A Novel Multilevel Quad-Inverter Configuration for Quasi Six-Phase Open-Winding Converter

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***Abstract*—This paper developed a novel quad-inverter configuration for multilevel six-phase asymmetrical open-winding AC converter. Proposal found to be suited for (low-voltage/high-current) applications such as AC tractions and 'More-Electric Aircraft' propulsion systems. Modular power circuit comprises of standard four three-phase voltage source inverter (VSI) and each connected to the open-end windings. Each VSIs are incorporated with one bi-directional switching device (MOSFET/IGBT) per phase and two capacitors with neutral point connected. Further, an original modified single carrier five-level modulation (MSCFM) algorithm is developed in this work and easy for implementing in real digital processors. The proposed modulation algorithm is capable of generating, 5-level voltages at each output of four VSI as one equivalent to multilevel inverter. The total power is among the four DC sources and quadruples the capabilities of VSIs. A set of observed results is presented with numerical software analysis (Matlab/PLECS) in balanced working conditions. Always the results shown good agreement in the developed theoretical background.**

***Keywords*—Dual three-phase inverter, quad-inverter, six-phase inverter, multilevel inverters, multiphase drives, asymmetrical inverters, multiple space vectors, pulse-width modulation.**

I. Introduction

Technological revolutions in Multiphase AC drives proved that are the predominant solution for limited rating (MOSFET/IGBT) device configurations [1-5]. In particular six-phase (dual three-phase) drives are preferred due to the reliability, redundant structure, limited DC link ripple, increased power density, fault tolerant, and reduced per-phase of inverter rating [5-10]. Configured by two adjacent phases are spatially shifted by 60^0 (symmetrical type) [14-18] or by 30^0 (asymmetrical) [2, 4, 5-10]. The benefit provides the feasibility to apply split phases and driven by multiple standard voltage source inverters (VSIs) as multiphase inverter [5-7]. Such topologies are referred as dual-, triple- and quadruple three-phase AC drives and applied in several low-voltage/high current AC traction and 'More-Electric Aircraft' applications (MEA) [5-14]. To be noted, multiphase AC drives replace the conventional hydraulic and pneumatic actuators, hence increase the reliability is assured in fault conditions and improve overall aeronautic propulsion in MEA [12-14]. Moreover, multiphase AC drives perform motoring/generator action during start and flight mode.

Multilevel inverters are the viable solution for high voltage synthesis can use sources and switching devices with lower voltage values, benefit includes reduced total harmonic distortion (THD) and lower dv/dt in the output voltages and to obtain high power ratings with voltage limited devices [15-17]. Still multilevel inverters are vulnerable to different potential anomalies, leading to total failure. A survey reveals that (31-37.9)% of failures are occurring due to power parts, mechanism with IGBT devices for high-power applications [18-19]. Another source of failures addressed with capacitors and gate control techniques [20]. It becomes evident that the combination of both multi-phase and multi-level inverter configuration leads to effective solution for obtains high power ratings with voltage- and current-limited devices [2, 5-7, 11, 21-24].

In this sense, classical VSIs still remains reliable and also reconfigured as both multi-phase and multi-level inverter by properly arranging the multiple VSIs [2-11, 21-24]. Generally, such topology is three-phase dual inverters, the three-phase VSI (two-level) are connected at the open-ends of windings [25-29]. The difference of two single inverter's leg potential constitutes the output voltages. Benefits include half the switching frequency and DC bus requirements, moreover, two different potential sources can be utilized (photovoltaic/fuel-cell). Further, compromise the benefit with standard MLIs and cancellation of common-mode currents are carried out by the PWM techniques or by keeping isolated DC sources [25-27]. Recently, such configurations have been addressed for z-source impedance network in the DC link for a buck/boost the output voltages with limited common-mode components and standard dual inverters for grid integration with/without isolation transformer [25-27]. But still, in all cases the dual inverters suffered by restricted levels in the output voltages, each leg is limited to three-levels and the output voltages appear in three-levels in lines and nine-level in phases, cannot be overcome with topologies addressed [2-11, 21-27].

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Motivated by above considerations and commercial inverters becoming more integrated, which reduce considerably its maintainability or reconfiguration. This paper work in perspective view articulates a novel configuration for dual three-phase asymmetrical multilevel inverter which fits open-winding loads, medium power (low-voltage/high-current) and MEA applications as shown in Fig. 1 [28, 11-14]. Also, this work developed an original modified single carrier five-level modulation (MSCFM) scheme (independent modulation for each VSIs) and capable generating 5-level outputs [28]. Modular converter circuit comprised of four classical six-phase voltage source inverters (VSIs H and L) with additional bi-bidirectional (IGBT) switch per phase and each one is connected across the open-end windings [28-31]. Additionally, two capacitors are incorporated with neutral connection with $VSI_H^{(1)}$, $VSI_L^{(1)}$, $VSI_H^{(2)}$, and $VSI_L^{(2)}$ for ensuring 5-level in each leg phases [28-29]. All four DC sources are isolated and common-mode currents are null [5]. To be noted, additional future holds the benefits that each VSIs generates 5-level in their line-to-line outputs irrespective of open-winding and/or star-winding structure. Hence, overcomes the drawback of standard dual inverter topologies addressed in the literatures. Also, the proposed converter shares the total power among the four DC sources and quadrupling the power capabilities of each VSIs (H and L). Moreover, reliable under faulty condition one or two or three VSIs fails and operable with single healthy VSI but with degraded power. The structure is easily scalable to nine-, twelve- or higher number of phases in the order multiple of three.

Proposed converter compromised the benefit of standard multilevel inverters with high reliability and fault tolerance [1, 12-14, 16-18, 21-22, 29-31]. To verify the performances, the complete system is numerically modelled and tested with Matlab/PLECs simulation software's. Observed set of simulation results is presented in this paper version to show the effectiveness of the converter in symmetrical operating conditions and response shown always a close conformity with a theoretical background.

II. Multiple and Split-Phase Decomposition Space Vector Transformation

A. Multiple space vector transformation

Numerical illustration of a six-phase asymmetrical system can be represented by multiple space vectors as given below [6, 23-24, 29-32]:

$$\begin{cases} \bar{x}_1 = \frac{1}{3}\left[x_1 + x_2\alpha^4 + x_3\alpha^8 + x_4\alpha + x_5\alpha^5 + x_6\alpha^9\right] \\ \bar{x}_3 = \frac{1}{3}\left[(x_1 + x_2 + x_3) + j(x_4 + x_5 + x_6)\right] \\ \bar{x}_5 = \frac{1}{3}\left[x_1 + x_2\alpha^8 + x_3\alpha^4 + x_4\alpha^5 + x_5\alpha + x_6\alpha^9\right] \end{cases} \tag{1}$$

To be noted α = *exp* (*j*π/6), spatial displacement between windings [10].

The multiple space vectors $\bar{x}_1, \bar{x}_3$ and $\bar{x}_5$ are the sub-zones i.e. d_1-q_1, d_3-q_3, and d_5-q_5 respectively. To introduce for dual three-phase open-windings supplied by four isolated DC source VSIs. Now, the six-phase system can be split into two three-phase sub-systems {1} and {2} as [6-7, 23, 29-32]:

$$\{1\}\begin{cases} x_1^{(1)} = x_1 \\ x_2^{(1)} = x_2 \\ x_3^{(1)} = x_3 \end{cases}, \quad \{2\}\begin{cases} x_1^{(2)} = x_4 \\ x_2^{(2)} = x_5 \\ x_3^{(2)} = x_6 \end{cases}. \tag{2}$$

The arbitrary rotating space vectors $\bar{x}^{(1)}$, $\bar{x}^{(2)}$ and the zero-sequence components, $x_0^{(1)}$, $x_0^{(2)}$ are defined for each three-phase sub-system {1} and {2} as:

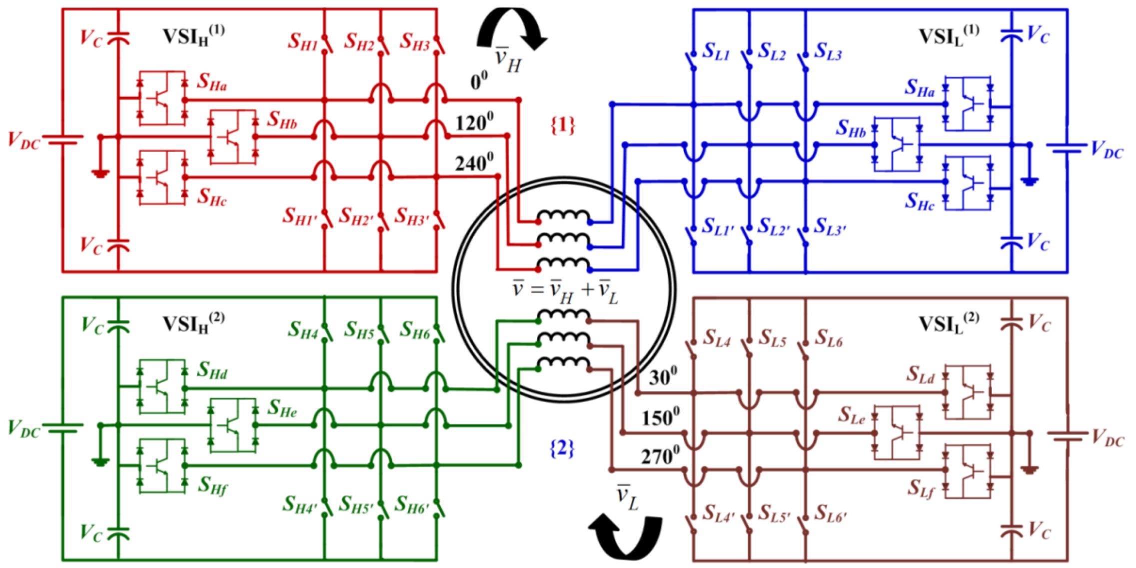


Fig. 1. Proposed configuration of quad-inverter system for asymmetrical six-phase open-winding multilevel converter for medium power application (low-voltage/high-current).

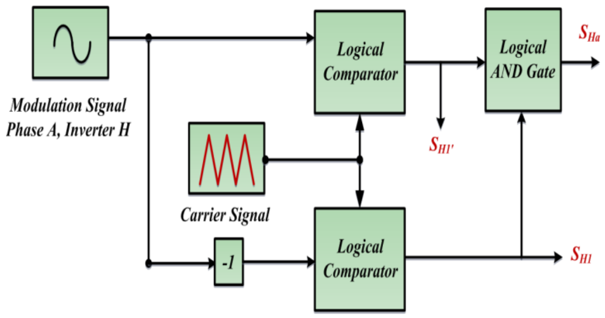


Fig. 2. Multilevel modulation scheme with one carrier for phase ‘a’ of inverter $VSI_H^{(1)}$.

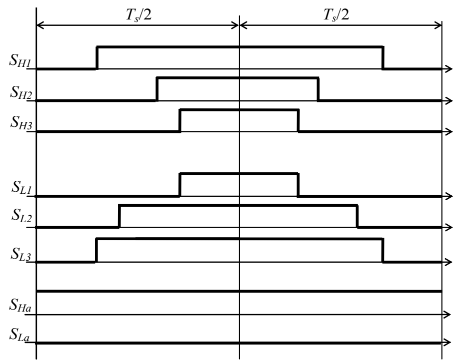


Fig. 3. PWM pattern of inverters $VSI_H^{(1)}$ (top-three) and $VSI_L^{(1)}$ (bottom-three) modulation Index = 0.8).

$$\{1\}\begin{cases}\bar{x}^{(1)} = \frac{2}{3}\left[x_1^{(1)} + x_2^{(1)}\alpha^4 + x_3^{(1)}\alpha^8\right] \\ x_0^{(1)} = \frac{1}{3}\left[x_1^{(1)} + x_2^{(1)} + x_3^{(1)}\right]\end{cases} ;\{2\}\begin{cases}\bar{x}^{(2)} = \frac{2}{3}\left[x_1^{(2)} + x_2^{(2)}\alpha^4 + x_3^{(2)}\alpha^8\right] \\ x_0^{(2)} = \frac{1}{3}\left[x_1^{(2)} + x_2^{(2)} + x_3^{(2)}\right]\end{cases} \tag{3}$$

Now, multiple space vectors and split-phase space vectors are related by substituting Eq. 2 and Eq. 3 in Eq. 1 and emphasized as below:

$$\begin{cases}\bar{x}_1 = \frac{1}{2}\left[\bar{x}^{(1)} + \alpha\,\bar{x}^{(2)}\right] \;;\bar{x}_5^* = \frac{1}{2}\left[\bar{x}^{(1)} - \alpha\,\bar{x}^{(2)}\right] \\ \bar{x}_3 = x_0^{(1)} + j\,x_0^{(2)}\end{cases}. \tag{4}$$

$$\begin{cases}\bar{x}^{(1)} = \bar{x}_1 + \bar{x}_5^* \\ x_0^{(1)} = \bar{x}_3 \cdot 1\end{cases}, \begin{cases}\bar{x}^{(2)} = \alpha^{-1}\left(\bar{x}_1 - \bar{x}_5^*\right) \\ x_0^{(2)} = \bar{x}_3 \cdot j\end{cases}., \tag{5}$$

Noted, where the symbols “*” and “·”denote the complex conjugate and scalar (dot) product, respectively.

III. Quad-Inverter Single Carrier Based Five-Level Modulation Algorithm

The total power P of the dual three-phase inverter can expressed as the sum of the power of the two three-phase windings {1} and {2} ($VSI_H^{(1)}$, $VSI_L^{(1)}$, $VSI_H^{(2)}$, $VSI_L^{(2)}$) [5-7, 21-23, 29-32]:

$$P = P^{(1)} + P^{(2)} = \frac{3}{2}\bar{v}^{(1)}\cdot\bar{i}^{(1)} + \frac{3}{2}\bar{v}^{(2)}\cdot\bar{i}^{(2)}$$
$$P = P^{(1)} + P^{(2)} = \frac{3}{2}\left[\left(\bar{v}_H^{(1)} + \bar{v}_L^{(1)}\right)\cdot\bar{i}^{(1)} + \left(\bar{v}_H^{(2)} + \bar{v}_L^{(2)}\right)\cdot\bar{i}^{(2)}\right] \tag{6}$$

Now, if the bi-directional switch per phase and two capacitors with neutral are neglected in the Fig. 1, the resultant transferred circuit is standard two-level inverters. Then, modulations are carried out like a standard VSIs. By space vector theory, the output voltage vector $\bar{v}$ of the dual three-phase inverter can be expressed as the sum of the voltage vectors of two three-phase windings $\bar{v}^{(1)}$ {1} and $\bar{v}^{(2)}$ {2} by the four three inverters ($VSI_H^{(1)}$, $VSI_L^{(1)}$, $VSI_H^{(2)}$, $VSI_L^{(2)}$), as given below [5-7]:

$$\bar{v} = \bar{v}^{(1)} + \bar{v}^{(2)} \tag{7}$$

By splitting six-phase windings into standard two three-phase windings then Eq. 7 by considering Eq. 3 then the modulating vectors can represent for first and second three-phase windings as below:

$$\bar{v}^{(1)} = \bar{v}_H^{(1)} + \bar{v}_L^{(1)} \tag{8}$$

$$\bar{v}^{(2)} = \bar{v}_H^{(2)} + \bar{v}_L^{(2)} \tag{9}$$

By considering Eq. 4, then Eq. 8 for inverters $VSI_H^{(1)}$ and $VSI_L^{(1)}$, the modulating vector can be expressed as:

$$\begin{aligned}\bar{v}_H^{(1)} &= \frac{1}{3}V_{DC}\left(S_{H1} + S_{H2}e^{j2\pi/3} + S_{H3}e^{j4\pi/3}\right) \\ \bar{v}_L^{(1)} &= -\frac{1}{3}V_{DC}\left(S_{L1} + S_{L2}e^{j2\pi/3} + S_{L3}e^{j4\pi/3}\right)\end{aligned} \tag{10}$$

$$\bar{v}^{(1)} = \frac{1}{3}V_{DC}\begin{pmatrix}S_{H1} + S_{H2}e^{j2\pi/3} + S_{H3}e^{j4\pi/3} - \\ S_{L1} + S_{L2}e^{j2\pi/3} + S_{L3}e^{j4\pi/3}\end{pmatrix} \tag{11}$$

Similar by considering Eq. 4, then Eq. 9 for inverters $VSI_H^{(2)}$ and $VSI_L^{(2)}$, the modulating vector can be expressed as:

$$\begin{aligned}\bar{v}_H^{(2)} &= \frac{1}{3}V_{DC}\left(S_{H4}\alpha + S_{H5}\alpha e^{j2\pi/3} + S_{H6}\alpha e^{j4\pi/3}\right) \\ \bar{v}_L^{(2)} &= -\frac{1}{3}V_{DC}\left(S_{L4}\alpha + S_{L5}\alpha e^{j2\pi/3} + S_{L6}\alpha e^{j4\pi/3}\right)\end{aligned} \tag{12}$$

$$\bar{v}^{(2)} = \frac{1}{3}V_{DC}\begin{pmatrix}S_{H4}\alpha + S_{H5}\alpha e^{j2\pi/3} + S_{H6}\alpha e^{j4\pi/3} - \\ S_{L4}\alpha + S_{L5}\alpha e^{j2\pi/3} + S_{L6}\alpha e^{j4\pi/3}\end{pmatrix} \tag{13}$$

By substituting Eq. 11 and Eq. 13 in Eq. 7, therefore, now the arbitrary modulating vector for dual three-phase inverter can be predicted as [5-7, 21-23]:

$$\overline{v}=\frac{1}{3}V_{DC}\begin{pmatrix}S_{H1}+S_{H2}e^{j2\pi/3}+S_{H3}e^{j4\pi/3}-\\ S_{L1}+S_{L2}e^{j2\pi/3}+S_{L3}e^{j4\pi/3}\end{pmatrix}+ \\ \frac{1}{3}V_{DC}\begin{pmatrix}S_{H4}\alpha+S_{H5}\alpha e^{j2\pi/3}+S_{H6}\alpha e^{j4\pi/3}-\\ S_{L4}\alpha+S_{L5}\alpha e^{j2\pi/3}+S_{L6}\alpha e^{j4\pi/3}\end{pmatrix} \quad (14)$$

To be noted switching states, upper-states $\{S_H, S_{H1}, S_{H2}, S_{H3}$ $S_{H4}, S_{H5}, S_{H6}\}$, $\{S_L, S_{L1}, S_{L2}, S_{L3}, S_{L4}, S_{L5}, S_{L6}\}$ = {1}, {0} of the inverter legs (VSI-H and VSI-L). Assumed balanced conditions, no zero-sequence currents in the system then Eq. 14 can be rewritten as four separate three-phase VSIs. For preliminary investigation, the analysis on the proposed converter are performed with single carrier based 5-level modulation is adapted in this paper [28]. The modulating reference signals are compared against the standard triangular carrier to provide maximum utilization of DC buses and the ability to generate multilevel operation. Extension can be performed with the power sharing regulation in symmetrical /asymmetrical conditions can be performed between the four DC sources of the inverters H and L.

Fig. 2 shows the single carrier (MSCFM) modulation algorithm for inverter $VSI_H^{(1)}$, generate 5-level across the leg-phase 'a'. The same strategy is applied to all other leg-phases (b, c, d, e, f, g) of VSIs H and L, keeping the proper phase-shift between the reference modulating signals as shown by Fig. 1. To be noted, for the phase 'a', switch S_{Ha} and S_{La} to be modulated throughout the fundamental cycle, i.e. swaps between {1, 0} with switching period. Switch S_{H1} modulated half of the fundamental period (first-half) {1} and retains {0} second half. Where reversely applied to the switch S_{L1} modulated half of the fundamental period (first-half) {0} and retains {1} second half. To be noted, the same strategy is applied to other phases (b, c, d, e, f) to generate a five-level outputs. Correspondingly, the switch pattern of the proposed 5-level modulation for inverters $VSI_H^{(1)}$ and $VSI_L^{(1)}$ is shown in the Fig. 3 for modulation index of 0.8.

IV. Numerical Simulation Results and Discussion

TABLE I. MAIN PARAMETERS OF DUAL THREE-PHASE MULTILEVEL VSIS.

DC Bus	V_{DC}	= 200Volts
Load Resistances	R	= 8 Ω
Load Inductances	L	= 10mH
Fundamental Frequency	F	= 50Hz
Switching Frequency	F_S	= 5 KHz
Capacitors	V_C	= 2200μF

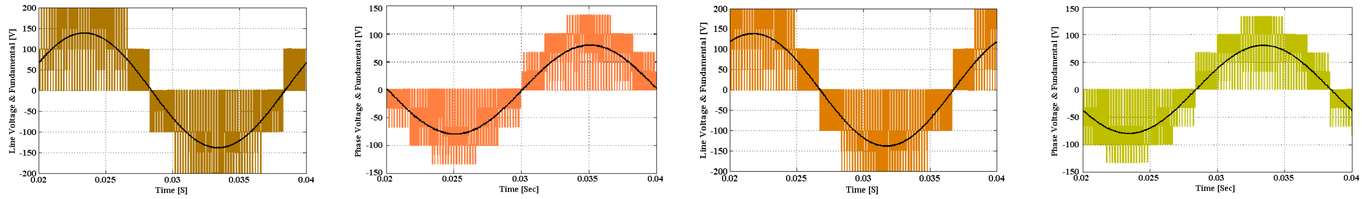
Table I elaborates the parameters taken for feasibility of testing and to verify the effectiveness the complete AC drive system numerically developed by simulation software package (Matlab/PLECS). The test conducted under the balanced conditions by fixing modulation index of four inverters ($VSI_H^{(1)}$, $VSI_L^{(1)}$, $VSI_H^{(2)}$, $VSI_L^{(2)}$) to 0.8 and overall modulation index of dual three-phase inverter is 0.8. Fig. 4 shows the complete simulation behavior of the system under symmetrical operation. Fig. 4(A) and Fig. 4(B) are the generated line-line voltage of inverters $VSI_H^{(1)}$ and $VSI_L^{(1)}$, with its time scale averaged fundamental components of first three-phase windings {1}. It is observed that they are out of phase with respect to each other. Fig. 4(G) and Fig. 4(H) are the generated line-line voltage of inverters $VSI_H^{(2)}$ and $VSI_L^{(2)}$, with its time scale averaged fundamental components of second three-phase windings {2}. Also, here it is observed that they are out of phase with respect to each other. Further, it is confirmed by the results that each single VSIs are modulated at 5-level of the developed modified single carrier five-level modulation (MSCFM) algorithm. Hence, it is proved that each VSIs are capable of generating multilevel output irrespective of open-windings/star-windings networks and overcomes the drawback of addressing dual inverter configurations [2-11, 21-27].

Fig. 4(C) and Fig. 4(D) are the artificially calculated phase 'a' voltage of inverters $VSI_H^{(1)}$ and $VSI_L^{(1)}$, with its time scale averaged fundamental components of first three-phase windings {1}. It is confirmed from the results that inverters generated 7-level of stepped wave which is actually predicted. Generated fundamental components in the agreement to Eq. 10 and they are out of phases to each other. Fig. 4(I) and Fig. 4(J) are the artificially calculated phase 'a' voltage of inverters $VSI_H^{(2)}$ and $VSI_L^{(2)}$, with its time scale averaged fundamental components of first three-phase windings {2}. Also, here it is confirmed from the results that inverters generated 7-level of stepped wave which is actually predicted. Generated fundamental components in the agreement to Eq. 12 and they are out of phases to each other. Further, it is verified that the fundamental components of the phase voltages generated are of same amplitudes and shown the balanced smooth operation (modulation index = 0.8).

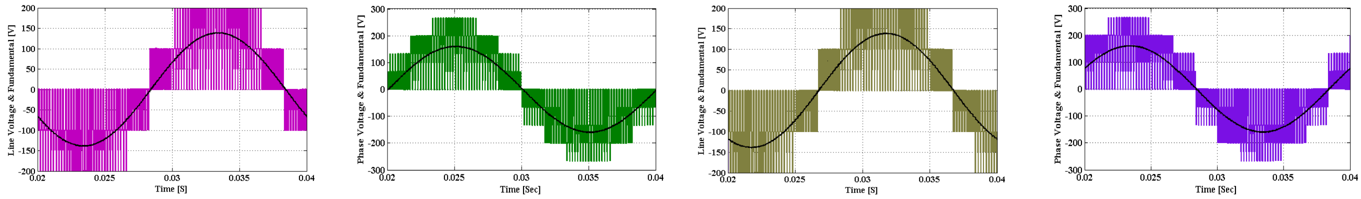
Fig. 4(E) and Fig. 4(K) are the generated phase voltage of the first-phase of a first three-phase open-winding (phase 'a') {1} and the first-phase of a second three-phase open-winding (phase 'd') {2} along with its time scale averaged fundamental component. First, it confirmed that the voltage generated are 7-levels in both open-windings and obtained amplitude is the vector addition of phase voltages of inverters ($VSI_H^{(1)}$, $VSI_L^{(1)}$) and ($VSI_H^{(2)}$, $VSI_L^{(2)}$). It is observed in both line-line and phase voltages are arbitrarily phase shifted by 30^0 between dual inverters ($VSI_H^{(1)}$, $VSI_L^{(1)}$) and ($VSI_H^{(2)}$, $VSI_L^{(2)}$) of two three-phase windings {1} and {2}.

Six-phase open-winding currents are shown in Fig. 4(F) (first three-phase {1}) and Fig. 3(L) (second three-phase {2}). It is observed that generated currents are sinusoidal in nature and equally balanced in amplitude with proper phase shifts of 30^0 between first three-phase windings {1} and second three-phase windings {2}. Conformity is shown that quad-inverter modulated sinusoidally by VSIs, propagates in balanced conditions and shares the total power among the four isolated DC sources. Finally, this preliminary test confirms the satisfactory behavior of the multiphase-multilevel inverter performances and shown good agreement with theoretical background.

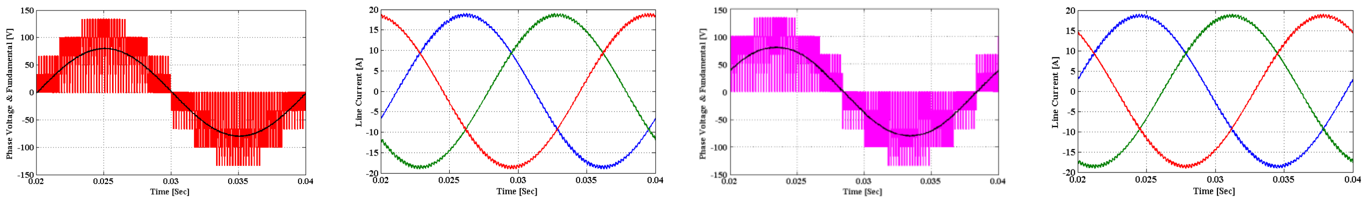
Finally, the trajectories of the six-phase currents are represented in alpha-beta (α-β) rotating planes as shown in Fig. 5. The total electrical power is equally shared among four inverters ($VSI_H^{(1)}$, $VSI_L^{(1)}$, $VSI_H^{(2)}$, $VSI_L^{(2)}$), as predicted the rotating component moves along a circular trajectory (at -



(A). Line–line voltage of inverter $\mathbf{VSI_H^{(1)}}$. (D). Artificially measured first-phase voltage of inverter $\mathbf{VSI_L^{(1)}}$. (G). Line–line voltage of inverter $\mathbf{VSI_H^{(2)}}$. (J). Artificially measured first-phase voltage of inverter $\mathbf{VSI_L^{(2)}}$.

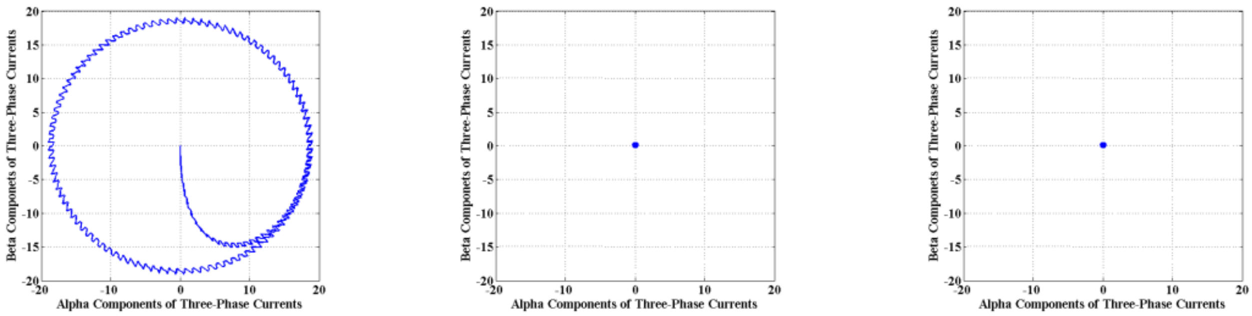


(B). Line–line voltage of inverter $\mathbf{VSI_L^{(1)}}$. (E). First-phase voltage across the open-winding ($\mathbf{VSI_H^{(1)}}$ and $\mathbf{VSI_L^{(1)}}$). (H). Line–line voltage of inverter $\mathbf{VSI_L^{(2)}}$. (K). First-phase voltage across the open-winding ($\mathbf{VSI_H^{(2)}}$ and $\mathbf{VSI_L^{(2)}}$).



(C). Artificially measured first-phase voltage of inverter $\mathbf{VSI_H^{(1)}}$. (F). First three-phase currents of the open-windings ($\mathbf{VSI_H^{(1)}}$ and $\mathbf{VSI_L^{(1)}}$). (I) Artificially measured first-phase voltage of inverter $\mathbf{VSI_H^{(2)}}$. (L). Second three-phase currents of the open-windings ($\mathbf{VSI_H^{(2)}}$ and $\mathbf{VSI_L^{(2)}}$).

Fig. 4. The numerical simulation behavior of the proposed quad-inverter based asymmetrical six-phase multilevel converter and modulation index of inverter ($VSI_H^{(1)}$, $VSI_L^{(1)}$, $VSI_H^{(2)}$, $VSI_L^{(2)}$) = 0.8 kept for balanced operation. Voltages are depicted with its corresponding time averaged fundamental components.



d_1-q_1 first sub-space. d_5-q_5 fifth sub-space. d_3-q_3 third sub-space.

Fig. 5. Trajectories of six-phase currents in sub-spaces of α-β rotating planes, first sub-space (right), fifth sub-space (middle), and third sub-space (left).

constant frequency) as shown by Fig. 5(left). Again, conformity is shown that each VSIs are modulated sinusoidally with developed PWM strategy throughout the propagation period. Further, the fifth sub-space (leakage components) and the third sub-space (common-mode/zero-sequence components) trajectories confirm that null as is given by Fig. 4(middle) and Fig. 4(left). It is concluded that the balanced operation of the quad-inverter is guaranteed by four VSIs.

V. Conclusion

A novel multiphase-multilevel open-winding converter based on four standard three-phase voltage source inverter configuration presented in this article. An original modified single carrier five-level modulation (MSCFM) algorithm also proposed and ensures each single VSIs (H and L) generates 5-level, multi-stepped waveforms as outputs and overcomes the drawback of standard dual-inverter versions. Confirmatory results are obtained by numerical modeling shown that the lower order harmonics are suppressed in the outputs with balanced power operations among four isolated DC sources. Proposed quad-inverter topology effectively utilized for multiple batteries or fuel-cells fed system for medium power, AC tractions and 'More-Electric Aircraft' (MEA) applications. Reliable under circumstances of asymmetrical available DC sources without affecting its multilevel operation subjected to quadrupling the power by four VSIs. Investigation is kept still under developments to frame a proper optimized multilevel (5-level) based on the carrier based or space vector modulation PWM generation methods with asymmetrical conditions for near future works.

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