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Article

Comparative study and overview of field-oriented control techniques for 6-phase PMSM

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Abstract: The paper interprets a comparison of two mostly used techniques of a field-oriented control for 6-phase electric drives, with their pros and cons, as well as their differences in construction and behaviour. Both of these approaches have been realized. Frequency and step responses analysis have been demonstrated with a 6-phase permanent magnet synchronous machine. Experimental results have been compared with simulations based on a mathematical model.

Keywords: permanent-magnet motors, electrical drives, torque and speed control, multiphase machine, 6-phase machine, field-oriented control, multiphase variable speed drives

1. Introduction

Multiphase electric machines have been highly discussed in recent years by worldwide professionals, where the term "multiphase" refers to machines with more than 3 phases. Results of various authors describe improvement in: efficiency, harmonic spectrum of MMF, lower phase current and torque ripple, plus the most significant parameters fault-tolerance and redundancy of a system [1-5]. For an attribute of the lower phase current are multiphase machines used in high-power (MW) applications such as huge cargo-ships, where all system features can be dimensioned to a lower level of a load capacity, because of the system parallelization, when compared with the use of their better-known 3-phase counterparts [6],[7]. All this advantages are of course dependent on many variables, given especially by a particular design of a machine. Various numbers of phases are used towards applications where *5,6,9,12,15*-phase machines are mostly mentioned. As the most preferred are 6-phase electrical machines and it's not just because of the possibility to control a drive by two conventional 3-phase VSIs. Nowadays, 6-phase electrical machines lead in the field of critical applications, where a higher level of the redundancy, safety and fault-tolerant behaviour is required [8-10].

Permanent magnet synchronous machines in general, are used in a large set of applications, where the exception is not an automotive industry. From comfort facilities towards electrical starters, pumps and power steering, to hybrid/main traction electric drives, PMSM found the place. This kind of electrical machines is often controlled by a well-known field-oriented control.

Several ways for realization of the field-oriented control can be accomplished with the 6-phase PMSM. In various applications and research works, two main approaches can be recognized according to a number of current controllers used for torque and flux producing components of a whole machine. One of them is the whole 6-phase machine reflected as the one entity, where control works in the one orthogonal system. Another approach looks onto the 6-phase machine like on two 3-phase machines in parallel and the control is divided into two orthogonal systems, each for the one 3-phase set. Both of these techniques were already realized in the past three decades by several authors with various, high-level, additional algorithms for a drive quality improvement.

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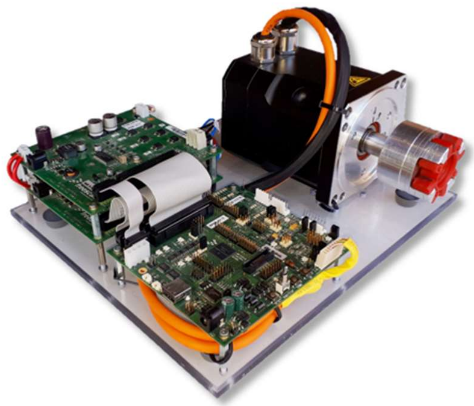
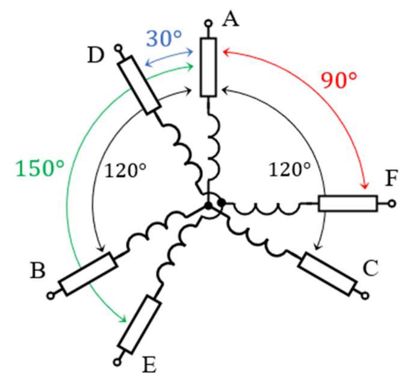
This paper demonstrates and summarizes characteristics, advantages and disadvantages of the two mentioned methods in comparison to each other, mainly from the software control application point of view. In chapters II. and III. the control methods are introduced, with synchronous reference frame orientation, in chapter IV. more details, problems and benefits are discussed. Finally, pros and cons are summarized in discussion with a focus on a fault-tolerant control unit realization.



a)



b)

Figure 1. a) 6-phase setup b) machine phases configuration.

An experimental verification has been demonstrated on the setup depicted in Figure 1 a). The phases configuration of the 6-phase PMSM is sketched in Figure 1 b). Towards the past, as the most advantageous a *30°* shift between 3-phase systems was clarified by several authors, because of the best reduction of the higher harmonic distortion in MMF and consequently in the produced torque [1],[2]. This configuration of the six-phase machine with the mechanical shift between 3-phase sets of windings different from *0°* or *60°* is often called as an asymmetrical 6-phase machine. As well the machine used in this experiment has the *30°* shift between two sets of star-connected 3-phase windings, with so called a dual-star configuration. The dual-star means that each 3-phase star has a separated neutral point. If these points are joint together, the whole machine has the one common neutral point for all 6 phases, then the configuration is called a single-star. The machine has been supplied by two standard 3-phase converters with a one common DC-bus. Both converters have been controlled by one microprocessor *MPC5643L (NXP)*. Currents have been sensed by shunt resistors and a resolver has been used as a speed sensor.

2. Control in two orthogonal systems

For a better overview an abbreviation “2 d-q” has been established in this paper as two orthogonal systems. This approach is also known as dual, modular or multiple 3-phase control of n x 3-phase machine ($n = 2,3,4,\ldots$) presented in [11-17]. As mentioned 3-phase field-oriented control is well-known among engineers of electric drives, even for control of two separated 3-phase PMSM by one microprocessor. Such an approach is taken over for control of the 6-phase machine where a control structure is adapted to a common speed loop as depicted in Figure 2.

Two identical control structures run in parallel, each for the one 3-phase system, where in the second system a transformation angle is shifted by *-30°* in direct and inverse Park transformations. Similarly, an n x 3-phase system can be controlled by functions intended for the control of conventional 3-phase machines, limited by MCU power and peripheral set. The point of connection for two parallel systems is in the speed loop, because the machine still contains just one shaft and produces one mechanical torque. In the 2 d-q control, all functions known for control of 3-phase machines can be used and a shape of Clarke transformations or modulation function doesn't need any change.

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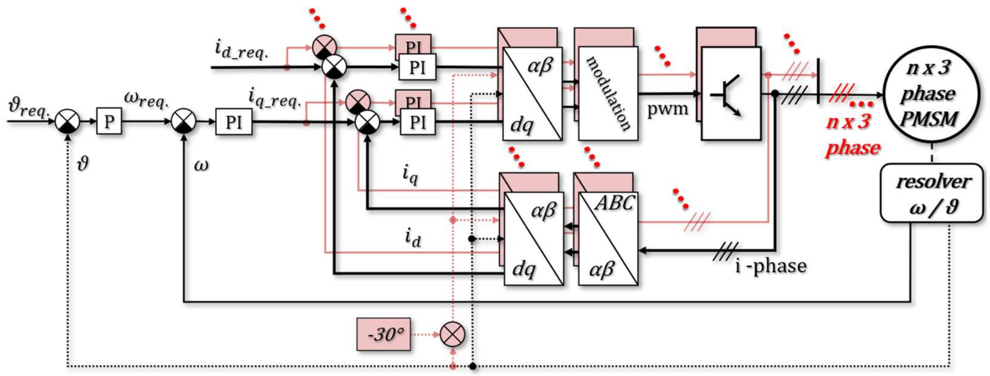

Figure 2. Field-oriented control structure 2 d-q.

As the result of the 2 d-q control approach, two aligned sets of d-q currents/voltages in the rotor reference frame can be observed as two current loops run in parallel, controlled by separated, individual current controllers. As well two sets of α-β orthogonal values in stator reference frame can be recognized where standardly α1 is aligned to phase A and β1 lead the α1 by *90°*, while second orthogonal set α2,β2 is shifted by *-30°* from the first one, as shown in Figure 3.

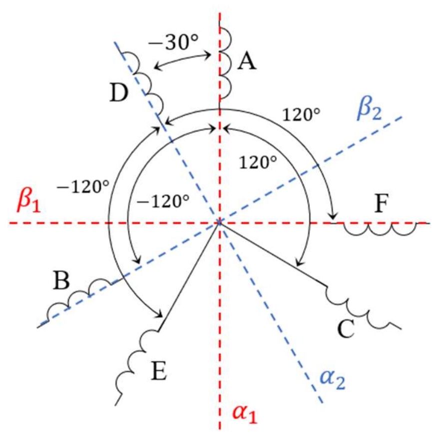

Figure 3. Axis orientation in 2 d-q system.

$$A_1, B_1, C_1 \rightarrow k = 1, \vartheta_{shift} = 0°$$

$$A_2, B_2, C_2 \rightarrow k = 2, \vartheta_{shift} = -30°$$

$$A_2, B_2, C_2 \Leftrightarrow D, E, F$$

$$i_{\alpha k} = i_{Ak} \tag{1}$$

$$i_{\beta k} = \frac{1}{\sqrt{3}}(i_{Bk} - i_{Ck}) \tag{2}$$

$$V_{Ak} = V_{\alpha k} \tag{3}$$

$$V_{Bk} = \frac{1}{2}(-V_{\alpha k} + \sqrt{3}V_{\beta k}) \tag{4}$$

$$V_{Ck} = \frac{1}{2}(-V_{\alpha k} - \sqrt{3}V_{\beta k}) \tag{5}$$

$$i_{dk} = i_{\alpha k}\cos(\vartheta_r + \vartheta_{shift}) + i_{\beta k}\sin(\vartheta_r + \vartheta_{shift}) \tag{6}$$

$$i_{qk} = i_{\beta k}\cos(\vartheta_r + \vartheta_{shift}) - i_{\alpha k}\sin(\vartheta_r + \vartheta_{shift}) \tag{7}$$

$$V_{\alpha k} = V_{dk}\cos(\vartheta_r + \vartheta_{shift}) - V_{qk}\sin(\vartheta_r + \vartheta_{shift}) \tag{8}$$

$$V_{\beta k} = V_{qk}\cos(\vartheta_r + \vartheta_{shift}) + V_{dk}\sin(\vartheta_r + \vartheta_{shift}) \tag{9}$$

3. Control in one orthogonal system

Furthermore, for a better overview an abbreviation “1 d-q” has been established in this paper, as the one orthogonal system. This approach is also known as the two controllers method and various modulation techniques might be applied as shown in chapter IV. With inclusion of higher harmonic control it's known as Vector Space Decomposition

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(*VSD*) method [5],[18-30]. An approach of the 1 d-q field-oriented control, specified to a 6-phase system is shown in Figure 4. A whole control structure is shaped like a standard one, for the 3-phase machine control. Parallel operation of current loops is not required, since the structure contains just one set of flux/torque producing components for the whole 6-phase system. On the other hand, transition sections between 6-phases and the one orthogonal system in both direct and inverse ways, have to be done by functions specified for a number of phases in a controlled machine.

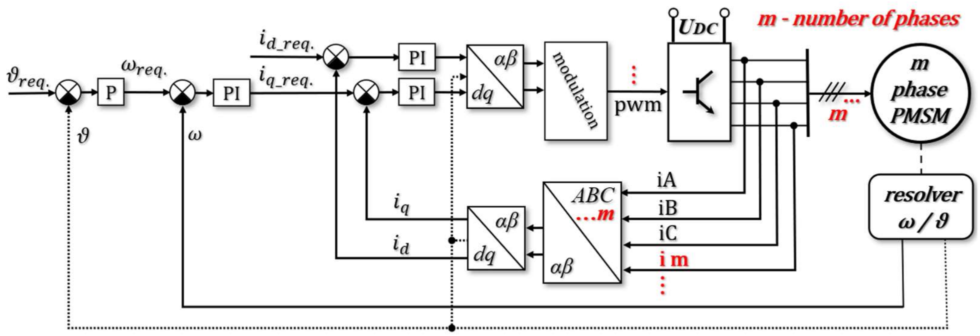

Figure 4. Field-oriented control structure 1 d-q.

Park transformations between an orthogonal rotor reference frame d-q and a stationary α-β reference frame are the same as the one used in the standard field-oriented control of the 3-phase PMSM. In this case, just the one orthogonal α-β system can be recognized, where α is aligned to phase A and β lead the α by *90°* as depicted in Figure 5. Also, just one set of d-q stator currents/voltages can be observed.

$$i_{\mathrm{d}} = i_\alpha \cos(\vartheta_r) + i_\beta \sin(\vartheta_r) \quad (10)$$

$$i_{\mathrm{q}} = i_\beta \cos(\vartheta_r) - i_\alpha \sin(\vartheta_r) \quad (11)$$

$$V_\alpha = V_{\mathrm{d}} \cos(\vartheta_r) - V_{\mathrm{q}} \sin(\vartheta_r) \quad (12)$$

$$V_\beta = V_{\mathrm{q}} \cos(\vartheta_r) + V_{\mathrm{d}} \sin(\vartheta_r) \quad (13)$$

Clark transformations in inverse and direct ways have been reconstructed under the rule of the generalized Park transformation with a zero position reference frame (Figure 5). This approach can be used for any number of phases according to known parameters: angles between phases, a number of phases and an arbitrary parameter, the reference frame position of the orthogonal α-β system. With a use of the 6-phase machine where at least one 3-phase star is convectional, balanced, symmetrical system with *120°* between phases, an advantage can be taken into an account. This first system can be calculated with the standard 3-phase Clark transformations and the other phases will be added into transformations equations according to their angles to the reference frame.

The transformation between the n-phase and the orthogonal system is always recalculated by coefficients of a proportion. For example with $k_d = k_q = 2/3$ for 3-phase machines, the transformed system is power non-invariant (an amplitude invariant) and the same applies to the 2 d-q system, described in the previous chapter. Transformations to the 1 d-q system with $k_d = k_q = 2/3$, will lead to a behaviour of a system with a double gain, so neither the power nor the amplitude is invariant. With the requirements of the amplitude invariant behaviour, the coefficients of a proportion $k_d = k_q = 2/6$ have been used [35]. The proposed transformation can be used for variable angle (ϑ_{shift}) between two symmetrical 3-phase systems. For the machine examined in this paper $\vartheta_{shift} = -30°$.

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$$V_A = \quad V_\alpha \tag{14}$$

$$V_B = \frac{1}{2}\left(-V_\alpha + \sqrt{3}V_\beta\right) \tag{15}$$

$$V_C = \frac{1}{2}\left(-V_\alpha - \sqrt{3}V_\beta\right) \tag{16}$$

$$V_D = \cos(\; - \vartheta_{\text{shift}})\, V_\alpha + \sin(\; - \vartheta_{\text{shift}})\, V_\beta \tag{17}$$

$$V_E = \cos\left(\;\frac{2}{3}\pi - \vartheta_{\text{shift}}\right) V_\alpha + \sin\left(\;\frac{2}{3}\pi - \vartheta_{\text{shift}}\right) V_\beta \tag{18}$$

$$V_F = \cos\left(-\frac{2}{3}\pi - \vartheta_{\text{shift}}\right) V_\alpha + \sin\left(-\frac{2}{3}\pi - \vartheta_{\text{shift}}\right) V_\beta \tag{19}$$

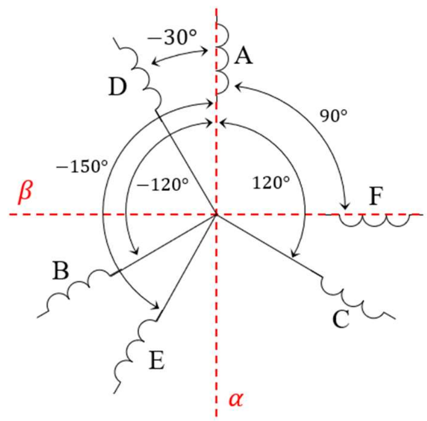

Figure 5. Axis orientation in 1 d-q system.

$$i_\alpha = \frac{2}{6}\left(\frac{3}{2}\, i_A + \cos(\vartheta_{shift})\, i_D + \right.$$
$$\left. + \cos\left(-\frac{2}{3}\pi + \vartheta_{shift}\right) i_E + \cos\left(\frac{2}{3}\pi + \vartheta_{shift}\right) i_F\right) \tag{20}$$

$$i_\beta = \frac{2}{6}\left(\frac{\sqrt{3}}{2}(i_B - i_C) - \sin(\vartheta_{shift})\, i_D - \right.$$
$$\left. - \sin\left(-\frac{2}{3}\pi + \vartheta_{shift}\right) i_E - \sin\left(\frac{2}{3}\pi + \vartheta_{shift}\right) i_F\right) \tag{21}$$

4. System realization and comparison

The aim of standard electric motor control is to supply a machine with phase voltages in the same order, shift and shape as the EMF of the supplied machine. Transformations carry a big impact to this requirement in the field-oriented control. Their correctness can be verified by a comparison of phase currents order, shift and shape in a motor mode with phase EMF sensed by oscilloscope in a generator mode, over the same direction of a shaft rotation. For a correct phase identification is the record of the EMF required as well.

The same applies to PWM references, except for the shape, which is dependent on a used modulation technique and not always follows the shape of the EMF. In the most of real applications controlled by micro-processor, PWM references are inputs for a timer-compare unit, which generates control signals for power transistors. PWM references might be accomplished by many modulation techniques. Few of them will be discussed in the following section in the state of the art spirit with emphasis to the 6-phase design implementation.

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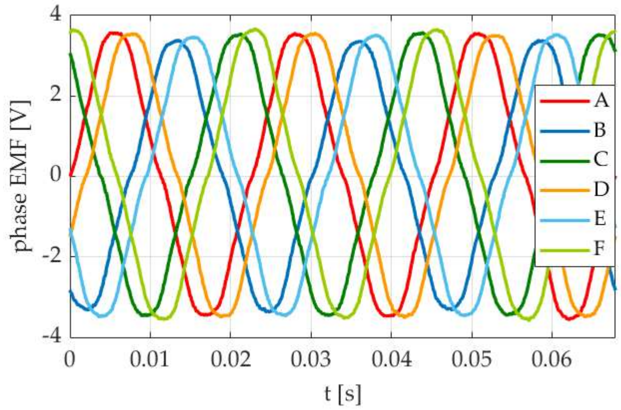

Figure 6. Phase electromotive force.

Modulation part of the 1 d-q control, can be accomplished for example by 12-sector diagram [18],[21],[31] (Figure 9 c), with separated 2x6 sector diagrams [21],[25] (Figure 9 b), or even 24 sector diagram [31]. The vector space decomposition (VSD) method is often used in the 1 d-q control approach, which was introduced in probably the most referred article by worldwide authors in the field of multiphase machines [18] with stationary reference frame. This technique is focused on harmonic spectra of stator currents, which might arise in 6-phase machine because of asymmetries and their elimination can be done, by various approaches, where the most beneficial for the impact of any kind of asymmetries (inverter, motor) is a VSD transformation to both synchronous and anti-synchronous reference frame [28]. VSD control of 6-phase machine is based on a transformation of phase values to an orthogonal z1z2 frame (by some authors xy frame [28]) through 5th harmonic arguments of goniometric functions. The transformation leads to a separation of currents i_{z1}, i_{z2}. This separated subspace represents unwonted higher harmonic currents of the order 5th , which are not torque/flux producing in the 6-phase machine with the configuration shown in Figure 1 b), but causes additional copper losses. For this reason, are i_{z1}, i_{z2} regulated to zero as explained in [18], [28].

As a matter of machine design, the asymmetries don't have to be present, with value demonstrated in [18] for every machine, or work conditions. Measured currents of the 6-phase PMSM investigated in this experiment shows that the impact of higher harmonics is minor in conditions near to a nominal load, as shown in Figure 7, while they are quite significant in lower level of stator currents as it is shown in Figure 8. Those harmonics might be caused by various system asymmetries including a dead-time effect.

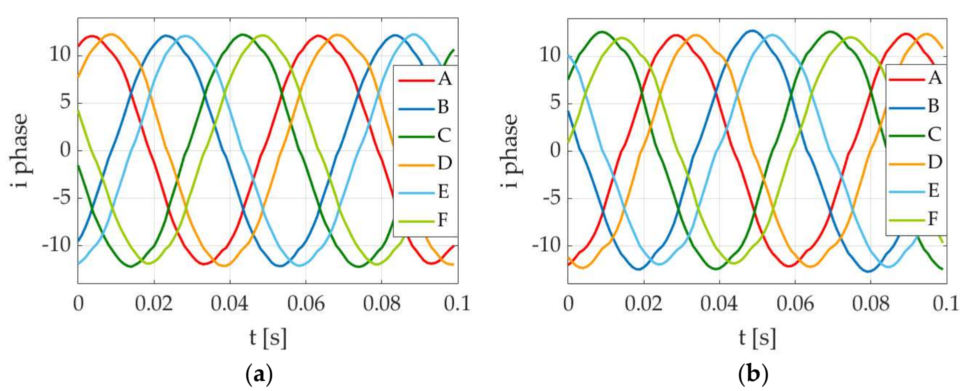

Figure 7. Phase RMS currents 8.5 A – a) 2 d-q , b) 1 d-q .

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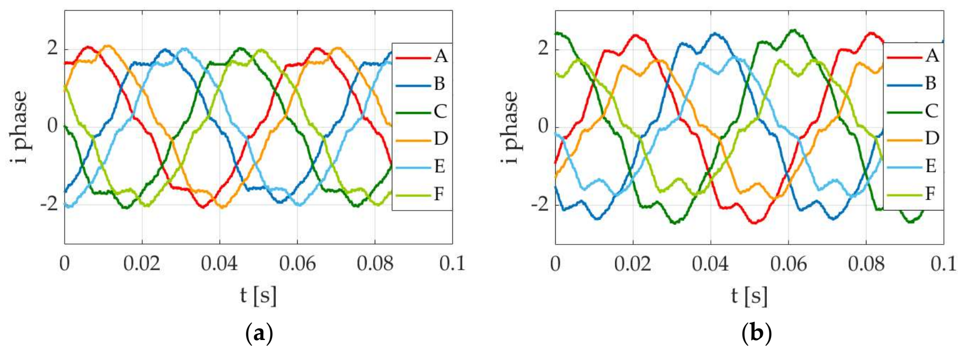

Figure 8. Phase currents reduced load – a) 2 d-q , b) 1 d-q .

For the 2 d-q control is a standard to use of well-known 6 sector modulation for control of 3-phase machines, with separately controlled inputs (Figure 9 a). To avoid the impact of the controlled system asymmetries, quite large decoupling algorithms are often used [33]. Some of the decoupling effects might be done by appropriate transformations, where the control structure starts to follow the VSD approach since required currents for the second orthogonal d-q system are zero [32]. VSD approach has been used for separated 3-phase control structures in [34].

So called double zero-sequence injection, which means 3th harmonic signal injected to every 3-phase system, can be utilized for a better DC-bus voltage use, as it is known from control of 3-phase machines and is reusable in n x 3 phase machines with separated neutral points, for every symmetrical 3-phase system [21],[25]. In the case of the 6-phase machine, it's an option for the dual-star configuration.

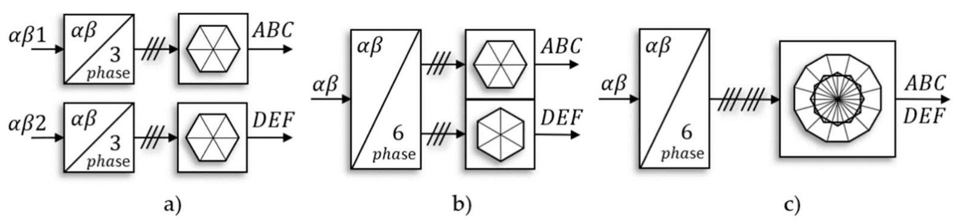

Figure 9. Basic modulation techniques a) 2d-q 2x6 sectors , b) 1d-q 2x6 sectors , b) 1d-q 12 sectors .

Modulation techniques shown in Figure 9 a) for 2 d-q control and Figure 9 b) for 1 d-q control have been realized, both with the double zero-sequence injection for an experimental part of this paper, as depicted in Figure 10. Steady-state current responses of this techniques are shown in Figures 7 and 8.

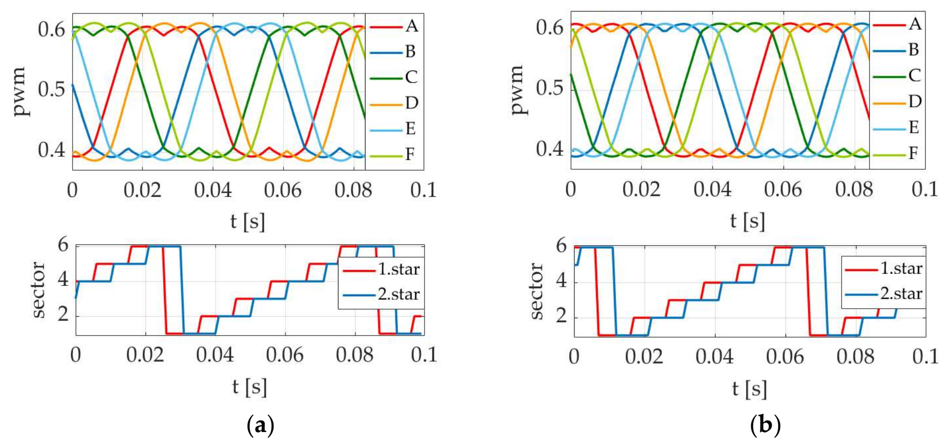

Figure 10. PWM references with double zero-sequence injection a) 2 d-q, b) 1 d-q .

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Another issue in multiphase systems is a current sharing. As shown in Figure 8, if hardware asymmetries are present in the n x 3-phase electric drive (n = 2,3,4,…), then for a better current/power sharing between 3-phase sets of windings the 2 d-q control, or the n d-q control is more convenient. The reason is, that individual RL circuits, which represents 3-phase windings, are controlled separately (dual-star configuration considered). This behaviour is almost negligible in Figure 7, around nominal load, but it's quite crucial with reduced load as shown in Figure 8. It can be seen from Figure 10, that in a purpose to keep amplitudes of phase currents at the same level, PWM references as a result of required voltages have with the 2 d-q control various amplitudes for the first and the second 3-phase systems. In the 1 d-q control might be the current sharing problem effectively handled by the VSD method, even when it's designed in default for the higher harmonics elimination [18],[28].

Table 1. Machine parameters.

P_N	$1\ kW$	R	$0.12\ \Omega$
m	6	L_d	$0.0005\ H$
n_N	$3000\ rpm$	L_q	$0.00052\ H$
I_N	$13.5\ A$	K_e	$0.0135\ Vs/rad$
$U_{DC\ N}$	$48\ V$	J	$0.0002586\ kg{*}m^2$

A current loop has been adjusted by inverse dynamic method, based on equality of a PI controller integrational time constant and a time constant of the motor electrical part (in 2 d-q system each current loop has been tuned separately). Speed and position loops have been adjusted by a pole-placement method [36], where zero in a transfer function of the speed loop caused by the speed PI controller, has been cancelled by a first order filter. Coefficients $k_d = k_q = 2/6$ are considered for 1 d-q control system as explained in chapter III., which leads to the same machine parameters transformed in the d-q system, for both 2 d-q and 1 d-q control, since 1 d-q system is now amplitude invariant too. Machine parameters are shown in Table 1. Measured data have been captured by run-time *FreeMaster* tool (*NXP*), imported to *Matlab* and compared to a simulation of the field-oriented control based on the mathematical model [36]. Frequency analysis has been executed and is performed for every control loop, to verify a behaviour of the system in dynamic states. Results are demonstrated by a comparison of two field-oriented control approaches for 6-phase electrical machines discussed in this paper.

4.1. Current Loop

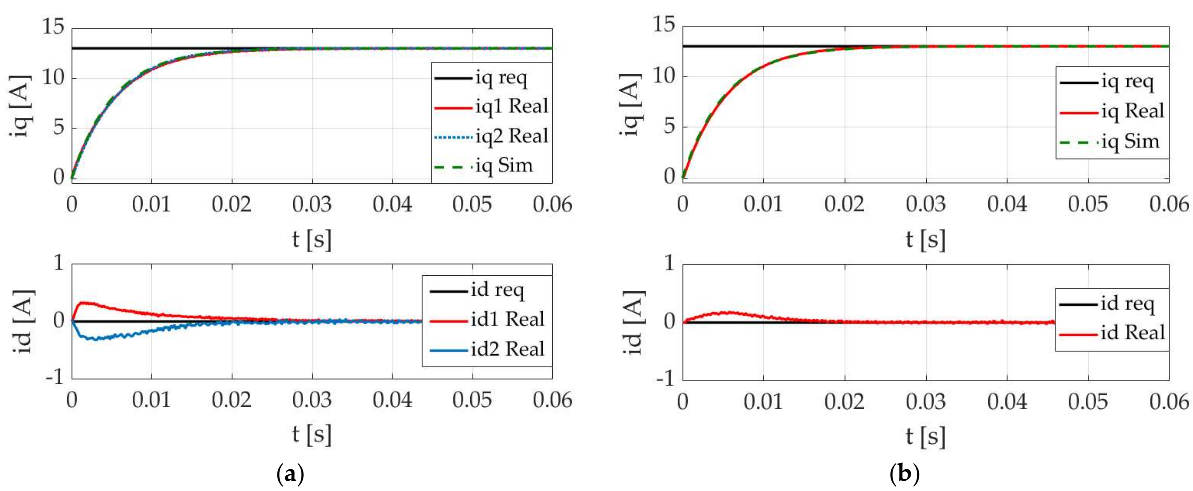

Figure 11. current loop step response – rotor fixed a) 2 d-q , b) 1 d-q .

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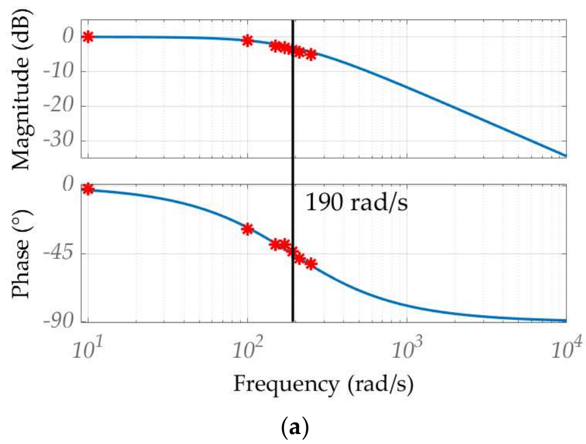

Figure 12. current loop frequency analysis – rotor fixed a) 2 d-q , b) 1 d-q .

4.2. Speed Loop

Losses in no-load conditions have been embedded in a simulation by an initial value of a torque load *0.07 Nm*. Experiments have been fulfilment with reduced power, due to a hardware limitations.

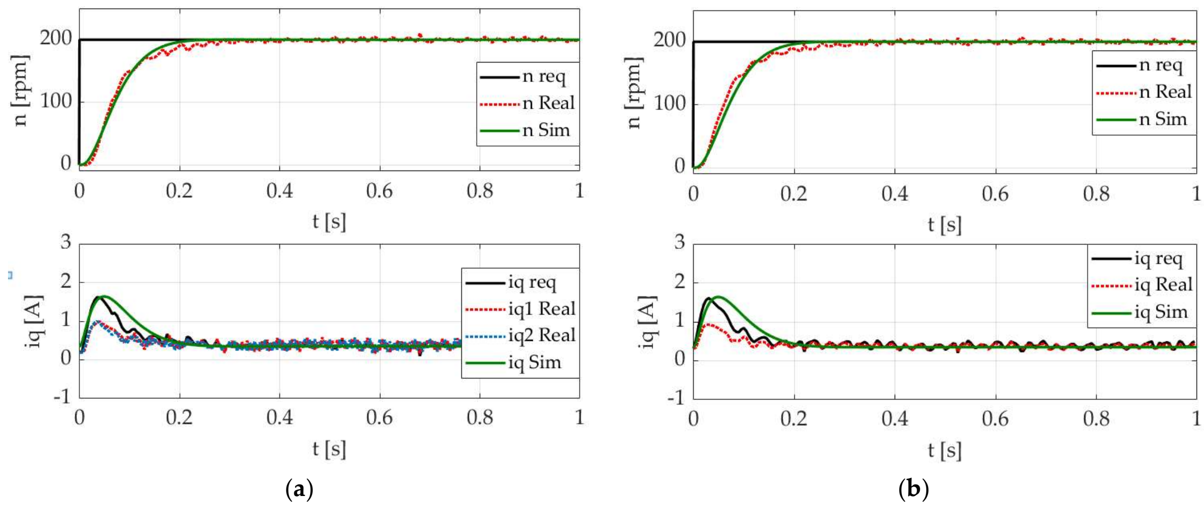

Figure 13. speed loop step response – no load a) 2 d-q , b) 1 d-q .

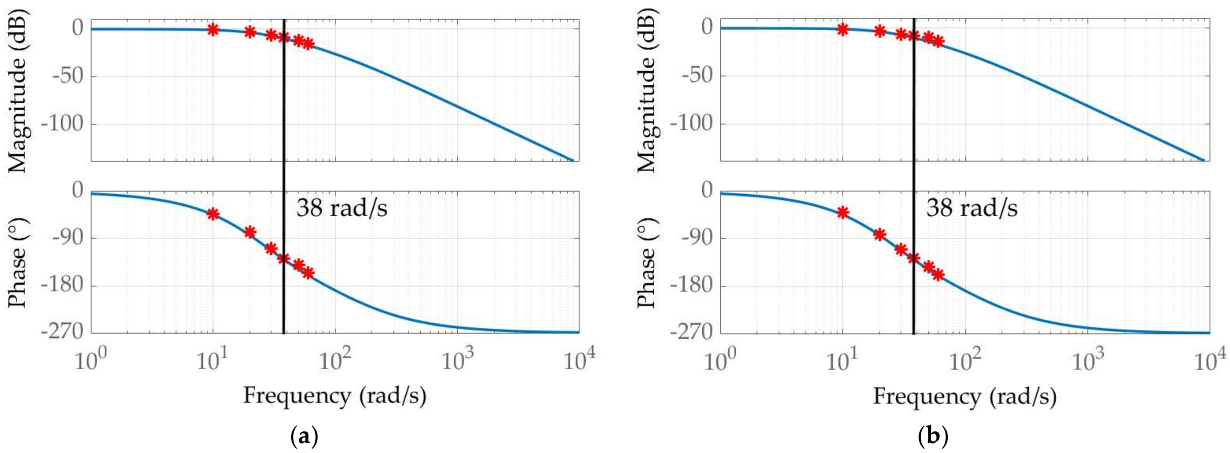

Figure 14. speed loop frequency analysis a) 2 d-q , b) 1 d-q .

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Speed control test with load (Figure 15), has been realized by coupling to a 3-phase permanent magnet synchronous machine. Moment of inertia and a friction of the load affects the test during a whole process, therefore it has been added to parameters of loaded machine for controllers adjustment and to simulations as well. At a time 0.7 s, setup has been loaded by electronical load connected to a winding of the 3-phase PMSM load. Measured results are significantly disturbed by a cogging torque of the 3-phase PMSM used as a load, anyway speed control is working for both the 2 d-q and the 1 d-q control as well, without any significant differences.

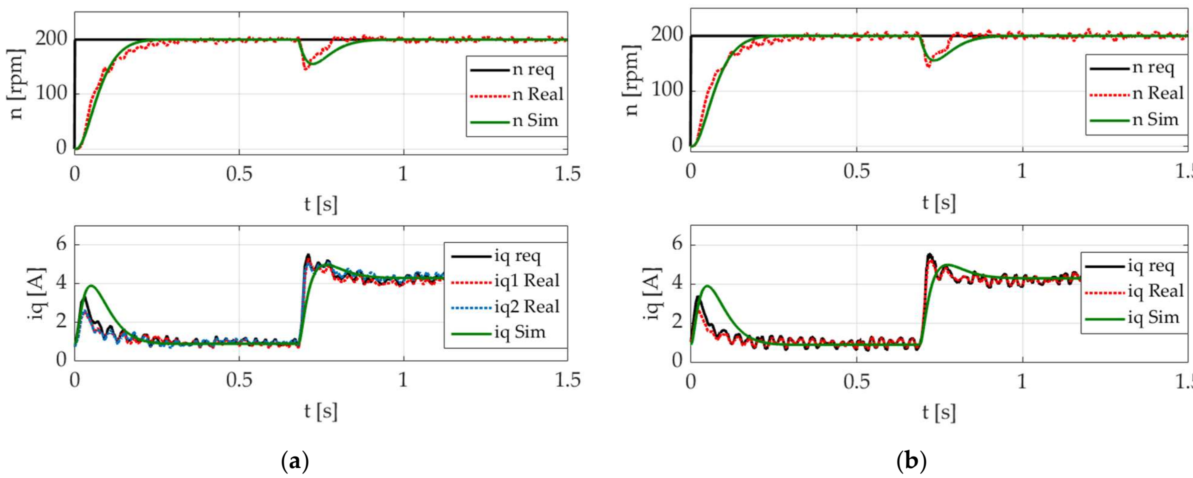

Figure 15. speed loop step response with load a) 2 d-q , b) 1 d-q .

4.3. Position Loop

Experiments and simulations (Figures 16, 17) are proposed without any load on a shaft. Both control techniques are useful, for all levels of cascade control (current-speed-position) constructed as the field-oriented control. Stator electrical values transformed to the synchronous rotational orthogonal reference frame, e.g. stator currents, indicate a same behaviour for both control approaches, however their real phase values varies as shown in Figure 8, especially with reduced load.

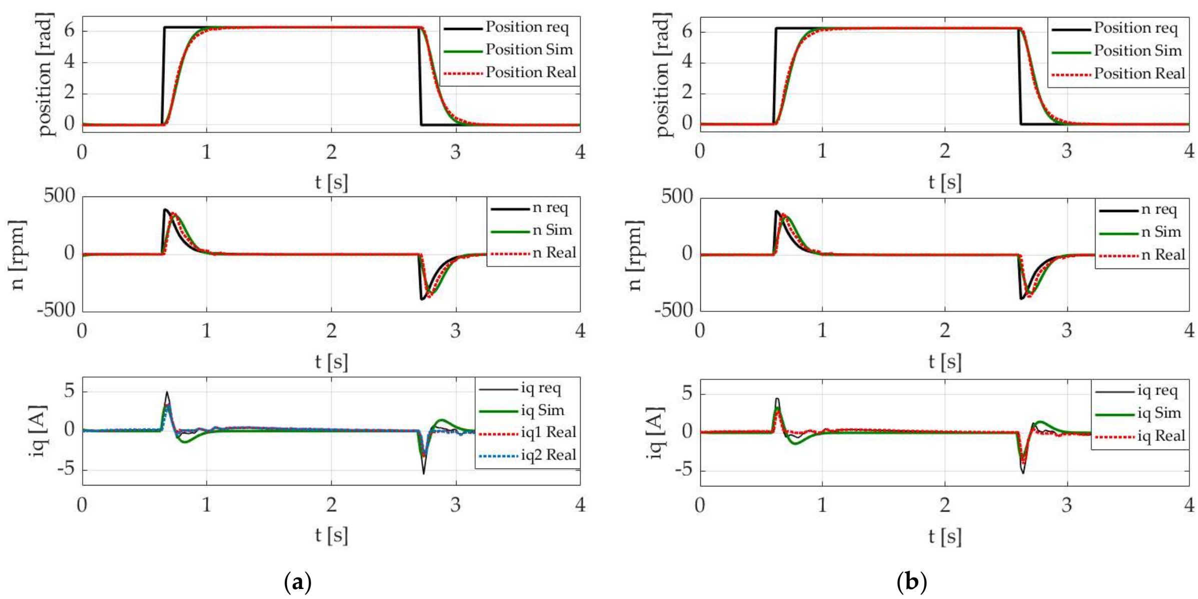

Figure 16. position loop step response a) 2 d-q , b) 1 d-q .

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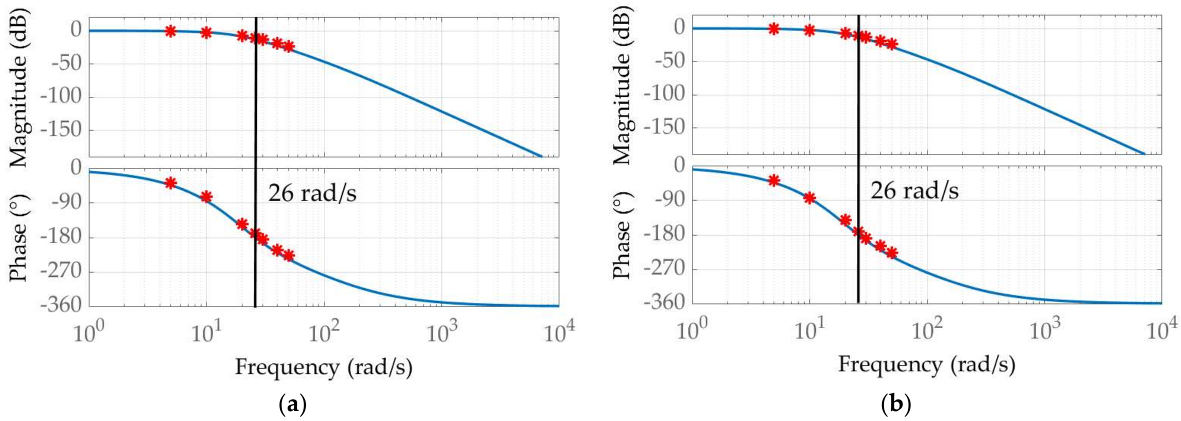


Figure 17. position loop frequency analysis a) 2 d-q , b) 1 d-q .

5. Discussion

Two approaches of the field-oriented control for the 6-phase PMSM have been segregated according to a number of current controllers for a flux and a torque producing components. Voltage modulation techniques overview has been presented, for both of them, where double zero-sequence modulation has been realized. To ensure a transparent and meaningful comparison of this two approaches and to show their real differences and problems in examined 6-phase PMSM, control structures have been demonstrated in the basic shape, without additional algorithms for a drive quality improvement.

Because two loops of a control algorithm run in parallel for the control in two orthogonal systems (2 d-q) shown in Figure 2, an execution time of the application might be longer than for the control in the one orthogonal system (1 d-q), shown in Figure 4. Such an application requires a more powerful MCU, which would lead to a higher price of a control unit or a longer sample time period, which leads to inaccuracies. This problem will be more significant in n d-q control, for 9, 12, 15… phases machines. The 1 d-q control technique requires a shorter computation time and also brings an advantage of a standard field-oriented control system, with only a one set of torque/flux producing components. On the other hand, the 2 d-q technique allows using a standard, well-known transformations for the control of 3-phase machines. Requirements for the execution time of a control algorithm would of course vary, with utilizing advanced algorithms, like VSD or various decoupling methods.

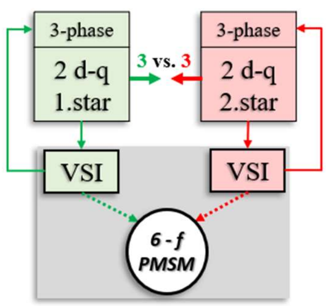
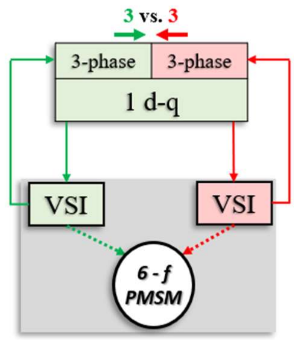
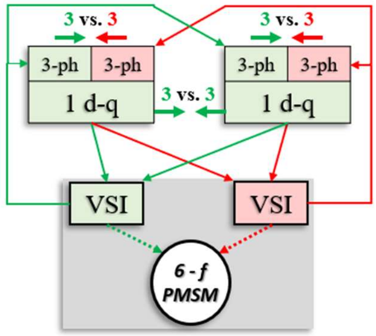
The 2 d-q technique is beneficial for natural current sharing between two 3-phase windings, across all load conditions (Figure 8). Since every 3-phase winding is controlled separately, various decoupling methods between them can be managed directly in the d-q control system. Nevertheless, the influence of the phase current higher harmonic spectra over the whole load conditions will not be cancelled in the 2 d-q, neither the 1 d-q control, without additional algorithms. To control harmonics and consequently to decrease the loses, the VSD method might be utilized, with shorter execution time for 1 d-q control, where current sharing problem will be solved by the VSD method too.

Both control approaches are able to achieve the same results of currents in synchronous reference frame, speed and position, as shown in Figures 11-17. This applies for standard operation, in steady-state and dynamic states as well. However, the same behaviour of two approaches doesn't apply for phase currents as shown in Figure 8.

In addition, the proposed results show correctness of mathematical models and transfer functions of both approaches, already presented by the author of this paper in [36]. Simulations of dynamic models are displayed in Figures 11, 13, 15 and 16 by green plots, by blue plots in Figures 12, 14 and 17, where red dots represents measured data.

As mentioned and highlighted before, a strong reason for multiphase machines applications is the redundancy. Not only the machine redundancy, but parallelization of the whole system, because of a safety attribute increasing. For this reason, the 2 d-q control technique seems to be more convenient. However it's all a software architecture question and a drive system with the 1 d-q control, can be assembled to the high safety requirements, where software control parallelization will keep the function, even in a fault state of a one 3-phase hardware part, as depicted in Table 2. Hardware power parts are in the grey sections, power paths are by dotted lines and signal paths are by solid lines.

Table 2. Fault system conditions.

2 d-q	1 d-q	1 d-q (redundant)
		

- healthy system conditions
- fault in one of a 3-phase hardware power system

In the case of a fault on one, or more phases in one 3-phase system, the system is identified and usually whole disconnected. A machine can continue with another 3-phase system in over-loaded conditions, or with half power. As follows from the information paths in control diagrams in Table 2., an identification of a fault in one of 3-phase hardware-power parts, can be executed in the 2 d-q control system from the values in two axis d-q frame, whereas in 1 d-q control structure the identification can be done, only from phase values. This fact doesn't put the 1 d-q control to the less valuable position, since the fault logic for every phase current is standard, in almost every motor control application.

On the other hand, the correctness of the control unit function, as another safety requirement, can be verified by comparison of whole algorithms running in parallel paths and compared to each other (Table 2.). Such a technique should be available even during the one 3-phase system fault condition, which can be more elegantly administrated in the 1 d-q control structure, because in the 2 d-q control would have to run four 3-phase control loops to achieve the same asset. For n x 3-phase machine controlled in n d-q control frames, it would require 2 x n control loops and consequently a quite large algorithm for the control unit safety compliance.

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