Modelling Approaches for an Asymmetrical Six-Phase Machine

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Abstract–**With currently available power electronic devices, the power range of a single three-phase power converter is limited well below the power ratings foreseen for remote offshore wind turbines. A solution is to use multiphase systems. By connecting each of the converters to one three-phase winding in the stator of the machine, a multiphase conversion system is obtained allowing to exploit its fault tolerance. In multiphase machines, the basic idea of the model transformations is the same as in the three-phase case, but, due to the increase in the dimension of the system, it introduces additional degrees of freedom. This work at first compares the two widely used modelling approaches regarding physical interpretation of the subspaces, harmonic mapping and representation of asymmetries applied to an asymmetrical six-phase machine. It further introduces an alternative transformation that is aimed at situations where power sharing between three-phase windings is desired and characterises its behaviour using the same figures of merit as for the existing transformations.**

I. Introduction

The purpose of the model transformation in ac machines is to obtain a new set of equations, usually fewer in number and less complex in nature, representing the machine's behaviour exactly as the original equations [1]. Initially applied to three-phase machines, the model transformation consists in referring the equations to a new reference frame constituted by three mutually orthogonal axes. Two of them are placed in the cross-sectional plane of the machine and are usually referred to as α-β or *d*-*q*. They represent the electromagnetic energy transfer across the airgap and constitute the so-called flux/torque producing subspace (α-β subspace herein after). The third axis, usually denoted as 0, represents the zero-sequence components and is seldom used, as, normally, the neutral point of the ac rotating machines is left isolated.

In recent times, extensive research on multiphase machine applications in electric vehicles, aerospace and ship propulsion has brought out some benefits of the multiphase machines and drives [2-3], such as:

i) The phase currents in a multiphase machine are reduced (compared to those in an equivalent three-phase machine) allowing to match them with the power semiconductor device capabilities.
ii) Multiphase machines and drives can continue to operate with one or more faulty phase, which increases overall reliability.
iii) Additional degrees of freedom, which exist in multiphase machines and are discussed next, can be used for numerous and diverse purposes – a feature that is not available in three-phase machines.

In multiphase machines with near-sinusoidal magneto-motive force (m.m.f.) distribution, considered here, the basic idea of the model transformations is kept the same but, due to the increase in the dimension of the system, it introduces additional degrees of freedom. There is again an α-β subspace representing the electromagnetic energy transfer across the airgap, but there appear additional, mutually orthogonal, subspaces whose components do not contribute to the energy transfer (*x*-*y* subspaces further on). The existence of the *x*-*y* subspaces introduces additional complications in the control as the currents in them do not give any benefit, but they may need to be controlled to avoid additional losses in the machine's stator windings and the converter [1, 4-6].

Regardless of the type of the machine (whether it is synchronous or induction), multiphase machines with near sinusoidal m.m.f. can be classified into two distinct types:

i) Machines with a prime number of phases, where spatial shift between any two consecutive phases is equal to $2\pi/n$ and there is a single neutral point [1, 7].
ii) Machines with an even number or a composite odd number of phases, which can be built with *k* windings, each having *a* phases, and where there may be a single or *k* neutral points. Such machines may have a spatial shift between the first phases of *k* windings with *a* phases equal to $2\pi/n$ (symmetrical machines) or π/n (asymmetrical machines) [8].

A specific design, that is usually of interest, is a situation with $a = 3$, in which case the total number of phases is $n = 3k$. In what follows, an asymmetrical six-phase machine, with 30° spatial shift between two three-phase windings is considered ($n = 6$, $k = 2$, $a = 3$), in typical configuration with two isolated neutral points.

A transformation (known as multiple *d*-*q* transformation), directly derived from that of three-phase machines, can be applied to multiphase machines with a number of phases $n = 3k$, $k = 2, 3, 4, \ldots$. In these machines, the *n*-dimensional domain can be divided into *k* three-dimensional domains each of which can be modelled as a three-phase machine. These *k* three-phase machines can be transformed into *k* common reference frames (flux/torque producing subspaces) by using trigonometric relations. The approach focuses on the flux/ torque producing subspace in which the energy conversion is represented, and "masks" in it the information about the other subspaces (the non-flux/torque producing) which have information about mutual interactions between the different three-phase systems that do not lead to energy conversion [9-10]. When this approach is used in conjunction with a six-phase machine, so called double *d*-*q* model results.

All the different transformation matrices for multiphase machines rely on the fact that the initial set of equations of a multiphase machine can be rearranged in the form of the equations of $(n-1)/2$ (for odd; $(n/2-1)$ for even phase numbers) mutually independent subspaces or submachines [11], with the remaining component(s) representing zero sequence. In this manner, control of each of the submachines becomes simple and control of all of them leads to control of the original multiphase machine. Examples can be found in [12-15]. It can be shown that all the modelling approaches described in [10-13] yield exactly the same results as those obtained with the so-called Vector Space Decomposition (VSD) approach, which was introduced in [16].

In [17], an analysis of the VSD approach for a nine-phase asymmetrical machine with a single neutral point is conducted. As the energy conversion is restricted to the first (flux/torque producing) plane, the VSD approach does not provide means to easily operate the machine with unbalanced current sharing between the three-phase systems. With this in mind, an alternative transformation is developed here. It is applied to an asymmetrical six-phase machine with two isolated neutral points and is aimed specifically at facilitating the current sharing between the different three-phase systems. Its full potential is likely to be fully utilisable in the control of machines with more than two three-phase windings. Further, properties of the novel transformation are compared to the multiple *d-q* and the VSD methods, in conjunction with a six-phase asymmetrical machine. The comparison focuses on aspects related to the harmonic mapping into different subspaces and reflection of imbalance between the three-phase systems in the transformed subspaces.

To obtain the physical interpretation of the different subspaces, transformations are compared to that of a three-phase machine applied to each of the three-phase systems. A correlation between the projections in the different subspaces and those from the three-phase transformation is sought. Assigning a physical interpretation to the non-flux/torque producing subspaces is not trivial as these can contain the information about the current sharing between the different three-phase systems. This can facilitate the control tasks in applications where different current (power) sharing between multiple three-phase systems is required, as the case may be in offshore wind turbine generating plants.

In general, three types of asymmetries can be found when operating an asymmetrical six-phase machine. For the comparison purposes, the following cases are considered:

i) CASE 1: Both three-phase systems are balanced but with different amplitudes (system number 1 at 1 p.u. and system number 2 at 0.9 p.u.)

ii) CASE 2: Both three-phase systems are equally unbalanced (phases *c* at 0.9 p.u.; all the other phases at 1 p.u.)

iii) CASE 3: Three-phase system no. 1 is balanced at 1 p.u., while system 2 is unbalanced, with two phases at 0.9 p.u.

For the analysis of the harmonic mapping, a six-phase voltage source supply is formulated to include the typical low-, medium- and high-order harmonics (up to the third side-band around the switching frequency), usually present in a power converter with sinusoidal PWM and dead time. For the sake of simplicity, a switching frequency of 1 kHz is selected, fundamental frequency is fixed at 50 Hz, and all the harmonics have the amplitude equal to 1 p.u.

In what follows the transformations are formulated and their behaviour investigated in accordance with the described conditions. The focus is purely on the decoupling transformation and, for simplicity, the resulting components are labelled with α–β, although the transformation is called multiple *d-q* (due to the subsequent rotating transformation application, which establishes the machine's model in the common rotating reference frame). In the asymmetry analysis, a rotational transformation into synchronous reference frame is also applied to the α-β components of the VSD and the novel transformation, and to components of both subspaces in the multiple *d-q* transformation (components are then labelled as *d-q*), so that any perturbation is easily observed as a deviation from a constant dc value.

II. Multiple *d-q* Transformation

The multiple *d-q* transformation consists of applying the three-phase machine transformation to each of the stator three-phase windings. The transformation is given with

$$\left[X_{\alpha 1\beta 101\ldots\alpha k\beta k0k}\right] = \left[C_{M\alpha\beta}\right]\cdot\left[X_{a1b1c1\ldots akbkck}\right] \tag{1}$$

In the following, whenever a transformation matrix for a multiple three-phase machine is described, the phase variables arrangement will be assumed as already stipulated, i.e.,

$$\left[X_{a1b1c1a2b2c2}\right] = [a1\ \ b1\ \ c1\ \ a2\ \ b2\ \ c2]^t \tag{2}$$

The transformation matrix $[C_{M\alpha\beta}]$ for the case of a six-phase machine with spatial shift of 30º between the three-phase systems is given with:

$$[C_{M\alpha\beta}] = k_3\cdot\begin{bmatrix} 1 & -1/2 & -1/2 & 0 & 0 & 0\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 & 0 & 0\\ c_3 & c_3 & c_3 & 0 & 0 & 0\\ 0 & 0 & 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 0\\ 0 & 0 & 0 & 1/2 & 1/2 & -1\\ 0 & 0 & 0 & c_3 & c_3 & c_3 \end{bmatrix} \tag{3}$$

Here k_3 and c_3 stand for scaling coefficients that govern the power relationship between the original and the transformed machine model and zero-sequence component, respectively. It can be seen how, in each row in (3), the non-zero coefficients affect only the phase variables of one of the three-phase systems, so that the transformation can be separated into two independent three-phase transformations.

A. Physical Interpretation

To obtain the physical interpretation of the axes of a transformation, corresponding rows have to be analysed and their physical meaning extracted. From the transformation in (3), the following meaning of each of the axes follows:

i) Row 1 in (3) represents the $\alpha 1$ axis, i.e., the projection on α axis of the components of the first three-phase system.

ii) Row 2 in (3) represents the $\beta 1$ axis, i.e., the projection on β axis of the components of the first three-phase system.

iii) Row 3 in (3) represents the 01 axis, i.e., the projection on 0 axis of the components of the first three-phase system.

iv) Row 4 in (3) represents the $\alpha 2$ axis.

v) The row 5 in (3) represents the $\beta 2$ axis.
vi) The row 6 in (3) represents the 02 axis.

As a consequence, it can be concluded that, with the application of the double *d-q* transformation, an independent approach to each of the three-phase systems is implicitly assumed. This yields results similar to those obtained considering two independent three-phase machines with phase shifted three-phase windings. The physical consequence of such an approach is that it generates two parallel three-dimensional subspaces to which the information of each of the three-phase systems is mapped and it cannot isolate the mutual interaction between the three-phase systems. As a consequence, it becomes very complicated to properly compensate for such couplings. This can be explained using Fig. 1, which illustrates how the double *d-q* approach treats the six-phase machine as two three-phase machines, leaving the mutual interactions unaddressed.

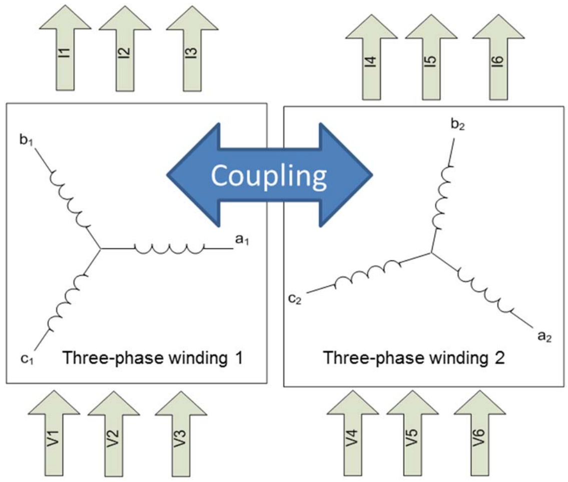

Fig. 1. Schematic illustration of the double *d-q* modelling approach.

B. Representation of Asymmetries

With this approach, as each of the three-phase systems is considered as independent, each of the subspaces will only reflect the asymmetries affecting the corresponding three-phase system. This is illustrated in Fig. 2, which illustrates the mapping of imbalances for the three cases, described in Section I. As it can be seen in Fig. 2, each subspace reflects only the asymmetries affecting its related three-phase system, thus ignoring what happens in the other one.

C. Harmonic Mapping

Applying the double *d-q* transformation to the harmonic voltage source described in Section I, the harmonic mapping depicted in Fig. 3 is obtained. It follows from Fig. 3 that the spectrum in the two subspaces $\alpha 1$-$\beta 1$, $\alpha 2$-$\beta 2$ is the same from the point of view of the harmonic mapping, thus confirming the fact that the two are parallel. Hence this modelling approach cannot separate the harmonics into different subspaces, which is a known conclusion and a drawback of the method once when it comes to current control in the Field Oriented Control (FOC) scheme.

III. Vector Space Decomposition

Arranging the phase variables as indicated in (2), the VSD transformation matrix for an asymmetrical six-phase machine can be formulated as:

$$[C_{VSD}] = k_6 \cdot \begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & -\sqrt{3}/2 & \sqrt{3}/2 & 1/2 & 1/2 & -1 \\ c_6 & c_6 & c_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & c_6 & c_6 & c_6 \end{bmatrix} \quad (4)$$

Coefficients k_6 and c_6 stand again for scaling that governs the power relationship between the original and the transformed machine model and zero-sequence component, respectively.

A. Physical Interpretation

A meaningful interpretation can be obtained by comparing the matrices in (3) and in (4). From (4), the relations between the original and the transformed variables can be obtained for the case of the VSD transformation and a 30º shift. Combining this result with the one obtained from (3), the following relationships result:

$$\begin{aligned} i_\alpha &= \frac{k_6}{k_3}\cdot(i_{\alpha 1}+i_{\alpha 2}) & i_\beta &= \frac{k_6}{k_3}\cdot(i_{\beta 1}+i_{\beta 2}) \\ i_x &= \frac{k_6}{k_3}\cdot(i_{\alpha 1}-i_{\alpha 2}) & i_y &= \frac{k_6}{k_3}\cdot(-i_{\beta 1}+i_{\beta 2}) \\ i_{z1} &= \frac{k_6\cdot c_6}{k_3\cdot c_3}\cdot(i_{01}) & i_{z2} &= \frac{k_6\cdot c_6}{k_3\cdot c_3}\cdot(i_{02}) \end{aligned} \quad (5)$$

From (5), the following conclusions can be drawn:

i) The α axis in VSD is proportional to the summation of components in $\alpha 1$ and $\alpha 2$ in the double *d-q* model.

ii) The β axis in VSD is proportional to the summation of $\beta 1$ and $\beta 2$ in the double *d-q* model.

iii) The x axis in VSD is proportional to the difference of $\alpha 1$ and $\alpha 2$.

iv) The y axis in VSD is proportional to the difference of $\beta 2$ and $\beta 1$.

v) The $z1$ axis in VSD is proportional to 01.

vi) The $z2$ axis in VSD is proportional to 02.

As a consequence, it can be concluded that the application of the VSD approach yields two transformed subspaces. The first one (α-β) is proportional to the summation of the α_i-β_i projections of each of the three-phase systems (with i being the number of the three-phase system). The second one (x-y) is proportional to the difference of the α_i-β_i projections of each of the three-phase systems. Finally, the two remaining components are the zero-sequence components and these are discarded in model applications as neutral points are isolated.

B. Representation of Asymmetries

By investigating the behaviour of the transformation for the same asymmetries as in Section II, the results shown in Fig. 4 are obtained. It can be seen that, in each of the three cases, asymmetries lead to excitation at fundamental frequency in the x-y subspace, but in a very different and unique manner. Additionally, it can also be observed that not all the asymmetries affect the α-β subspace where the torque-flux production is mapped. In particular, CASE I does not produce distortion in the α-β subspace.

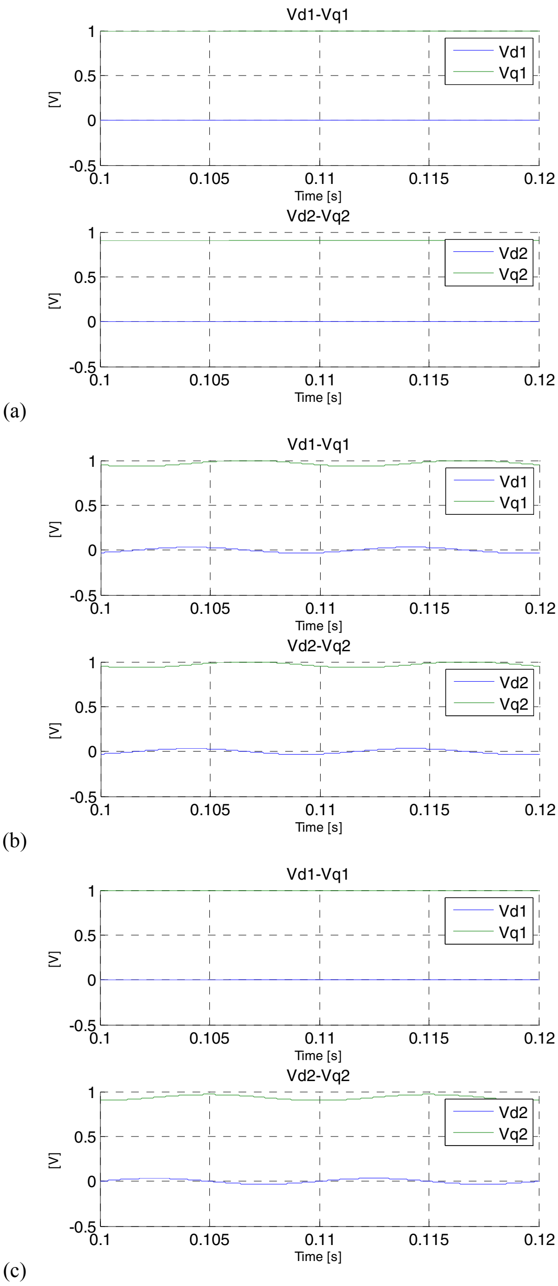

Fig. 2. Projections on $d1$-$q1$ (upper) and $d2$-$q2$ (lower) subspace axes for different asymmetries: (a) CASE 1, (b) CASE 2 and (c) for CASE 3.

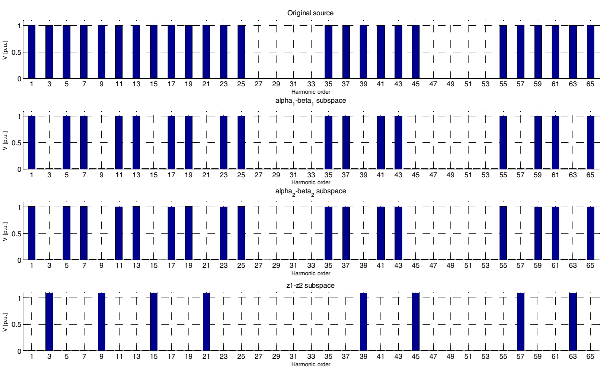

Fig. 3. Harmonic mapping using double d-q transformation.

It can be deduced from Fig. 4 that, if different current sharing between the three-phase systems of the machine is required (equivalent to an asymmetry of CASE 1), some fundamental frequency current components will appear in the x-y subspaces and hence they will have to be controlled.

C. Harmonic Mapping

Applying the VSD transformation to the harmonic voltage source, the harmonic mapping shown in Fig. 5 is obtained. It can be seen that the 5th and 7th harmonic are not mapped into the α-β subspace, which is a well-known property of the VSD approach for this machine. They map completely into the x-y subspace where the VSD approach establishes a current flow path with only the stator resistance and leakage inductance as impedances [14]. This explains the known problem of circulation of high low-order harmonic currents, as the stator leakage inductance of this subspace is usually very low due to the winding design features.

It can also be seen in Fig. 5 that each harmonic is mapped exclusively into only one subspace. This makes it very easy to control any current harmonic in a FOC scheme, since only its corresponding subspace should be focused on.

IV. Alternative Transformation

As discussed in Section I, an alternative transformation is developed, aimed at facilitating the load sharing between all the three-phase systems in the machine. For this purpose, a main subspace is defined, which will gather information about the electromagnetic energy conversion within the entire machine (it corresponds to the α-β subspace in VSD transformation). In addition to this, one auxiliary subspace is also defined, gathering information about the relationship between the two three-phase systems. This subspace is referred to as an auxiliary subspace 12 further on. In general, the three-phase system number 1 is taken as the reference. The other three-phase system will be compared with the reference so that all the information about the machine state in the auxiliary subspace is gathered with regard to the three-phase system number 1. Following the above mentioned requirements, a transformation matrix can be constructed for a general case of a machine with k three-phase systems and n-phases. When there are two three-phase windings, as the case is here, the matrix has to satisfy the following requirements:

- Axis α: it reflects the summation of α components of both three-phase systems.
- Axis β: it reflects the summation of β components of both three-phase systems.
- Axis $\alpha 12$: it reflects the difference in α components between the three-phase systems number 1 and 2.
- Axis $\beta 12$: it reflects the difference in β components between the three-phase systems number 1 and 2.

Using the described procedure, the transformation matrix

$$[C_{Alt}] = k_6 \cdot \begin{bmatrix} 1 & -1/2 & -1/2 & \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & 1/2 & 1/2 & -1 \\ 1 & -1/2 & -1/2 & -\sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 & -1/2 & -1/2 & 1 \\ c_6 & c_6 & c_6 & -c_6 & -c_6 & -c_6 \\ c_6 & c_6 & c_6 & c_6 & c_6 & c_6 \end{bmatrix} \qquad (6)$$

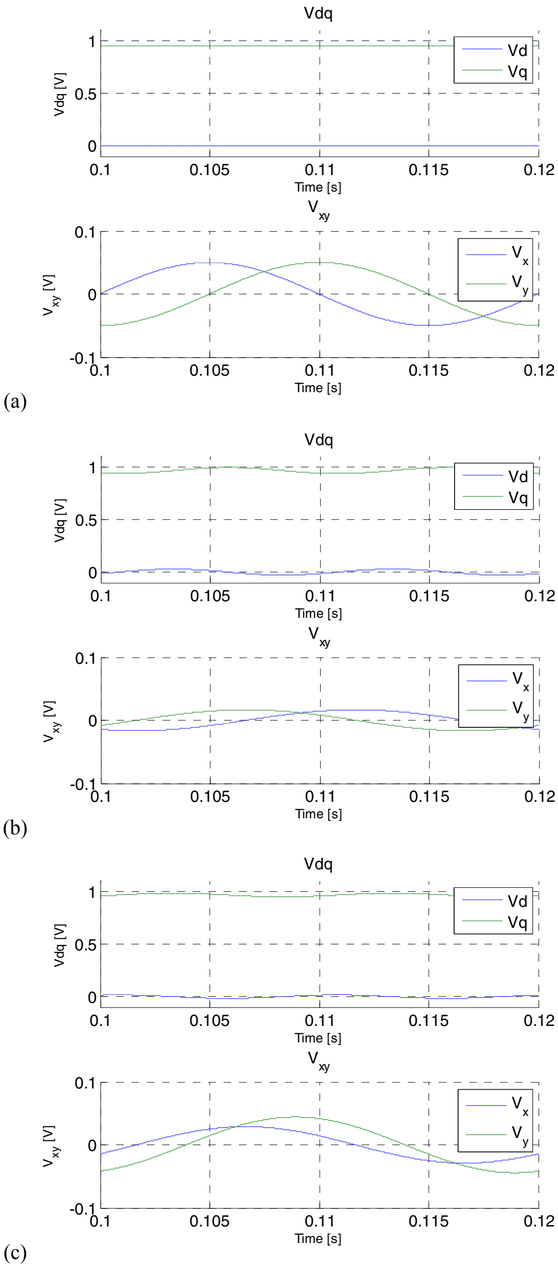

Fig. 4. Projections in *d–q* (upper) and *x-y* (lower) subspaces for different asymmetries: (a) CASE 1, (b) CASE 2 and (c) for CASE 3.

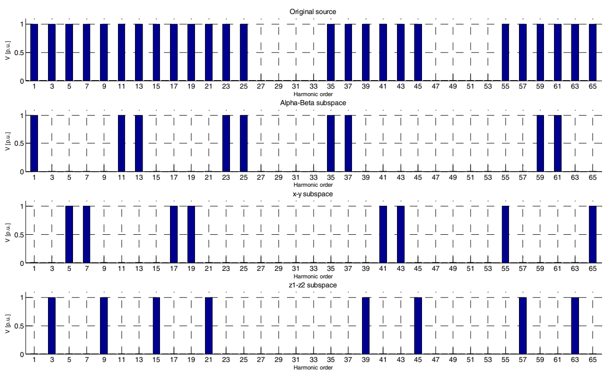

Fig. 5. Harmonic mapping using VSD transformation.

can be constructed for a six-phase machine with 30º spatial phase shift. Comparing (4) and (6), it can be seen that both matrices are very similar and only differ in the sign of the fourth row. The similarity with VSD transformation makes its behaviour identical in terms of harmonic mapping (which is therefore not shown in what follows), but slightly different in terms of the physical interpretation of the auxiliary subspace and representation of asymmetries.

A. Physical Interpretation

A meaningful interpretation can be easily obtained by simply comparing the matrices in (3) and in (6). From (6), the relations between the original and the transformed variables can be obtained for the case of the alternative transformation and a 30º spatial shift of three-phase windings. Combining this result with the one obtained from (3), the following is obtained:

$$
\begin{aligned}
i_\alpha &= \frac{k_6}{k_3}\cdot(i_{\alpha 1}+i_{\alpha 2}) & i_\beta &= \frac{k_6}{k_3}\cdot(i_{\beta 1}+i_{\beta 2}) \\
i_{\alpha 12} &= \frac{k_6}{k_3}\cdot(i_{\alpha 1}-i_{\alpha 2}) & i_{\beta 12} &= \frac{k_6}{k_3}\cdot(i_{\beta 1}-i_{\beta 2}) \\
i_{z01} &= \frac{k_6\cdot c_6}{k_3\cdot c_3}\cdot(i_{01}-i_{02}) & i_{z02} &= \frac{k_6\cdot c_6}{k_3\cdot c_3}\cdot(i_{01}+i_{02})
\end{aligned}
\tag{7}
$$

From (7), the following conclusions can be drawn:

i) The α axis in the alternative transformation is proportional to the summation of $\alpha 1$ and $\alpha 2$ components in the double *d-q* model.

ii) The β axis in the alternative transformation is proportional to the summation of $\beta 1$ and $\beta 2$ components in the double *d-q* model.

iii) The $\alpha 12$ axis in the transformation (6) is proportional to the difference of $\alpha 1$ and $\alpha 2$ components.

iv) The $\beta 12$ axis in the transformation (6) is proportional to the difference of $\beta 1$ and $\beta 2$ components.

v) The z01 axis in the alternative transformation is proportional to the difference of 01 and 02 components.

vi) The z02 axis in the alternative transformation is proportional to the summation of 01 and 02 components.

B. Representation of Asymmetries

In what follows the following notation is used: variables obtained after application of the transformation (6) are denoted as α, β for the main subspace and $\alpha 12$, $\beta 12$ for the auxiliary, while variables after subsequent rotational transformation are labelled again as *d*, *q* (rotational transformation is applied only to the α–β components).

By investigating the behaviour of the alternative transformation for the same asymmetries as defined in Section I, the results shown in Fig. 6 are obtained. Comparing Fig. 4 and Fig. 6, it can be seen how the only difference is the phase of the projection in the auxiliary subspace (due to the change in sign in the fourth row of (5)).

V. Conclusion

The double *d-q* transformation is directly derived from that of three-phase machines. Its application is straightforward and simple. On the other hand, it is characterised with some drawbacks as it considers each of the three-phase systems separately. This creates two parallel subspaces to which all the information is mapped, thus making the isolation of the mutual interactions between them difficult; hence the compensation of the interactions becomes complicated.

The VSD transformation provides a general approach that treats the multiphase machine as a whole and thus implicitly takes care of all the mutual interactions in the machine. The *x-y* subspace can be easily interpreted as the difference in a variable (say, voltages or currents) of the two three-phase systems. This implies that, in order to operate the machine with different current sharing between the two three-phase systems, some fundamental-frequency currents will have to be controlled in the *x-y* subspace. Such an interpretation of the *x-y* subspace is no longer applicable in machines with number of phases higher than six. This fact makes the application of current sharing strategies in such machines by using VSD approach difficult.

The alternative transformation presented here is very similar to the VSD in the case of asymmetrical six-phase machines. However, it provides a general method to transform asymmetrical machines with number of phases higher than six when current sharing between the different three-phase systems is required. Hence the approach reveals the full potential when applied in conjunction with machines with more than two three-phase windings, as will be shown shortly in a companion paper using a nine-phase machine.

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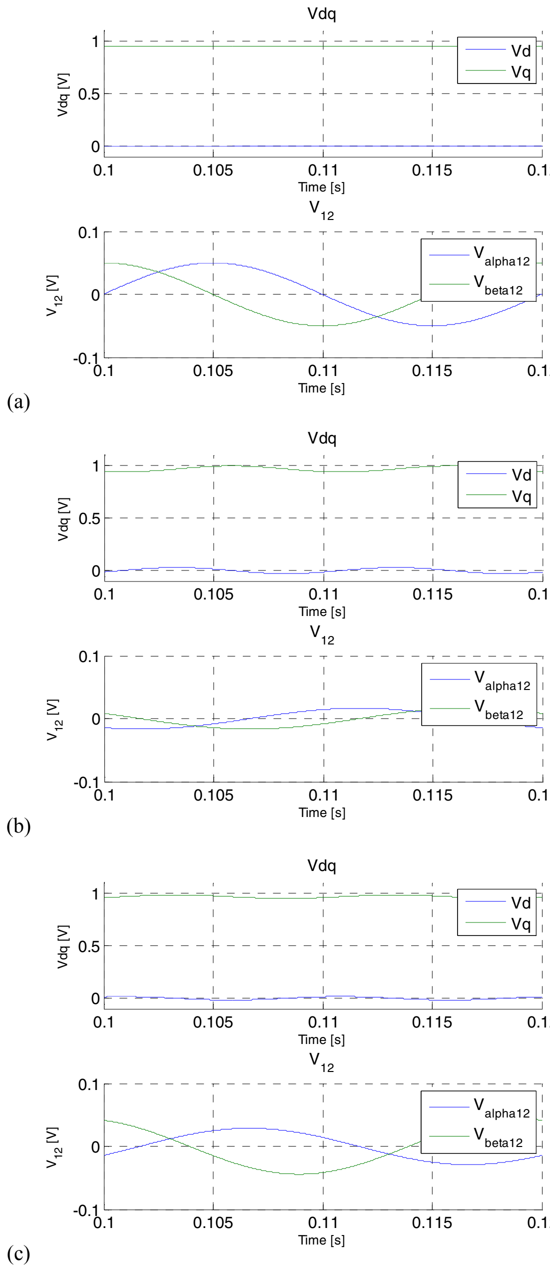

Fig. 6. Projections in d–q (upper) and $\alpha12$-$\beta12$ (lower) subspaces for different asymmetries: (a) CASE 1, (b) CASE 2 and (c) for CASE 3.