_8 = \text{on and } S_7 = \text{off} 
\end{cases}$$

These four switching functions define the output voltages of ALB, $V_{IN}$ for $i = a, b, c, n$ as:

$$V_{IN} = S_i V_{dc}$$

where $V_{dc}$ is the DC-side voltage of the four-leg inverter.

The space reference vector of inverter output voltage ($V_i$) based on (5) and the zero-sequence voltage generated by the forth leg ($V_n$) are indicated by:

$$\tilde{V}_i = \frac{2}{3} V_{dc} \left( S_a + a S_b + a^2 S_c \right)$$

$$V_n = S_n V_{dc}$$

where “$a$” is the unit of complex vector equal to $e^{j2\pi/3}$ [27].

Considering all switching combinations for the switching functions $S_a$, $S_b$, $S_c$, and $S_n$, sixteen switching states and sixteen space reference vectors for the output voltage of the ALB are formed. These states and vectors are shown in Table 1 and Fig. 2. It must be mentioned that the magnitudes of two vectors in Table 1 are zero and $V_{IN}$ equal to zero. Consequently, the four-leg inverter is modeled by two families of seven states of switching, and the control system aim is to decide and select the best switching state in each sampling time.

B. LC FILTER

The simple single-line block diagram of the LC filter for the ALB converter is shown in Fig. 3.

This model composes of two families of equation, one for the filter inductance dynamic and the other one for the filter
TABLE 1. Switching states and voltage vectors

| Voltage vector $\tilde{V}_i$ | $V_{s}$ | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $V_{o}$ |
|-----------------------------|--------|-------|-------|-------|-------|--------|
| $V_0 = 0$                   | 0      | 0     | 0     | 0     | 0     | 0      |
| $V_1 = \frac{2}{3}V_{dc}$   | 0      | 1     | 0     | 0     | 0     | 0      |
| $V_2 = \left(\frac{1}{3} + j\frac{\sqrt{3}}{3}\right)V_{dc}$ | 0     | 1     | 1     | 0     | 0     | 0      |
| $V_3 = \left(\frac{1}{3} + j\frac{\sqrt{3}}{3}\right)V_{dc}$ | 0     | 0     | 1     | 0     | 0     | 0      |
| $V_4 = -\frac{2}{3}V_{dc}$ | 0      | 0     | 1     | 1     | 0     | 0      |
| $V_5 = \left(\frac{1}{3} - j\frac{\sqrt{3}}{3}\right)V_{dc}$ | 0     | 0     | 0     | 1     | 0     | 0      |
| $V_6 = \frac{1}{3}V_{dc}$   | 0      | 0     | 1     | 0     | 1     | 0      |
| $V_7 = 0$                   | 0      | 1     | 1     | 1     | 1     | 0      |

| Voltage vector $\dot{V}_f$ | $V_{s}$ | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $V_{o}$ |
|-----------------------------|--------|-------|-------|-------|-------|--------|
| $V_8 = 0$                   | $V_{dc}$ | 0     | 0     | 0     | 0     | 1      |
| $V_9 = \frac{2}{3}V_{dc}$  | $V_{dc}$ | 0     | 1     | 0     | 0     | 0      |
| $V_{10} = \left(\frac{1}{3} + j\frac{\sqrt{3}}{3}\right)V_{dc}$ | $V_{dc}$ | 0     | 1     | 1     | 0     | 0      |
| $V_{11} = \left(-\frac{1}{3} + j\frac{\sqrt{3}}{3}\right)V_{dc}$ | $V_{dc}$ | 0     | 1     | 0     | 1     | 0      |
| $V_{12} = -\frac{2}{3}V_{dc}$ | $V_{dc}$ | 0     | 0     | 1     | 1     | 0      |
| $V_{13} = \left(-\frac{1}{3} - j\frac{\sqrt{3}}{3}\right)V_{dc}$ | $V_{dc}$ | 0     | 0     | 1     | 1     | 0      |
| $V_{14} = \frac{1}{3}V_{dc}$ | $V_{dc}$ | 0     | 1     | 0     | 1     | 1      |
| $V_{15} = 0$              | $V_{dc}$ | 0     | 1     | 1     | 1     | 1      |

FIGURE 1. The inverter in the ALB system with LC filter.

It is assumed that the inductance current and capacitance voltage of the LC filter are the state variables; then we have:

$$
\frac{d}{dt} \begin{bmatrix}
    i_{f,abc} \\
    v_{c,abc}
\end{bmatrix} = \begin{bmatrix}
    -R_{eq} & -1 \\
    \frac{L_{eq}}{I} & 0
\end{bmatrix} \begin{bmatrix}
    i_{f,abc} \\
    v_{c,abc}
\end{bmatrix}
+ \begin{bmatrix}
    1 & 0 \\
    \frac{1}{C_f} & 0
\end{bmatrix} \begin{bmatrix}
    v_{i,abc} - V_n \\
    i_{o,abc}
\end{bmatrix}
$$

(9)
where:
\[
R_{eq} = \begin{bmatrix}
R_f + R_n & R_n & R_n \\
R_n & R_f + R_n & R_n \\
R_n & R_n & R_f + R_n
\end{bmatrix}
\]
\[
L_{eq} = \begin{bmatrix}
L_f + L_n & L_n & L_n \\
L_n & L_f + L_n & L_n \\
L_n & L_n & L_f + L_n
\end{bmatrix}
\]

In (9) ‘I’ an identity matrix with dimension 3 × 3. The state space model of proposed system in (9) can be derived from the model of the converter (See the Appendix).

To summarize the equations, we have:
\[
x = \begin{bmatrix} i_{f,abc} \\ v_{c,abc} \end{bmatrix}; \quad A = \begin{bmatrix} -R_{eq} & -1 \\ \frac{1}{L_{eq}} & \frac{1}{C_f} \end{bmatrix} \quad 6 \times 6
\]
\[
B = \begin{bmatrix} 0 \\ -\frac{1}{C_f} \end{bmatrix} \quad u = \begin{bmatrix} v_{i,abc} - V_n \\ \frac{v_{o,abc}}{i_{o,abc}} \end{bmatrix}
\]
\[
\frac{dx}{dt} = Ax + Bu
\]

In these equations, \(i_f\) and \(v_c\) are measured or estimated values while \(V_i\) is the calculated value by (5). In this paper, the output current of ALB, i.e. \(i_f\) is obtained from the state variables as below:
\[
i_f = \begin{bmatrix} 1 \\ 0 \end{bmatrix} x
\]

The discrete-time model of the LC filter is generated from (12) as:
\[
x[k+1] = A_d x[k] + B_d u[k]
\]
where \(A_d\) and \(B_d\) are the discrete components of the LC filter model and are computed based on [31], [32] as follows:
\[
A_d = e^{AT_s}, \quad B_d = \int_0^{T_s} e^{AT_s} B d\tau
\]

It is clear that for the prediction of the inductance current, the load current \(i_o\) and PCC voltage \(v_c\) are required.

The simple estimation form of the load current can be described by:
\[
i_{est,o} = i_f[k+1] - \frac{C_f}{T_s} (v_c[k+1] - v_c[k])
\]

where \(T_s\) is sample time.

III. ALB PROPOSED OBSERVERS

Clearly, from (14) to predict the ALB output current, \(i_f\), the inverter voltage, load current, and PCC voltage are required. The inverter voltage can be calculated by (6). Other items will be observed instead of measured which are presented in this section.

A. THE CURRENT OBSERVER

As the load current depends on the type of load, which is unknown, some assumptions are needed to observe load current, [32], [33]. Furthermore, unlike the reference [33], in this paper, the estimated PCC voltage \((v_{est,ca} \text{ and } v_{est,cb})\) has been used to observe the load current.

However, the load current approximation can be performed by the following equations [32]:
\[
i_{est,o} = i_f - C_f \frac{dv_{est,c}}{dt}
\]

By wisely changing the reference framework, we have:
\[
\begin{bmatrix} i_{est,o} \\ i_{est,ob} \end{bmatrix} = \begin{bmatrix} i_f \\ i_{fb} \end{bmatrix} - C_f \frac{dv_{est,ca}}{dt} \quad (20)
\]

The presence of the voltage derivation term in the above equation is a shortcoming. Furthermore, if some kind of noise or disturbances exist in the PCC voltage, it will be exaggerated, possessing the derivative term. In the next section, the PCC voltage has been estimated, too.

In this algorithm, the accuracy of the estimated current is reliant on the sampling time period, which may increase the noise amplitude.

Based on [32], a simple and high accurate load current observer is used. In this scheme the derivation term dose not applied to estimated PCC voltage.

By considering the estimated PCC voltage as:
\[
\begin{align*}
\sum_{n=1,3,5,\ldots} V_n \sin(n\omega t - \theta_n) \\
\sum_{n=1,3,5,\ldots} V_n \sin(n\omega t - \theta_n - 2n\pi/3) \\
\sum_{n=1,3,5,\ldots} V_n \sin(n\omega t - \theta_n + 2n\pi/3)
\end{align*}
\]

And by put on the stationary reference framework to (21), we have:
\[
\begin{align*}
\sum_{n=1,5,7,11,\ldots} V_n \sin(n\omega t - \theta_n) \\
\sum_{n=1,7,13,\ldots} V_n \cos(n\omega t - \theta_n) \\
+ \sum_{n=5,11,17,\ldots} V_n \cos(n\omega t - \theta_n)
\end{align*}
\]

As the study system is a three-phase four-wire, so the triplen harmonics are not present. The derivative form of (22)
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Figure 4 shows the single-line diagram of the ALB converter in the following section.

1) PCC VOLTAGE ESTIMATION

In the above section, the PCC voltage is estimated. The proposed method to estimate the PCC voltage is described in the following.

As it was mentioned in [32], the proposed technique only solves these equations, which is the subject of this section.

As seen in (20), in the noisy polluted area the noise value may exaggerated. In the proposed method, the derivation term is removed by a linear equation which is shown in (26).

As the estimated voltage of PCC is hypothesized to be pure sinusoidal, (23) can be rewritten as:

\[ \frac{d}{dt}v_{est,\alpha} \approx \omega V_1 \cos(\omega t - \theta_1) \]
\[ \frac{d}{dt}v_{est,\beta} \approx \omega V_1 \sin(\omega t - \theta_1) \]

From (24) and the fundamental component of (22), we have:

\[ \frac{d}{dt}v_{est,\alpha} \approx -\omega v_{est,\beta} \]
\[ \frac{d}{dt}v_{est,\beta} \approx \omega v_{est,\alpha} \]

Finally, by implanting (25) into (20), we have

\[ i_{est,\alpha} = I_{f\alpha} + C_f \omega v_{est,\beta} \]
\[ i_{est,\beta} = I_{f\beta} - C_f \omega v_{est,\alpha} \]

The current estimation of (26) is an algebraic formula, including simple summation and multiplication processes.

As seen in (20), in the noisy polluted area the noise value may exaggerated. In the proposed method, the derivation term is removed by a linear equation which is shown in (26).

As it was mentioned in [32], the proposed technique only suffers from uncertainties of the capacitance value of the LC filter.

B. THE PCC VOLTAGE OBSERVER

In the above section, the PCC voltage is estimated. The proposed method to estimate the PCC voltage is described in the following section.

1) PCC VOLTAGE ESTIMATION

Figure 4 shows the single-line diagram of the ALB converter for electrical power transport in a compensatory state.

Based on this figure, active \((p)\) and reactive \((q)\) transportation powers can be written as follows:

\[ S = p + jq = V_c \times \left( \frac{V_c \omega \varphi_L - V_c}{r_L + jx_L} \right)^* \]

\[ \Rightarrow \begin{cases} 
    p = \frac{V_c}{r_L + jx_L} \left( r_L V_i \cos \varphi_L - r_L V_c - x_L V_i \sin \varphi_L \right) \\
    q = \frac{V_c}{r_L + jx_L} \left( -r_L V_i \sin \varphi_L - x_L V_c + x_L V_i \cos \varphi_L \right)
\end{cases} \]

where \(x_L\) and \(r_L\) are the equivalence reactance and resistance of the filter, respectively and \(\varphi_L\) is the transportation power phase (phase difference between the PCC voltage and ALB converter voltage).

As shown in (27), transportation powers are strongly dependent on the filter impedance. Therefore, to solve this problem and simplify the relation, the concept of virtual power has been used [33]. Using this concept, the active and reactive powers are obtained as:

\[ \begin{cases} 
    p = V_c V_i \sin \varphi_L \\
    q = V_c \left( -V_c + V_i \cos \varphi_L \right)
\end{cases} \]

(28)

In equation (28), assuming that \(V_i, p\) and \(q\) are known, the set of two nonlinear equations can be solved, \(V_c\) and \(\varphi_L\) can be obtained at each sampling period. After calculating \(\varphi_L\), the phase and voltage of the PCC are obtained by knowing the phase voltage of the converter.

\[ \varphi_{PCC} = \varphi_{ALB} - \varphi_L, \quad \varphi_{ALB} = \tan^{-1} \left( \frac{V_{L\beta}}{V_{L\alpha}} \right) \]

(29)

Now, one can obtain the instantaneous voltage of the PCC in the stationary reference framework as follows:

\[ \begin{cases} 
    v_{est,\alpha} = V_c \sin \varphi_{PCC} \\
    v_{est,\beta} = -V_c \cos \varphi_{PCC}
\end{cases} \]

(30)

However, for calculating the PCC voltage at each sampling period, by using any mathematical tool, equation (28) must be solved to compute \(V_c\) and \(\varphi_L\). Then, after calculating the phase and the voltage at the PCC, the components of the instantaneous voltage in the \(\alpha\beta\) frame can be calculated from (30).

2) NUMERICAL SOLUTION OF RELATION (28)

As indicated above, in order to obtain \(V_c\) and \(\varphi_L\), the Eq. (28) must be solved in each sampling period. This equation is a pair of nonlinear equations, and the analytical solution for this system is not possible. Therefore, we need to use a numerical method to solve these equations, which is the subject of this section.

The Newton-Raphson numerical method is used to solve this equation and obtain the exact values of \(V_c\) and \(\varphi_L\).
For using the Newton-Raphson algorithm the equation (28) is rewritten as follows:

\[
\begin{align*}
    f &= p - V_i V_c \sin \varphi_L = 0 \\
    g &= q - V_c (V_i \cos \varphi_L - V_c) = 0
\end{align*}
\] (31)

where \( f \) and \( g \) represent the mismatches of active and reactive powers. To calculate \( p \) and \( q \), we have:

\[
\begin{align*}
    p_{\text{est}} &= \frac{V_{\text{est},c}}{r_L^2 + x_L^2} \left\{ r_L V_i \cos \varphi_{\text{est},L} - r_L V_{\text{est},c} \right\} + x_L V_i \sin \varphi_{\text{est},L} \\
    q_{\text{est}} &= \frac{V_{\text{est},c}}{r_L^2 + x_L^2} \left\{ -r_L V_i \sin \varphi_{\text{est},L} - x_L V_{\text{est},c} \right\}
\end{align*}
\] (32)

The numerical solution based on Newton-Raphson algorithm is:

\[
\begin{align*}
    \left[ \begin{array}{c}
        \varphi_L \ [j+1] \\
        V_c \ [j+1]
    \end{array} \right] &= \left[ \begin{array}{c}
        \varphi_L \ [j] \\
        V_c \ [j]
    \end{array} \right] - \left[ \begin{array}{cc}
        \frac{\partial f}{\partial \varphi_L} & \frac{\partial f}{\partial V_c} \\
        \frac{\partial g}{\partial \varphi_L} & \frac{\partial g}{\partial V_c}
    \end{array} \right]^{-1} \left[ \begin{array}{c}
        f \ [j] \\
        g \ [j]
    \end{array} \right]
\end{align*}
\] (33)

where,

\[
\begin{align*}
    \frac{\partial f}{\partial \varphi_L} &= V_c \ [j] \times V_i \ [j] \times \cos (\varphi_L \ [j]) \\
    \frac{\partial g}{\partial \varphi_L} &= -V_c \ [j] \times V_i \ [j] \times \sin (\varphi_L \ [j]) \\
    \frac{\partial f}{\partial V_c} &= V_i \ [j] \times \sin (\varphi_L \ [j]) \\
    \frac{\partial g}{\partial V_c} &= V_i \ [j] \times \cos (\varphi_L \ [j]) - 2V_c \ [j]
\end{align*}
\] (34)

Iterations continue until the mismatches \( f \) and \( g \) persist with a predetermined error value ($\epsilon_f$, $\epsilon_g$).

In most practical cases, the power angle is small. Therefore, we can consider the reasonable assumptions of $\sin(\varphi_L) = 0$ and $\cos(\varphi_L) = 1$. Therefore, the above equations are simplified in the following form:

\[
\begin{align*}
    \left[ \begin{array}{c}
        \varphi_L \ [j+1] \\
        V_c \ [j+1]
    \end{array} \right] &\approx \left[ \begin{array}{c}
        \varphi_L \ [j] \\
        V_c \ [j]
    \end{array} \right] - \frac{V_i \ [j] \times V_i \ [j]}{\frac{\partial g}{\partial \varphi_L}} \times \left[ \begin{array}{c}
        f \ [j] \\
        g \ [j]
    \end{array} \right]
\end{align*}
\] (35)

Finally, we have:

\[
\begin{align*}
    \varphi_L \ [j+1] &= \varphi_L \ [j] - \frac{f \ [j]}{V_i \ [j] \times V_i \ [j]} \\
    V_c \ [j+1] &= V_c \ [j] - \frac{g \ [j]}{V_i \ [j] - 2V_c \ [j]}
\end{align*}
\] (36)

In general, the synchronization with the distorted and harmonically polluted grids, the phase-locked-loop (PLL), or band-pass-filter (BPF) are used to extract the fundamental component of the voltage.

Increasing computing burden, complexity, and reducing system dynamics are the most important weaknesses of these methods. In the proposed method, the main component of the voltage is extracted without using any PLL or BPF.

As can be seen from equation (36), the estimator needs the output voltage of the ALB to calculate the PCC voltage. The output voltage of the ALB is determined by the switching pattern states as (5).

Therefore, in the proposed method, the estimation of the fundamental component of the PCC voltage is performed according to the nature of the control system.
IV. PROPOSED PREDICTIVE SENSOR-LESS CONTROL

In this paper, to control the proposed ALB converter system, the MPC in [31]–[33] is developed. The main concepts of using MPC are the convenient performance and ease of digital implementation, even for the constrained nonlinear systems. The desired performance in this controller can be optimized as a cost function. By predicting all the operation states of the four-leg inverter for the next switching step, the most proper performance is selected with respect to the least amount of cost function. Then, the nominated switching function will be applied to four-leg inverter.

The block diagram of the proposed control system of the four-leg inverter fortified with an LC filter in ALB application is shown in Fig. 5. As shown in Fig. 5, the main contribution of this work in reducing the number of sensors in the MPC by estimating voltage of PCC and load current.

By using the estimated voltage of PCC $v_{est,c}(k)$, measured value of filter current $i_f(k)$ and the estimated load current $i_{est,o}(k)$, for all 16 possible switching states the output current of ALB converter for the next sampling step $i_f(k+1)$ is predicted. Based on (14), to predict the ALB output current, the load current $i_o(k)$ and PCC voltage $v_c(k)$ are obligatory.

To improve reliability, costs, and quality of compensation, in the proposed algorithm the estimated values of voltage and current are used instead of the measured values. To estimate the load current and the PCC voltage, the proposed observers based on (26) and (30) are presented, respectively. Regarding the lowest cost function, the best switching vector (among 16 possible states) has been selected; and the best switching state has been applied to the ALB converter.

As the ALB converter has to provide the reference current waveform, the following cost function is adopted:

$$g = g_1 + Ag_2$$

$$g_1 = (i_{f\alpha} - i_{f\alpha})^2 + (i_{f\beta} - i_{f\beta})^2$$

$$g_2 = |i_n|$$

(37)
TABLE 2. Test system parameters

| Parameters                          | Value               |
|-------------------------------------|---------------------|
| DC link Voltage (Vdc)               | 600 [V]             |
| Grid voltage                        | 220 [V], 50 [Hz]    |
| IGBTs                               | IXGH48N60           |
| Inductance of filter (Lf)           | 1 [mH]              |
| Resistance of filter (Rf)           | 0.1 [Ω]             |
| Capacitance of filter (Cf)          | 20 [μF]             |
| Capacitance of DC link (Cdc, abc)   | 1000 [μF]           |
| Resistance of linear load (Rl)      | 20 [Ω]              |
| Three phase nonlinear load:         | Cap. (C): 3000 [μF] |
| full-bridge diode rectifier         | Res. (R): 60 [Ω]    |

where $i_f^α$ and $i_f^β$ are the real and imaginary components of the reference current vector while $i_o^α$ and $i_o^β$ are real and imaginary components of the predicted filter current $i_f(k+1)$. $A$ is the weighting factor. $g_1$ and $g_2$ is the cost function of reference current and null current, respectively. The algorithm of the proposed control system is described as a flowchart in Fig. 6.

As shown in Fig. 6, after calculating grid voltage based on proposed algorithm in section III-B, the currents of $L$-filter are measured. In the load current observer side, the $αβ$ values of load current are estimated by using $L$-filter current and grid side calculated voltage. After estimating the load current, three vectors of measured $i_o^abc$-estimated $v_{c,abc}$ and estimated $i_o^abc$ are fed to predictive control algorithm. In this part, the current of $L$-filter will be predicted for the next sampling time. As seen in this figure, for prediction of $i_f^abc[k+1]$ we need the discrete model of grid side filter i.e. $A_d$, $B_d$, state and input parameters which were estimated or measured before. Then the predicted values of $L$-filter current are compared with reference values as cost functions to improve the quality of load and reduce the grid side null current. This loop is repeated for 16 times for each switching state in Table 1. After evaluating all of cost functions, the minimum value of them is selected and applied to the four-leg inverter.

V. EXPERIMENTAL VALIDATION

As shown in Fig. 7, the proposed algorithm is applied on the ALB which consists of a four-leg inverter with LC filter, and the proposed observers and MPC control system are implemented through STM32F407 floating point microcontroller. The parameters of the test system are presented in Table 2.

Implementation of the proposed control system including the proposed load current observer and PCC voltage observer with a sampling time of $T_s = 20 \mu s$ is attainable.

The performance of the proposed control system, for nonlinear and unbalanced load has been validated by experimental tests.

Fig. 8 shows the steady-state operation of the proposed ALB converter with the predictive control system. As shown in Fig. 8(a), in the case of a resistive linear load in the presence of a real and harmonically polluted grid voltage, the proposed converter compensates the grid current and a proper current on the grid side is seen.

Fig. 8(b) is a demonstration of three-phase grid current and the grid null current. As can be seen, the grid current is not harmonically polluted and the null current of the grid is also negligible. Fig. 8(c) provides a representation of the three-phase load current and the null current, indicating load balance.

Fig. 9 shows the behavior of the proposed converter in the presence of a full-bridge diode rectifier as a nonlinear load. As can be seen, deposit the nonlinearity of load, a proper quality of current is flowed at the grid side. Also, the null current is observed with a very small magnitude at the grid side. As it was mentioned in [32], in the presence of nonlinear load, the Luenberger observer error in estimating will increase due to setting the gain of observing at an equilibrium point. The proposed load current observer uses an algebraic equation which is independent of a working point. Therefore, the proposed observer offers a lower error in the presence of nonlinear loads.

Fig. 10 is a demonstration of the unbalance load compensation by the proposed converter. As can be seen, the null current of load which is around 5 A is compensated by the ALB converter and the grid null current is around 0.1 A.

In Fig. 11, the stepwise variations of the two-phase of load in the presence of the proposed converter and the compensation of the null current are shown. As can be seen, the proposed predictive control system compensates the transient variation between balanced to an unbalanced load.

Fig. 12 shows the proposed estimated and measured values of the load current of the linear load. As can be seen, $α$ and $β$ currents are estimated by the proposed estimator, accurately.

Fig. 13 shows the proposed estimated and measured values of the PCC voltage. As can be seen, $α$ and $β$ voltages are estimated by the proposed estimator, accurately. As shown in this figure, the error of estimated PCC voltage is lower than 4 volts.

By adjusting the weighting factor $A$, as shown in Fig. 14, the amount of grid current THD and magnitude of the grid
null current are changed. It is clear that increasing the weighting factor leads to decrease in the RMS of the grid null current and increases the THD of the grid current.

A comparison of proposed PCC voltage and load current observer and the conventional approaches are made in Table 3. Compared to the modified second-order generalized integrator (MSOGI-PLL) and multiple adaptive vectorial filter frequency-locked loop (MAVF-FLL), the proposed algorithms track the frequency and phase with zero-steady state error. Furthermore, due to the transfer functional base of all SOGI methods, these approaches have a stability issue and it is necessary to design these systems in a stable point. The proposed voltage estimator is based on recursive algorithm which offers accurate and converges solution even with the more computational burden. Furthermore, a quantitative comparison is provided in Table 4. As shown in this table, due to simple, accurate and fast response of proposed
TABLE 3. Summary of comparison proposed and conventional observers

| Observer:           | Methods:                                         |
|---------------------|--------------------------------------------------|
| Load current estimating: | Stability issue                                 |
|                     | Lower error of estimating for linear load       |
| Luenberger          | Higher error of estimating for non-linear load  |
| Proposed            | Low computation burden                          |
| MAVF-PLL            | Algebraic equation                              |
| Proposed            | Stability issue                                 |
| PCC voltage estimating: | Low computation burden                          |
| MAVF-PLL            | DC offset estimation                            |
| Proposed            | Stability issue                                 |
|                     | Very Low computation burden                     |
|                     | No DC offset estimation                         |
|                     | Recursive algorithm (no stability issue)        |
|                     | DC offset estimation                            |

The comparison load current estimation is also illustrated in this table. The Leunberger load current observer suffers from the stability issue of designing the gain of estimating and lower accuracy of nonlinear load current. The proposed algorithm of load current observing is based on an algebraic equation that offers lower error on estimating than Leunberger observer.

VI. CONCLUSION

In this paper, the new observers for model predictive control system to improve the compensation of the active load balancer in the presents of the harmonically polluted unbalanced load is proposed. The proposed PCC voltage and load current observers through the MPC control system have been validated by experimental results. The operating principles, predictive controller design, new voltage, and current observers designs, are presented. Through the theoretical analyses and the experimental results from a 4 kW prototype, it is demonstrated that the proposed ALB possesses the advantages such as high quality of compensation, simple PWM scheme, low natural current, reducing the number of voltage and current sensors leads to the high reliability of the operating system, reduction in costs and lower complexity of observers because of the new linear estimator, fast and smooth transitions between the modes of operation and high quality of grid current. Hereafter, ALB is proper for compensation of the on-grid nonlinear and unbalance industrial load applications. As a theorem of results, the performance of three-phase four-leg active load balancer can be improved by applying predictive control system. Furthermore, the load current observer and grid voltage estimator can be used to make the realization of ALB and predictive control more cost effective, high reliable and even more accurate. Furthermore, the proposed load current observer and grid voltage estimator can be used in many different applications to reduce the cost and improve the reliability.

As the future works, the proposed voltage estimator can be used in some other applications such as the predictive torque control (PTC) of induction motors, predictive control system of active front converters, predictive control system of matrix converters etc. Furthermore, the proposed voltage estimator can be developed by using of advanced numerical solution for the nonlinear equation in (28) and finding the solution with lower computational burden.
The state space model of proposed system in (9) can be obtained as:

\[
\frac{d}{dt} \begin{bmatrix} i_{f,a} \\ i_{f,b} \\ i_{f,c} \\ v_{c,a} \\ v_{c,b} \\ v_{c,c} \end{bmatrix} = \begin{bmatrix} -\frac{R_{eq}}{L_{eq}} & \frac{1}{L_{eq}} & 0 & 0 & 0 & 0 \\ \frac{1}{L_{eq}} & -\frac{R_{eq}}{L_{eq}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{C_f} & 0 & 0 & 0 \\ v_{i,abc} & v_{i,abc} & v_{i,abc} & v_{i,abc} & v_{i,abc} & v_{i,abc} \end{bmatrix} \begin{bmatrix} i_{f,a} \\ i_{f,b} \\ i_{f,c} \\ v_{c,a} \\ v_{c,b} \\ v_{c,c} \end{bmatrix}
\]

where the state variables and inputs are:

\[
\begin{align*}
i_{f,abc} &= \begin{bmatrix} i_{f,a} \\ i_{f,b} \\ i_{f,c} \end{bmatrix}, \\
v_{c,abc} &= \begin{bmatrix} v_{c,a} \\ v_{c,b} \\ v_{c,c} \end{bmatrix}, \\
v_{i,abc} &= \begin{bmatrix} v_{i,a} \\ v_{i,b} \\ v_{i,c} \end{bmatrix}, \\
i_{o,abc} &= \begin{bmatrix} i_{o,a} \\ i_{o,b} \\ i_{o,c} \end{bmatrix}
\end{align*}
\]

Furthermore, the constant matrixes are,

\[
R_{eq} = \begin{bmatrix} \frac{R_f + R_n}{L_f + L_n} & \frac{R_n}{L_n} & \frac{R_n}{L_n} \\ \frac{R_n}{L_n} & \frac{R_f + R_n}{L_f + L_n} & \frac{R_n}{L_n} \\ \frac{R_n}{L_n} & \frac{R_n}{L_n} & \frac{R_f + R_n}{L_f + L_n} \end{bmatrix},
\]

\[
L_{eq} = \begin{bmatrix} \frac{L_f + L_n}{L_n} & \frac{L_n}{L_n} & \frac{L_n}{L_n} \\ \frac{L_n}{L_n} & \frac{L_f + L_n}{L_f + L_n} & \frac{L_n}{L_n} \\ \frac{L_n}{L_n} & \frac{L_n}{L_n} & \frac{L_f + L_n}{L_f + L_n} \end{bmatrix}
\]

Therefore, the equation (9) with details as shown at the top of the page.

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