Experimental implementation a PWM strategy for dual three-phase PMSM using 12-sector vector space decomposition applied on electric ship propulsion

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ABSTRACT
The current paper aims at presenting and examining an implementation on a digital signal processor (DSP) of the conventional space vector pulse width modulation (CSVPWM) so as to control the dual three phase permanent magnet synchronous motors (DTP-PMSM) drives applied on electric ship propulsion. It is also an attempt to accomplish a developed control of this technique based on vector space decomposition (VSD) strategy. By this strategy, the analysis and the control of the machine are achieved in three two-dimensional orthogonal subspaces. Among the 12 voltage vectors having maximum, the conventional technique namely the adjacent two-vectors (12SA2V) is chosen. Thereby, the test platform allows the implementation of the chosen vectors which are modeled on MATLAB/Simulink using block diagrams and the automatically generated code which is targeted in the DSP card processor. Simulation and experimental results have exposed the efficiency of the proposed test bench of 5 KW prototype machine by using a low-cost TMS32F28379D.

Keywords:
Current harmonics
Digital signal processor
DTP-PMSM
Electric ship propulsion
Space vector modulation
Vector space decomposition

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1. INTRODUCTION
Since the 1980s, the introduction of electric propulsion systems for use in ships offers various advantages. This electric propulsion has various benefits that are ships maneuverability, maintenance and acoustic noise. Several researches relating to the electric propulsion system have been addressed to minimize the occurrence of marine environmental pollution and maintenance costs in civil and military ships. Therefore, electric propulsion has seen a remarkable development in the last years and many ships are now electrically propelled equipped [1, 2].

Multiphase machine drives have many improvements over three-phase machine drives like lower torque pulsations, harmonic currents and higher reliability. Effectively, the increase of the number of phases allows a segmentation of the power and hence a reduction of the voltages switched to a given current, where high performance requirements are more needed. Multiphase drives are existing in the maritime domain, automobile, and avionics [3-10]. The most used type of multiphase drives is the dual-three phase (DTP)
machines. These are distinguished by a multiphase structure within the same stator frame such as two stars having similar characteristics which are spatially shifted by 30 electrical degrees [1].

Permanent magnet synchronous motors (PMSM) have been widely examined as viable solution for variable velocity electric drives ship propulsion notably. Nowadays, the use of multiphase PMSM has become widely used in the training of high-power systems. Among these machines, dual three phase permanent magnet synchronous motors (DTP-PMSM) has been used in many applications like electric propulsion. It has a high defect toleration and dependability [8, 11]. Nevertheless, the machines concerned have considerable harmonic content while being supplied by a pulse width modulation (PWM) inverter.

Spatial modulation namely space vector PWM (SVPWM) control using the vector space decomposition theory (VSD) is mainly used in recent control of DTP-PMSM and induction machines to get sinusoidal waveforms at the inverter outputs [12-17]. This technique is examined and developed in this paper. Under this control approach, the model of the overall machine, for instance; fundamental, harmonic and components of zero sequence, is changed and divided into three decoupled subspaces and inscribed in three separate space coordinates, marked and nominated in the order given as, (α,β): the subspace of torque-component, (z₁,z₂): the subspace of harmonic-component and (oz₁,oz₂): the subspace of zero-sequence [1, 18-23]. The main components and its harmonics take part in the conversion of the energy of electromechanical. While, the current components (z₁, z₂) and (oz₁, oz₂) do not participate to the change of the energy of electromechanical. Therefore, the stator resistance and the leakages inductance symbolize the only obstacle [24-26]; similarly, the additional harmonic currents generate only stator losses.

In this paper conventional modulation based on the choice of adjacent two-vectors (12SA2V) is proposed with SVPWM control of DTP-PMSM using 12-sector VSD applied on electric ship propulsion [27-28]. The purpose is to get an implementation on DSP. In order to justify the simulation results, an experimental test, is fulfilled. What remains of present work is organised as follows: Section 2 deals with the machine model which will be shown based on VSD; Section 3 discusses the proposed PWM approach in detail; Section 4 comprises simulation results; Sections 5-6 discuss the experimental results followed by Conclusion and References.

2. MACHINE’S DYNAMIC MODEL

The following two Figures 1 and 2 represent the machine windings structure and their supply sources, these double windings of three-phase stator are shifted in the space, with an electrical angular offset of 30 degrees with two unconnected neutral points [29].

![Figure 1. Drive system and its power supply](image1)

![Figure 2. Windings of the machine](image2)

Depending on the VSD theory [11], the transformation matrix can be identified by (1).
The difficult motor system is divided into three mutually decoupled orthogonal subspaces (α-β), (z₁, z₂) and (o₁, o₂). The variables equations characterizing the machine, according to the indicated suppositions in [16], can be specified in stationary model by:

\[
\begin{align*}
[p_{\alpha\beta}] & = [R_s][i_{\alpha\beta}] + \frac{d}{dt}[\Psi_{\alpha\beta}] = [R_s][i_{\alpha\beta}] + \frac{d}{dt}[L_{\alpha\beta}][i_{\alpha\beta}] + \Psi_{PM}[\cos \Theta] \\
[p_{z1z2}] & = [R_s][i_{z1z2}] + \frac{d}{dt}[\Psi_{z1z2}] = [R_s][i_{z1z2}] + [L_{z1z2}] \frac{d}{dt}[i_{z1z2}] \\
[p_{o1o2}] & = [R_s][i_{o1o2}] + \frac{d}{dt}[\Psi_{o1o2}] = [R_s][i_{o1o2}] + [L_o] \frac{d}{dt}[i_{o1o2}]
\end{align*}
\]

Where:
- \((L_d, L_q)\) : Direct and indirect inductances;
- \((L_s, L_o)\) : Transformed of inductances conventional and mutual leakage;
- \((\Psi_{PM})\) : Permanent magnet flux;
- \((\Theta)\) : Rotor position.

The current components in the (α-β) subspace contribute to the conversion of electromechanical. Nevertheless, the variables of current in (z₁, z₂) and (o₁, o₂) do not participate effectively in the conversion of electromechanical which generates losses of stator. The conversion matrix should be used to illustrate the immobile (α, β) plane in the revolving plane (d, q) which is presented as follows [30]:

\[
T_r = \begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
\sin \theta & -\cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

In the (d-q) plane, the electric and the mechanic equations of the machine are expressed as follows:

\[
\begin{align*}
[p_{d}] & = [R_s][i_{d}] + \frac{d}{dt}[\Psi_{d}] + \frac{d}{dt}[\Psi_{q}] = [R_s][i_{d}] + \frac{d}{dt}[L_o][i_{d}] + \frac{d}{dt}[L_q][i_{q}] + \sqrt{3}\psi_{PM}[\sin \Theta] \\
I_{em} & = p(i_d\Psi_d - i_q\Psi_q) \quad (p : \text{Number pair poles})
\end{align*}
\]

3. RESEARCH METHOD
3.1. SVPWM strategy for DTP- PMSM

In machine drives control, the current approach tends to define the (α-β) frame as being the reference of the stator voltage vector produced by the control system. After that, the harmonics coming out in the planes (z₁, z₂) and (o₁, o₂) only generate losses. To minimize these harmonics, the middling voltage vectors generated in the two planes should be zero [31]. The following equation can express the phase voltages:

\[
\begin{align*}
[p_{a1}] & = \begin{bmatrix} 2 & -1 & -1 \end{bmatrix} \\
[p_{b1}] & = \begin{bmatrix} -1 & 2 & -1 \end{bmatrix} \\
[p_{c1}] & = \begin{bmatrix} -1 & -1 & 2 \end{bmatrix} \\
[p_{a2}] & = \begin{bmatrix} 0 & 0 & 2 \end{bmatrix} \\
[p_{b2}] & = \begin{bmatrix} 0 & 0 & -1 \end{bmatrix} \\
[p_{c2}] & = \begin{bmatrix} 0 & 0 & -1 \end{bmatrix}
\end{align*}
\]

While \((S = S_{a1}, S_{b1}, S_{c1}, S_{a2}, S_{b2}, S_{c2})\) are the states of switch, \(E\) is the continuous bus.
According to relationship (1), the voltage vectors expressed in the two referentials can be specified by the following relationship:

\[
\begin{bmatrix}
V_\alpha \\
V_\beta \\
V_{z1} \\
V_{z2} \\
V_{01} \\
V_{02}
\end{bmatrix} = T \begin{bmatrix}
V_{a1} \\
V_{b1} \\
V_{c1} \\
V_{a2} \\
V_{b2} \\
V_{c2}
\end{bmatrix}
\]

(9)

The machine drive comprises 64 diverse voltage vectors. A number of decimals is matching to binary numbers and regarded in the following classify \([S_{a1} S_{a2} S_{b1} S_{b2} S_{c1} S_{c2}]\). It is used to stand for each vector. Consequently, in the submodels (\(\alpha - \beta\)) and (\(z_1 - z_2\)), there are 60 vectors with non null voltage and 4 null ones (0, 7, 56, 63) which are expressed in two Figures 3 and 4 [32].

![Figure 3. Illustration of space vectors using VSD in (\(\alpha - \beta\))](image1)

![Figure 4. Illustration of space vectors using VSD in (\(z_1 - z_2\))](image2)

According to the two above figures, the (\(\alpha - \beta\)) vectors of voltage can be divided into four dodecagons with diverse amplitudes (from innermost to outermost: \(D_1, D_2, D_3, D_4\)) [33] which are expressed as follows:

\[
\begin{align*}
U_{D1} &= \frac{\sqrt{(2-\sqrt{3})}}{\sqrt{3}} E \\
U_{D2} &= \frac{1}{\sqrt{3}} E \\
U_{D3} &= \frac{\sqrt{2}}{\sqrt{3}} E \\
U_{D4} &= \frac{\sqrt{(2+\sqrt{3})}}{\sqrt{3}} E
\end{align*}
\]

(10)

The voltage vectors, having an utmost magnitude in the (\(\alpha - \beta\)) subspace, will have a smallest magnitude in the (\(z_1 - z_2\)) subspace; however, the others retain the same magnitude.

### 3.2. 12-Sector conventional modulation (12SA2V)

In this strategy, the 12 and the 24 voltage vectors which have respectively highest and half amplitude share the (\(\alpha - \beta\)) subspace into 24 sectors. The vectors of voltage chosen allow to obtain the minimum amplitude vectors in the (\(z_1 - z_2\)) subspace, which warrants the least current content of harmonics in the (\(z_1 - z_2\)) subspace. Therefore, contribute to the minimization of losses [3].

The vectors of voltage having highest magnitude (45-37-36-52-42-18-26-27-11-9-41) allow synthesizing the reference voltage vector \(V_{ref}\) as shown in Figure 5. In accordance with the site of the reference voltage vector \(V_{ref}\) in the (\(\alpha - \beta\)) subspace as shown in Figure 3, this idea is the same as the conventional method. Just two adjacent voltages are employed to synthesize the reference voltage vector \(V_{ref}\). Take the example where the reference voltage vector is placed in sector \(S_1\), the two attached voltage vectors (37-36) and null voltage vectors (7-56) are used. The period corresponding to each voltage vector is defined by the relationship as follows:
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4. RESULTS AND DISCUSSION

4.1. MATLAB/Simulink Simulation

In the third section, the approach suggested will be reasonably investigated via Matlab/Simulink environment and experimental test. The principal characteristics of the DTP-PMSM, through a 5 KW model machine for ship propulsion are enumerated in the simulation tests provided in Table 3. According to the simulation results, the load torque is set at 15 N.m, the machine velocity is maintained at 300 rpm and the drive switching frequency is fixed at 5 kHz. The Figures 7 to 10 illustrate the simulation tests of the exposed approach.

As it can be seing from the simulation results, we can notice that the current of stator phase is not purely sinusoidal and that the large current harmonic appears in motor phase current for the conventional SVPWM technique as shown in Figures 7-8. In fact, the phase current, has a great quantity of the 5th and the 7th order harmonics of current that are dominant. The total harmonic distortion (THD) is 63.7%. Conversely, the amplitude of the 5th and the 7th order current harmonics is extremely important. It is worth pointing out that these constituents of stator current do not participate to the air gap flux and will simply cause energy losses. Figure 9 stands for the currents in (α-β) subspace which have a smooth and a normal trajectory for this method. The response of velocity is showed in Figure 10; the speed gets its mention with good static and dynamic presentation.

Table 3. Machine’s principal components

| Designation                              | Value/unit |
|------------------------------------------|------------|
| DC continous bus : E                    | 200 V      |
| Resistance of stator : R_s               | 1.096 Ω    |
| Inductance direct : L_d                  | 8.45 mH    |
| Inductance quadrature : L_q              | 8.45 mH    |
| Flux of permanent magnet : Ψ_PM          | 0.184 Wb   |
| Moment of total inertia: J               | 93.10^-3 kgm^2 |
| Coefficient of total viscous friction : f| 0.01 Nms/rad |
| Pair poles number: p                     | 3          |

Figure 7. Stator phase current

Figure 8. Harmonic analysis (FFT)

Figure 9. Trajectory of space current vectors in two subspaces: (a) (α-β) and (b) (z1-z2)

Figure 10. Machine’s speed
4.2. Experimental Based on TMS320F28379D

So as to approve the possibility of the recommended SVPWM technique, a set of tests is fulfilled. The photograph of experimental results is shown in Figure 11. This latter is consisting of a dual three phase voltage source inverter (VSI) supplying a 5 KW experimental setup machine, and the entire control strategy is tested on a DSP TMS320F28379D card processor. In fact, it is feasible to apply the 12-sector PWM technique related to the implemented SVPWM technique.

The experimental results which use conventional technique with the similar characteristics and working conditions like those of tests, are expressed in Figures 12-14. Figures 12 and 13 are the experimental tests equivalent to the simulation results of Figures 7 and 8, respectively. Figure 14 is the experimental result equivalent to the simulation result of Figure 10. There is a reliable association between the experiments and the simulations results. The suggested PWM strategy is successfully experimented and the resulting assumptions can be drawn from these experimental tests: In this technique, the phase current is not purely sinusoidal and has a harmonics great quantity, the 5th and the 7th particularly. The latter two, appearing in the \( (z_1-z_2) \) subspace, are very large because and cause signal distortion due to the absence of control over currents in the \( (z_1-z_2) \) subspace. This shows the feasibility of the suggested strategy.

Figure 14 illustrates the machine velocity under the double open loop control strategy. It also indicates the rapid speed response of the control system. This stabilizes at a 300-rpm value.
5. CONCLUSION

The principal goal of the suggested work is to carry out an implementation on SVPWM conventional method to control the DTP-PMSM drives. In fact, the SVPWM using the conventional adjacent two voltage vectors (12SA2V) modulation has been presented under stator current total harmonic distortion (THD). After that, this method has been applied on DSP board TMS32F28379D. In the tests, the sensor of current is sampled by the control of open-loop. As deduced from the simulation results, the conventional SVPWM control based on vector space decomposition gives reasonable results regarding the experimental tests. It has been confirmed that the suggested method can be easily implemented digitally versus other methods using four voltage vectors whose implementation will be the subject of a future article. The farther investigation will concentrate on the detailed experimentations for the DTP-PMSM.

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