A Three-Phase Non-Isolated Pseudo Six-Phase-Based Integrated Onboard Battery Charger for Electric Vehicles

Mahmoud Said Abdel-Majeed, Abdullah Shawier, Abdelrahman Habib, Ayman Samy Abdel-Khalik, IEEE Senior Member, Mostafa S. Hamad, IEEE Senior Member, Shehab Ahmed, IEEE Senior Member, Noha A. Elmalhy

Abstract—The trending modern designs of electric vehicle motors are concerned with maximizing the machine torque density while offering a fault tolerance capability. Among different available stator winding layouts, the so-called pseudo-six-phase winding has recently been proposed, which offers an improved torque density and fault tolerance over conventional six-phase distributed winding. An integrated onboard battery charger (IOBC) has also been proposed as a new leading technology that employs the propulsion components of the EV in the charging process to achieve the highest possible charging current with zero machine torque production. In this context, this paper proposes a new pseudo six-phase-based IOBC system. Two different controllers have been investigated, namely, conventional proportional resonant (PR)-based current control and predictive current control (PCC) techniques. Under charging mode, the control objectives aim at achieving a balanced three-phase grid current while nullifying machine torque production. To this end, the sequence stator currents are regulated to ensure a balanced $xy$ current while both the $a^p$ and $0^p$ current components are controlled to zero. Furthermore, a novel postfault controller using a PR-based current controller has been proposed which ensures balanced grid line currents under one open phase fault. A comparative experimental study has been carried out under different controllers for both vehicle to grid (V2G) and grid to vehicle (G2V) modes using a 2 Hp prototype machine.

Index Terms—IOBC, six-phase, Pseudo six-phase, PR, PCC, virtual vectors, post-fault, electric vehicles.

I. INTRODUCTION

Recently, electric vehicles have received great attention in the automotive area and impose themselves as a competitive alternative to the traditional gas/petrol engines. A recent forecast has predicted that more than half of the vehicles sold worldwide will be electric by 2035[1],[2]. Transportation electrification, however, implicates several challenges associated with the powertrain system design. Torque density, fault tolerance and motor size constraints are the main design concerns of electric motors employed in the automotive industry [3].

Multiphase motors are recently favored in EV applications thanks to their several advantages, such as reduced per phase rating, increased degrees of freedom, and improved post-fault tolerant capability [4]. Consequently, literature has investigated several machines with different number of phases [5] and/or different winding configurations [6]. Special interest has been given to six-phase thanks to their modular three-phase structure, which benefits from the well-established three-phase technology [6].

One of the promising introduced proposals to enhance multiphase performance is the so-called pseudo-six-phase machine (P6P) [7]. This novel winding design employs single-layer quadrable three-phase winding sets, which are connected in such a way as to provide six terminals only. Consequently, two three-phase inverters can be used similar to conventional six-phase machines. In addition, the P6P machine provides a $5\%$ improvement in the machine torque density over the classical asymmetrical six-phase (A6P) motor due to the improvement in the fundamental winding factor for the same copper volume. Also, the single-layer design allows for a higher fill factor and simple insulation requirements. Additionally, the P6P machine provides higher secondary subspace impedance, which naturally mitigates the problem of circulating secondary current components, leading to improved motor efficiency [8].

From the EV point of view, battery chargers play a very important role in the development of electric vehicles. Lifetime and charging time strongly depend on the battery charger characteristics, which are categorized into two general types, namely, off-board and on-board charging techniques. Off-board chargers are installed at certain stations and support high-power charging. On the other hand, on-board chargers allow charging wherever electricity is available [9]. However, this technology adds extra cost, weight, and volume to the vehicle. In addition, it provides low power capabilities, which affects the battery charging.
time. The so-called integrated onboard charger (IOBC) is recently proposed to conserve the advantages of onboard chargers while overcoming their drawbacks. The IOBC re-exploits the propulsion components, the motor and the power converter, instead of using external bulky charging circuits in the charging process, which allows charging at the same power rating of the propulsion converter [10]. However, the main technical challenge of IOBCs is to ensure zero average/ripple torque during charging and to ensure minimum winding reconfiguration when changing over between propulsion and charging modes.

The literature has shown several approaches to nullify/minimize torque production during charging. For three-phase IM, one of the suggested solutions is to split the winding into two equal parts to cancel out the air gap flux production during charging [11]. On the other hand, the torque production in multi-phase machines can simply be eliminated by controlling the \(a\beta\) sequence current components to zero, while charging can be implemented by controlling the current components of the non-torque producing subspace (\(xy\) subspace) [12]. For synchronous machines, a torque cancellation strategy has been proposed in [13],[14] for both symmetrical and asymmetrical permanent magnet six-phase machines. While [15] has introduced the required optimal phase currents during post-fault operation of a nine-phase-based IOBC to ensure three-phase grid charging currents and zero torque production concurrently.

The reference charging current in multi-phase machines-based IOBC is commonly derived based on either constant voltage (CV) or constant current (CC) approaches over the complete charging cycle [13],[14]. Whereas, conventional proportional-integral (PI) or proportional resonant (PR) current controllers are commonly recruited [16, 17]. Recently, more complicated control algorithms have been introduced such as model predictive, fuzzy logic, and sliding mode control thanks to their ability to handle nonlinear constraints and the ease of considering multiple objectives [18]. To the best of the authors’ knowledge, there is limited work done in the available literature to employ MPC in multi-phase-based IOBC.

In [18], the symmetrical six-phase (S6P) has been controlled in propulsion and charging mode using MPC. In charging mode, the three-phase grid currents are directly controlled by reconfiguring the six-phase stator winding as an equivalent three-phase winding, while being connected to the grid in such a way similar to grid-tied inverters.

Thanks to the several advantages of P6P winding over conventional A6P winding, this paper introduces a new non-isolated P6P induction machine-based IOBC for EV applications. The required controller structure is introduced, which ensures zero average/ripple torque and balanced grid line currents during the charging process. To this end, two current controllers have been compared, namely, the conventional PR current controller and predictive current controller (PCC). The PCC of P6P under propulsion mode has previously been introduced in [19] based on a nonstandard vector space decomposition (VSD) transformation of this particular winding layout, which is derived in [20]. The main contributions are, therefore, summarized in the following bullets:

- Suggesting a suitable winding connection to the grid under charging mode that ensures balanced three-phase grid currents and zero torque production.
- Investigating two possible controller types, namely, PR current control and PCC techniques.
- Investigating the optimal voltage vectors and the objective function suitable for the proposed PCC technique.
- Proposing a new postfault current controller that ensures the same control objectives under one-phase open.

A brief description of the pseudo-six-phase machine and the suggested connection to the grid is first proposed in section II. In section III, the proposed control algorithms are presented. While in section IV, the experimental validation of the two current controllers is presented. Finally, the conclusions are given in section V.

II. PSEUDO SIX-PHASE MACHINE

This section provides a brief description of the P6P machine and the proposed connection with the grid that maximizes the line charging current and nullifies the torque-producing \(a\beta\) current components.

The P6P machine has been introduced in [7], where its winding layout consists of four three-phase winding sets forming two identical winding groups \((abc_1, abc_2)\) and \((abc_3, abc_4)\), as shown in Fig. 1(a). Single layer construction is used, where phases \(abc_3\) and \(abc_4\) are wound together sharing the same slots, as shown in Fig. 1(b), with a number of turns equal to 0.532 times the number of turns of \(abc_1\) and \(abc_2\) winding sets. The winding sets \((abc_1, abc_2)\) are connected in series to form the first main three-phase set of the P6P machine, while the series connection of winding sets \((abc_3, abc_4)\) forms the second main three-phase set. As proved in [20], fundamental MMF is obtained when the arbitrary phase shift angle between the first and second phase current groups \((i_{abc_1} \text{ and } i_{abc_2})\) is 40\(^\circ\), as shown in Fig. 2(a), which is achieved when the phase shift angle between the two applied three-phase voltage sets is ideally 26.16\(^\circ\). Whereas the MMF fundamental component is completely cancelled \((xy\)-excitation\) for a phase shift angle of 206.16\(^\circ\), which is shown in Fig. 2(b). With this unusual phase shift angle to excite different subspaces, particular VSD matrices are derived in [20] for voltage and current transformations, which are given by (1) and (2), respectively. For a six-phase system, the sequence current components \((a\beta, xy, \text{ and } 0^\circ0^-)\) are obtained from (3).

\[
\begin{align*}
T_{VSD_1} &=
\begin{bmatrix}
0.333 & -0.202 & -0.132 & 0.281 & -0.299 & 0.018 \\
0.040 & 0.269 & -0.309 & 0.183 & 0.152 & -0.335 \\
0.333 & -0.312 & -0.202 & -0.281 & 0.299 & -0.018 \\
0.040 & -0.309 & 0.269 & 0.183 & 0.152 & -0.335 \\
0.281 & 0.281 & 0.281 & 0.052 & -0.052 & 0.052 \\
0.177 & 0.177 & 0.177 & 0.511 & 0.511 & 0.511
\end{bmatrix}
\end{align*}
\]

(1)

\[
\begin{align*}
T_{VSD_2} &=
\begin{bmatrix}
-0.333 & 0.202 & 0.132 & -0.281 & 0.299 & -0.018 \\
-0.040 & -0.269 & 0.309 & -0.183 & -0.152 & 0.335 \\
-0.333 & 0.312 & 0.202 & 0.281 & -0.299 & 0.018 \\
-0.040 & 0.309 & -0.269 & -0.183 & -0.152 & 0.335 \\
-0.281 & -0.281 & -0.281 & -0.052 & 0.052 & -0.052 \\
-0.177 & -0.177 & -0.177 & -0.511 & -0.511 & -0.511
\end{bmatrix}
\end{align*}
\]

(2)
set to zero. The resultant phase currents have a 206.2° phase shift angle between the two three-phase sets, as shown in Fig. 2(b) [20]. Fig. 3 shows the suggested external connection with the grid to maximize the charging line current, which is done by connecting the winding terminals \((a_1 \text{ and } b_2), (b_1 \text{ and } c_2), (c_1 \text{ and } a_2)\) to the three-phase grid lines. Fig. 2(b) also shows that the phase shift angle, \(\gamma\), between phase currents \(a_1\) and \(b_2\) is 33.8°. Hence, the resultant line current \(i_{d}^s\) equals 1.91 times the phase current, as given by (4).

\[
i_d^s = 2I_s e^{j\pi/2}
\]

where, \(I_s\) is the phase current magnitude.

### III. PROPOSED CONTROL TECHNIQUES

This section discusses the feasibility of employing P6P machine-based IOBC using either PR current control or PCC techniques for healthy operation. The derivation of the reference currents is the same in both techniques and the main difference will be in the current control stage. This section also proposes the optimal postfault currents that ensure the same control objectives under one phase open fault (1OPF). However, the PR controller is only employed, while the postfault PCC is postponed for a future study since it still entails further investigations. The proposed controllers are only given for the charging mode since the propulsion mode is already given in previous work [19].

According to the current decoupling matrix \((T_{VSYD})\) given by (2), the motor phase currents are decomposed into three subspaces. The \(\alpha\beta\) subspace is responsible for flux/torque production, while the \(xy\) subspace is commonly assumed as a zero flux/torque producing subspace when distributed stator winding layout is employed. The propulsion mode is activated by exciting the \(\alpha\beta\) subspace. Whereas, the battery charging is achieved by exciting the \(xy\) subspace and the reference \(\alpha\beta\) current components are set to zero to ensure zero magnetizing flux production. Assuming a star-connected grid, the machine is regarded as a single neutral (1N) P6P machine. Hence, the effect of the 0°-0° sequence should be included in the control algorithm. Thus, the 0°-0° sequence currents are always maintained at zero alongside the \(\alpha\beta\) current components to ensure zero flux/torque production with a high-quality current waveform.

The block diagram of the proposed current controller for the charging mode is shown in Fig. 3. In which, the desired grid charging current is set in the \(dq\) synchronous reference frame. The corresponding reference \(\alpha\beta\) grid currents, \(i_{\alpha\beta}^g\), in the stationary reference frame are obtained using inverse Park’s transformation, while the synchronization with the grid is done through a standard phase-locked-loop. As clear from Fig. 2(b), the grid line currents are shifted by an angle \(\gamma/2 = 16.9°\) from the stator reference frame, where \(\gamma\) is the phase angle between \(a_1\) and \(b_2\). To synchronize the reference frame of the machine variables with the grid, the reference \(\alpha\beta\) grid current components should be shifted by the angle \(\gamma/2\) to obtain the corresponding reference \(xy\) components, \(i_{xy}^g\), of the machine phase currents. The other sequence components, \(i_{d}^*, i_{a}^*, i_{b}^*, i_{c}^*\), are set to zero. In the following context, two current controllers are proposed, namely, conventional PR-based current controller and PCC, to obtain the required stator voltages.
A. PR Current Controller

To fully control all sequence current components, two pairs of PR controllers are used for both \(a\beta\) and \(xy\) subspaces. Since \(i_{0^+} = i_{0^-}\), and hence \(v_{0^+} = v_{0^-}\), a single PR controller is enough to control the zero subspace. The PR controllers’ outputs are then transformed into six-phase references voltages for the modulation stage.

It is worth mentioning that the same controller structure can be used under either healthy or post fault operation with one phase disconnected, which represents the main advantage of this current controller type. In [15], the required optimal currents to ensure a balanced three-phase grid for a nine-phase-based IOBC are derived. Following the same concept, it can mathematically be shown that balanced three-phase line currents as well as zero \(a\beta\) current components can still be ensured with 1OPF, where the number of degrees of freedom becomes four. The corresponding optimal phase currents can be derived as follows. Assuming that phase \(a\) is disconnected, and according to (3), then,

\[
i_a^* + i_x^* + i_y^* = 0
\]

In order to achieve these two mentioned objectives, the reference sequence currents should follow (6).

\[
\begin{bmatrix}
i_a^* \\
i_x^* \\
i_y^*
\end{bmatrix} = \begin{bmatrix}
0 \\
1\angle 0 \\
1\angle 90^0
\end{bmatrix} T_{VSD1} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

The corresponding machine currents could be obtained from the inverse of (2) as in (7).

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} = [T_{VSD1}]^{-1} \begin{bmatrix}
0 \\
1\angle 0 \\
1\angle 90^0
\end{bmatrix} = \begin{bmatrix}
0.1731\angle -150^0 \\
0.545\angle 76.904 \\
1.91\angle 16.914
\end{bmatrix}
\]

It is obvious from (7) that the largest current of the remaining healthy phases exceeds the rated value by 91%. Hence, in order to avoid winding hot spots due to current overloading under 1OPF, the maximum reference charging current is reduced to 1/1.91 = 0.5236 pu, i.e. the charger is derated to 52.36% of its full capacity.

B. PCC technique:

Thanks to the decent dynamic behaviour and flexibility in defining more control objectives, model predictive control (MPC) has become one of the most promising control strategies. Despite the high computational burden of the predictive algorithm [21], it gains great attention in the control of electric drives and power electronics since non-linear constraints can simply be added. In the area of multi-phase systems, predictive current control (PCC) has an added strength point over classical techniques that requires the tuning of several gains for each subspace-currents [22]. These current controllers can simply be replaced by a constraint in the cost function of the PCC algorithm [6].

For single neutral six-phase systems, there are 64 possibilities of switching states. Consequently, the phase voltages can be expressed as a switching state pattern of the upper switches, as given by (8).

\[
V_{a1\rightarrow c2} = \frac{V_{dc}}{3} \begin{bmatrix}
v_{a1} \\
v_{b1} \\
v_{c1} \\
v_{a2} \\
v_{b2} \\
v_{c2}
\end{bmatrix} S
\]

where \(S\) is the switching pattern vector \(\in\{000000 \rightarrow 111111\}\). The vectors numbering is in binary, i.e., vector number 35 has a switching pattern of 10011. The resultant 64 voltage vectors can be mapped into \(xy, a\beta\) and \(0^+0^-\) subspaces by simply applying the voltage vector space decomposition matrix (1) as given by (9).

\[
V_{a\beta xy0^+0^-} = T_x V_{a1\rightarrow c2}
\]
The obtained voltage vectors VVs are classified as shown in Fig. 4 and Table I in which, the αβ and xy voltage vectors are mapped into seven different levels (Fig. 4), while 0°-0° vectors are mapped into 4 different levels (Table I) in only two opposite directions. To ensure balanced three-phase grid currents under charging mode, xy subspace current shall be controlled at a certain value according to the required charging current, while the αβ and 0°-0° currents are maintained at zero to nullify torque production during charging mode and prevent zero-sequence current circulation.

Based on Fig. 4, the vectors of level 6 in the xy subspace may be a suitable set since they are mapped into small vectors in the αβ subspace and zero vectors in the 0°-0° subspace. However, experimental validation showed that this selection fails to minimize the induced αβ currents, which yields slightly unbalanced line currents. On the other hand, experimental validation showed that using the voltage vectors of levels 6 and 7 can almost eliminate the αβ and 0°-0° currents completely through a proper weighting factor design. It also enhances the controllability of the PCC controller to minimize the cost function by evaluating a higher number of feasible vectors that map to different twelve directions. This conclusion is pretty the same as the conventional asymmetrical six-phase machine, where a minimum of 12 voltage voltages are required [23].

Table I  Voltage Vectors mapping into zero subspace

<table>
<thead>
<tr>
<th>Vectors</th>
<th>Mag. (p.u.)</th>
<th>0°-0° subspace - Vectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>0</td>
<td>[0,9,10,12,17,18,20,27,29,30,33,34,36,43,45,46,51,53,54,63]</td>
</tr>
<tr>
<td>S</td>
<td>0.2375</td>
<td>[1,2,4,8,11,13,14,16,19,21,22,23,26,28,31,32,35,37,38,41,42,44,47,49,50,52,55,59,61,62]</td>
</tr>
<tr>
<td>M</td>
<td>0.4714</td>
<td>[3,5,6,15,23,24,39,40,48,57,58,60]</td>
</tr>
<tr>
<td>L</td>
<td>0.7071</td>
<td>[7,56]</td>
</tr>
</tbody>
</table>

where $V^\text{grid}_k$ is the αβ component of the three-phase grid voltage at instant $k$, $T_s$ is the sampling time, $R_s$ is the stator winding resistance, and $I^{αβ}_{ls}$, $I^{xy}_{ls}$, and $I^{0°0°}_{ls}$ are the stator leakage inductance for the three subspaces, respectively.

These predicted values are fed to the objective function given by (13) to determine the optimum vector among the feasible voltage vectors, which attains the best current tracking. This optimum voltage vector is then applied at the next instant.

$$g(V^{K+1}) = \left[ (i^{K*}_s - i^{K+1}_s)^2 + (i^{K*}_y - i^{K+1}_y)^2 \right] +$$

$$\rho \left[ (i^{K*}_s - i^{K+1}_s)^2 + (i^{K*}_y - i^{K+1}_y)^2 \right] +$$

$$\delta \left[ (i^{K*}_r - i^{K+1}_r)^2 + (i^{K*}_r - i^{K+1}_r)^2 \right]$$

where $\rho$ and $\delta$ are the normalized weighting factors of $αβ$ and $0°0°$ subspaces, respectively.

There are two approaches that can be suggested for realizing predictive current control of P6P-based IIBC. The first one is the simplest technique, which utilizes the vectors of level 6 only, similar to the symmetrical six-phase case, which has been recently introduced in [24]. The main advantage of this approach is the low computational burden of the PCC algorithm since it utilizes 6 vectors only. In addition, the $0°0°$ subspace term and its associated weighting factor can be excluded from the objective function since level 6 vectors have zero magnitudes in the $0°0°$ subspace. However, this technique cannot completely eliminate the $αβ$ subspace current, which slightly affects the balancing of the machine phase currents [23].

Fig. 4 Voltage vector mapping into (a) αβ subspace. (b) xy subspace.
On the other hand, the second approach is to utilize the vectors of levels 6 and 7 [19]. This technique almost eliminates the $a\beta$ subspace current, however, it introduces $0^\perp$ $0^\perp$ subspace voltage, which affects the current quality. Nevertheless, it ensures balanced phase and grid line currents, as will be investigated in the experimental result section. Under appropriate tuning of the $a\beta$ and $0^\perp 0^\perp$ weighting factors, the subspaces currents can be accurately controlled to the intended reference values.

IV. EVALUATION RESULTS

A. Experimental setup

The experimental validation of the proposed IOBC has been carried out using the prototype shown in Fig. 5. An off-the-shelf 2Hp, 380V, three-phase IM has been rewound with quadable three-phase winding forming a P6P stator with the same number of conductors per slot. The full winding details can be found in [7]. The number of turns for the abc$_1$ and abc$_2$ winding sets are 40 turns/coil, while for the abc$_3$ and abc$_3$ sets, it is 21 turns/coil. The conductor cross section for all windings is 0.85mm. The P6P machine specifications and parameters of the are listed in Tables II and III, respectively. The P6P is fed from a six-phase inverter that is constructed using two 600V, 20A three-phase inverter modules supplied by a battery pack. A sinusoidal PWM signals at $f_{sw}=5kHz$ is used to drive the dual three-phase inverter under PR control. Therefore, under PCC control, the sampling time is set to 25μs, which gives the average switching frequency of $f_{sw} = 5 kHz$. Both control techniques were developed through a model-based approach using the Matlab/Simulink platform, then deployed on a MicroLabBox dSPACE®. The measurements are carried out using hall-effect current sensors and voltage transducers.

B. Experimental results

The experimental investigation has been done under both techniques for the healthy case, while for the 1OPF case, only the PR technique is performed. Experiments have been done for both controllers under both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes. This can simply be done by changing the sign of the reference direct current component of the gridline currents.

1) PR current control:

Under the healthy case, the V2G mode has been firstly investigated by setting the reference $xy$ subspace currents to 1pu, which yields a grid line current magnitude of 1.91 p.u., as shown in Fig. 6(a). The relation between the phase and line currents is shown in Fig. 6(b). Typically, according to the IEC 61000-3-12 standards [25], charging should be carried out under balanced line currents and at a unity power factor, which has been achieved using the proposed PR controller as shown in Fig. 6(a). The results show also a THD in the line current of 6.12%. Fig. 6(c) shows the corresponding sequence components of the phase currents, which proves that the controller can properly track the $xy$ reference current, while eliminating all other sequence currents. It is worth mentioning that the current waveforms experience some low order harmonics due to corresponding grid voltage harmonics, which can be suppressed by employing harmonic current compensation at the cost of more complex controllers and higher number of PR controllers [13].

<table>
<thead>
<tr>
<th>Table II</th>
<th>Prototype Machine Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated RMS phase Voltage (V)</td>
<td>110</td>
</tr>
<tr>
<td>Rated Power (Hp)</td>
<td>2</td>
</tr>
<tr>
<td>Rated Speed (rpm)</td>
<td>1400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table III</th>
<th>Prototype Machine and Controller Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Parameters</td>
<td>$R_0$ 1.9Ω</td>
</tr>
<tr>
<td></td>
<td>$L_{abc}$ 6.42mH</td>
</tr>
<tr>
<td></td>
<td>$L_{abc}^{\perp}$ 10 mH</td>
</tr>
<tr>
<td>PR Controller</td>
<td>$K_p$ 2</td>
</tr>
<tr>
<td>PCC</td>
<td>$\rho$ 0.32</td>
</tr>
<tr>
<td>Base Values</td>
<td>$V_{dc}(\text{rms})$ 110 V</td>
</tr>
</tbody>
</table>

Under G2V mode, there are two charging profiles, namely, constant current control (CC) and constant voltage control (CV). The CC control is similar to the V2G mode except that the sign of the reference direct current is changed. Hence, the power flow will be from the grid to the vehicle, as shown in Fig. 7(a). On the other hand, the CV control requires an external voltage control loop to generate the required reference current that regulates the battery voltage at the required voltage reference, 1 pu, as shown in Fig. 7(b).

The open-phase case is investigated by physically disconnecting the phase a1. As mentioned earlier, the charging power must be reduced to 52.36% of the rated power, which is realized by reducing the $xy$ reference current to 0.523pu. Clearly, for the derived optimal phase currents given by (7), the line currents are balanced three-phase with $1.91 \times 0.52 = 1pu$ magnitude, as shown in Fig. 8(a). The line current THD is 6.92%. Since phase a1 is disconnected, the line current $i_{a2}$ equals the phase current $i_{a2}$, as illustrated in Fig. 8(b). The sequence components of the phase currents are shown in Fig. 8(c), where $i_{a2} = 0$, $i_{a+} = -i_{a-} = -i_x$, and $i_{xy} = 0.523$ p.u.

2) Predictive Current Control:

In this subsection, the experimental results for the V2G mode under the proposed PCC are shown. The PCC algorithm is experimentally executed for two cases: the first case utilizes

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level 6 vectors only, while the second case employs voltage vectors of both levels 6 and 7. The experimental results for the two cases are shown in Figs. 9 and 10, respectively. The CC-G2V mode is experimentally investigated under PCC using level 6 only, which is shown in Fig. 11(a), while the same control is employed using levels 6 and 7 and is shown in Fig. 11(b).

The computational burden and the average switching frequency are shown in Table IV. The first technique yields a lower computational burden and higher average switching frequency since the total number of vectors is smaller.

As discussed in section III, vectors of level-6 produce \( \alpha \beta \) voltage components, which results in a small unbalance in the line currents, as shown in Fig. 9(a). Fig. 9(b) also proves that the current magnitude in both winding groups is not exactly the same, which yields an approximately \( \alpha \beta \) current component of 0.2pu, as shown in Fig. 9(c). However, the zero-sequence current is ideally zero for this case. Fig. 2(b) indicates that the ideal phase shift angle between phases \( a_1 \) and \( b_2 \) shall be \( 33.8^\circ \). However, Fig. 9(b) shows that the obtained angle is found to be about \( 28^\circ \) only, which proves that the desired phase angle to completely cancel out the \( \alpha \beta \) sequence currents cannot be achieved when using six vectors only. Additionally, Fig. 9(b) depicts that the phase currents experience a small unbalance component, which has a negligible influence on the line currents shown in Fig. 9(a). The THD% of the line currents under the PCC controller using V6 only is 8.81%. Thus, this case represents a simple compromise between computational burden and charger performance.

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<table>
<thead>
<tr>
<th>Vector levels</th>
<th>Level 6</th>
<th>Level 6 &amp; Level 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden time (µs)</td>
<td>12.33</td>
<td>14.33</td>
</tr>
<tr>
<td>Avg. switching frequency (kHz)</td>
<td>6.4</td>
<td>5</td>
</tr>
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</table>

Fig. 6. Experimental results under the healthy case and V2G mode using a PR current controller. (a) Grid line currents and grid phase voltage. (b) Phase currents \( i_{a1}, i_{b2} \) and their resultant grid line current \( i_{aL} \). (c) Subspace currents \( i_{αβ}, i_{xy}, \) and \( i_{0+0−} \).

Fig. 7. Experimental results under healthy case G2V mode under PR controller. (a) CC mode battery current. (b) CV mode battery voltage, grid line current, and grid voltage.
Fig. 8 Experimental results under 1OPF case using PR current controller. (a) Grid line currents and grid phase voltage. (b) Phase currents $i_a, i_b$ and their resultant grid line current $i_{aL}$. (c) Subspace currents $i_{x\beta}, i_{x\gamma}$, and $i_0^+ - i_0^-$. 

Fig. 9. Experimental results under healthy case using PCC with V6 only. (a) Grid line currents and grid phase voltage. (b) Phase currents $i_{aL}, i_{bL}$ and their resultant grid line current $i_{aL}$. (c) Subspace currents $i_{x\beta}, i_{x\gamma}$, and $i_0^+ - i_0^-$. 

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Fig. 10 Experimental results under healthy case using PCC with V6 and V7. (a) Grid line currents and grid phase voltage. (b) Phase currents $i_{a1}$, $i_{b2}$ and their resultant grid line current $i_{aL}$. (c) Subspace currents $i_{αβ}$, $i_{xy}$, and $i_{0/+0−}$.

Fig. 11. Experimental results under 1OPF case CC-G2V mode (a) using V6 and (b) V6V7.

On the other hand, employing voltage vectors of levels 6 and 7 in the optimization process can effectively suppress the undesirable $αβ$ current component, which nullifies the torque production. However, the weighting factor design becomes more sophisticated. Besides, the average switching frequency becomes less than case 1, as indicated in Table V. This yields a higher THD of 11.8% and a higher ripple, as indicated in Figs. 10(a) and (b). Under this case, both $αβ$ and zero sequence currents are minimized, as shown in Fig. 10(c). The optimal angle between phases $a_1$ and $b_2$, $γ = 33.8°$, has also been achieved, which ensures almost zero $αβ$ current, balanced three-phase line currents, and zero torque production.

To further compare different controllers, the machine torque under charging mode has been estimated based on experimental measured currents and the corresponding estimated torque waveforms are depicted in Fig. 12. Clearly, there is a small torque component under PCC using level-6; however, using either PR-based current control or PCC with VV levels 6 and 7, the estimated torque is almost zero.

In the same context, the induced vibration and noise levels are of important concern in this application. Generally, the
acceptable range of vibration velocity for small machines (class I) is between (0.28-0.71 mm/s) according to ISO 10816. To investigate the effect of different current controllers on the vibration level, it has been measured using a vibration analyzer (schenck® smart balancer v2) and the results are given in Table V. Clearly, the vibration level is considered very low and within acceptable limits and being the lowest under PR current control.

On the other hand, the noise level was very neglected to be distinguished from the surrounding noise in all scenarios since the machine torque ripple as well as the vibration level were very small.

Table V

<table>
<thead>
<tr>
<th>Control technique</th>
<th>Vrms (mm/s)</th>
<th>Main component (mm/s)</th>
<th>Freq. main comp. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR Controller</td>
<td>0.099</td>
<td>0.121</td>
<td>0.5</td>
</tr>
<tr>
<td>PCC (V6)</td>
<td>0.114</td>
<td>0.125</td>
<td>100</td>
</tr>
<tr>
<td>PCC (V6 and V7)</td>
<td>0.304</td>
<td>0.388</td>
<td>11</td>
</tr>
</tbody>
</table>

II. CONCLUSION

This paper proposes a new non-isolated pseudo six-phase-based IOBC for EV application. The same machine has recently shown several potentials over conventional asymmetrical six-phase machines under motoring mode. The main motivation to employ this winding type in this application is the possible 5% enhancement in the machine torque density and the notable increase in the xy impedance, which highly improves the machine current quality. The machine connection to the grid as well as the required control objectives under charging mode has been introduced. Two current controllers were then investigated, namely, PR-based current control and PCC. For the latter controller, the IOBC performance under two possible subsets of voltage vectors was assessed. The experimental validation showed that the current quality is the best under PR-based current control with a THD of 6.12%. On the other hand, PCC design is simpler since it avoids the required tuning of PR controllers. Under PCC, employing level 6 VVs yields a THD of 8.81%. However, a small current unbalance and torque ripple component are obtained. On the other hand, employing levels 6 and 7 VVs ensures balanced currents and almost zero torque production at a slightly lower current quality with a THD of 11.8%. A novel postfault PR-based current control under 1OPF has also been proposed, which ensures balanced grid line current and zero torque production. The same control objectives cannot be achieved for higher number of disconnected phases. The required optimal currents were derived and experimentally verified. It has been shown that the maximum achievable charging power under 1OPF is limited to 52.36% of the converter power rating.

REFERENCES

Mostafa S. Hamaad (SM’19) obtained the B.Sc. and M.Sc. degrees in Electrical Engineering from Alexandria University, Alexandria, Egypt, in 1999 and 2003, respectively, and the Ph.D. degree in Electrical Engineering from Strathclyde University, Glasgow, U.K., in 2009. From 2010 to 2014, he was an Assistant Professor in the Department of Electrical and Control Engineering, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport (AASTMT), Alexandria, Egypt, where he is currently a professor. His research interests include power electronics applications in power quality, electric drives, distributed generation, HVDC transmission systems, and renewable energy.

Abdullah Shawier received the B.Sc. and M.Sc. degrees in electrical engineering from Alexandria University, Alexandria, Egypt, in 2016 and 2021. He is currently a lecturer assistant with the Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt. His current research interests include electric drives, battery chargers, multiphase machine, smart grids, and power electronics.

Abdelrahman Habib received the B.Sc. degree in electrical engineering from Alexandria University, Alexandria, Egypt, in 2018. He is currently a Demonstrator with Electrical Engineering Department, Faculty of Engineering, Alexandria University. His current research interests include electric drives, battery chargers, electric vehicles, embedded systems, and solid-state power conversion.

Ayman S. Abdel-khalik (SM’12) received the B.Sc. and M.Sc. degrees in electrical engineering from Alexandria University, Alexandria, Egypt, in 2001 and 2004, respectively, and the Ph.D. degree in electrical engineering from Alexandria University, and Strathclyde University, Glasgow, U.K., in 2009, under a dual channel program. He is currently a Professor with the Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt. He serves as the Editor-in-Chief of Alexandria Engineering Journal. He also serves as an Associate Editor of IEEE Transactions on Industrial Electronics and IET Electric Power Applications Journal. His current research interests include electrical machine design and modelling, electric drives, energy conversion, and renewable energy.

Shehab Ahmed (SM’12) received his BSc degree from Alexandria University in 1999; his MSc and Phd degrees from Texas A&M University, College Station, in 2000 and 2007 respectively. He was with Schlumberger Technology Corporation, Houston, TX, from 2001 to 2007, developing downhole mechatronic systems for oilfield service products. He was with Texas A&M University at Qatar from 2007 to 2018. He is currently Professor and Chair of the Electrical and Computer Engineering program within the CEMSE Division at King Abdullah University of Science and Technology, Saudi Arabia. His research interests include subsurface mechatronics, solid-state power conversion, electric machines, and drives.

Noha Elmalhy received the B.Sc. and M.Sc. degrees in electrical engineering from Alexandria University, Alexandria, Egypt, in 2005 and 2010, respectively, and the Ph.D. degree in electrical engineering from Alexandria University in 2017. She is currently a Lecturer with the Electrical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt. Her current research interests include electrical machine and drives, energy conversion, and renewable energy.