Modelling Approaches for Triple Three-Phase Permanent Magnet Machines

M. Zabaleta, E. Levi, M. Jones

***Abstract* – Standard modelling approaches for a triple three-phase (i.e. nine-phase) machine include vector space decomposition (VSD) and triple *d-q* modelling procedure. Each is characterised with certain benefits and shortcomings. This paper introduces a novel transformation, applicable to multiple three-phase winding machines in general, especially aimed at facilitating the power (current) sharing between the three-phase systems. The easiness of the current sharing with the novel transformation, introduced here, is demonstrated via simulations in MATLAB.**

***Index Terms* – Nine-phase machine, multiphase machine transformation, multiphase machine modelling, triple three-phase machine.**

I. Introduction

As a consequence of the accelerated development of the power electronics in the second half of the twentieth century, a strong research effort has been directed toward the modelling of electrical machines. This is so because modern power electronic converters allow almost instantaneous torque/flux control of the machines and suitable dynamic models are then required. Additionally, the power electronics allow to isolate the machine from the grid (usually a three-phase system) allowing the use of a different number of phases (higher than three) in the machine. Increasing the number of phases in the machine yields the following major benefits ([1] and [2]):

- the phase currents in a multiphase machine are reduced (compared to those in an equivalent three-phase machine); and,
- multiphase machine drives can continue to operate with one or more faulty phases, thus increasing the overall system reliability.

These benefits have raised the interest in multiphase machines, especially for high power and safety critical applications. Amongst them, offshore wind is one of the targeted sectors, mainly because in it the requirement for an immediate maintenance access to the plant is unacceptable, requiring that the wind turbine has as much fault tolerance built in as possible. This has increased the interest in use of multiphase machines as they inherently include this fault tolerant capability.

Nowadays, the top-level electrical machines manufacturers have deep experience and knowledge in designing and manufacturing electrical machines to be used in conjunction with electronic drives. As a consequence, the influence of machine's stator insulation breakdown issues ([3] and [4]) on the wind turbine availability is negligible. On the other hand, failures in the power converter devices are much more likely to happen as these devices are normally subjected to strong thermal cycles and overloads.

All this increases the interest in providing the power converter with means to remain in operation after a failure in any of its power devices, such as in [5] where an additional converter leg for each three-phase systems has been included. This solution increases the cost and size of the converter and may not be applicable to some cost- or size-sensitive applications (such as wind electricity generation). In the case of several three-phase systems with isolated neutrals, after a failure in one phase, it is possible to take out of service the whole three-phase system in which the faulty phase is, and operation can continue with the other healthy three-phase systems as it is described in [6]. The main benefit of this strategy is that the control algorithm needs to be only slightly modified (principally, the generation of the controller set-points and feed-forward terms) for the operation after a failure. The drawback is that this technique strongly de-rates the capability of the drive after a failure as it disconnects one entire three-phase system, thus unnecessarily reducing the number of operational phases, and hence the available torque. In the case of a single neutral point for all the phases, after a fault, it is no longer required to disconnect a whole three-phase winding; instead, disconnection of only the faulty phase is possible, thus keeping the number of operational phases at a maximum at all times. It should be noted that, to produce a constant-amplitude rotating magneto-motive force (MMF) with a set of non-uniformly spatially distributed windings, the currents flowing through those windings will inevitably need to be unbalanced in amplitudes [7]. Even though it may look as advantageous to use just one neutral point for all the phases, this leads to some drawbacks such as lower dc-bus voltage utilization [8] and the practical difficulty of safely isolating one leg of the converter both from the ac and dc sides.

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. This requires the use of several power converters in parallel, which brings in its own problems if used in conjunction with a single three-phase winding. However, by connecting each of these converters to

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one three-phase winding in the stator of the machine, a multiphase conversion system can be obtained allowing to exploit its fault tolerance. In the case of low-voltage converters, a minimum of three should be used to reach current wind turbine's ratings [9], [10] and this is where the interest in triple and quadruple three-phase machines (i.e. nine- and twelve-phase machines) comes from.

The multiple three-phase winding machinery related literature basically covers two modelling approaches for the said machines: one is the multiple *d-q* and the other is the vector space decomposition (VSD). The former is a straightforward transformation directly derived from that of three-phase machines. It can only be applied to multiphase machines with a number of phases $n = 3k$, $k = 2, 3, 4, \ldots$. In these machines, the multi-dimensional n-domain can be divided into k three-dimensional domains each of which can be modelled as a three-phase machine. To the best of the author's knowledge, [11] and [12] are the only published works in which the multiple *d-q* approach has been applied to asymmetrical machines with $n > 6$ (nine- and twelve-phase machines) to obtain the equivalent circuit and its parameters. The VSD approach transforms the original n-dimensional space (where n is the number of phases) into a set of $(n–1)/2$ (when n is an odd number and a single neutral point is assumed) mutually orthogonal two-dimensional subspaces [13]. With this, the machine's model can be easily formulated using a set of decoupled subspaces. For a set of three-phase systems with k isolated neutral points, such as those considered here, VSD approach yields equations in k mutually orthogonal subspaces and k zero-sequence components.

A large body of work has been published about different control schemes applicable to multiple three-phase winding machines, with main differences stemming primarily from the modelling approach (whether it is a VSD or a multiple *d-q* approach). The straightforward approach, based on a three-phase machine theory, is followed in [14], where it is shown that it is possible to supply a dual three-phase induction machine (with windings shifted by 30º) from converters with independent control and with different load sharing between them by means of a current distribution strategy. Reference currents for both three-phase stator windings are generated and applied to the current regulators of each three-phase winding. Similarly, work in [15] introduces a dual-star synchronous machine fed by two independent voltage source converters and implements independent three-phase vector control for each of them. The main problem of these strategies is that having independent current regulators for each three-phase winding yields a complex control structure, since the stator-stator cross-couplings need to be taken into account and compensated for to provide adequate transient response.

An interesting feature of these multiple three-phase conversion stages is the ability to operate them with different load sharing and thus aiming to optimize the system's efficiency [9] or to keep the operation in an event of a failure in any converter of the conversion stage. Following the VSD theory, work in [16] demonstrates that the fundamental frequency components in the currents in the non-flux/torque producing subspaces can create current imbalances between the different three-phase systems in the machine. This can be used to operate the three-phase systems with different load sharing as desired. With the VSD approach, the current references for the non-flux/torque producing subspaces can be easily found for six-phase machines. This however becomes a complex issue for machines with a phase number higher than six [17]. This is so as no relationship between the non-flux/torque producing subspaces and the flux/torque producing one can be obtained. Hence it follows that no physical meaning of the former subspaces can be arrived at when using the VSD transformation [18]. With this difficulty in mind, the present work describes a novel transformation applicable to multiple three-phase winding machines (with n greater than six) which facilitates the current reference generation for the non-flux/torque producing subspaces to obtain a desired current (power) sharing amongst the three-phase systems in the machine.

II. Novel Transformation

The basic idea behind a transformation is to obtain an inductance matrix with constant coefficients, and diagonal in form. This makes it easier to tune the regulators as constant inductance values are obtained and furthermore, if the matrix is diagonal, independent regulation in each axis is possible reducing the cross-couplings to only parasitic components such as leakage coupling [19]. Additionally, during balanced operation, the fundamental frequency projections in all the non-flux/torque producing subspaces should be zero. This condition facilitates the correction of unbalances that may appear in the operation. To the above mentioned requirements for a transformation (already satisfied by VSD), an additional condition can be added as follows:

- A physical interpretation for each non-flux/torque producing subspace should be provided to facilitate the control task.

For this purpose, a main subspace will be defined, which will gather information about the electromagnetic energy conversion within the entire machine (correspondent to the α-β subspace in VSD transformation). In addition to this, $(k–1)$ auxiliary subspaces will also be defined, gathering information about the relationship between each of the three-phase systems and the reference one. These will be referred to as auxiliary subspaces $1i$ with i varying from 2 to k. In general, the three-phase system number 1 will be taken as the reference. All the other three-phase systems will be compared with the reference so that all the information about the machine state in the auxiliary subspaces is gathered with regard to the three-phase system number 1. It can be easily deduced that the auxiliary subspaces will not be mutually orthogonal as they all share the information about the reference three-phase system but, as will be further demonstrated, this is not really a problem. With this, the transformation matrix for a machine with k three-phase systems and n-phases can be constructed as follows:

- Axis α: reflects the summation of the projections on α axis of all the three-phase systems;
- Axis β: reflects the summation of the projections on β axis of all the three-phase systems;
- Axis $\alpha 12$: reflects the difference in the projections on α axis of the three-phase systems number 1 and 2;
- Axis $\beta 12$: reflects the difference in the projections on β axis of the three-phase systems number 1 and 2;
- ……
- Axis $\alpha 1k$: reflects the difference in the projections on α axis of the three-phase systems number 1 and k;
- Axis $\beta 1k$: reflects the difference in the projections on β axis of the three-phase systems number 1 and k;
- Axis $z12$: reflects the difference in the projections on 0 axis of the three-phase systems number 1 and 2;
- ......
- Axis $z1k$: reflects the difference in the projections on 0 axis of the three-phase systems number 1 and k;
- Axis zn: reflects the summation of the projections on 0 axis of all the three-phase systems.

The resulting transformation matrix for a triple three-phase machine is given with the following expression (σ represents the phase shift between the three-phase systems, and c determines the amplitude of the zero-sequence components in the transformed model; k_9 is a scaling factor that governs power variance/invariance of the transformation matrix):

$$C = k_9 \cdot \begin{bmatrix} 1 & cos(2\cdot\pi/3) & cos(4\cdot\pi/3) & cos(\sigma) & cos(2\cdot\pi/3+\sigma) & cos(4\cdot\pi/3+\sigma) & cos(2\cdot\sigma) & cos(2\cdot\pi/3+2\cdot\sigma) & cos(4\cdot\pi/3+2\cdot\sigma) \\ 0 & sin(2\cdot\pi/3) & sin(4\cdot\pi/3) & sin(\sigma) & sin(2\cdot\pi/3+\sigma) & sin(4\cdot\pi/3+\sigma) & sin(2\cdot\sigma) & sin(2\cdot\pi/3+2\cdot\sigma) & sin(4\cdot\pi/3+2\cdot\sigma) \\ 1 & cos(2\cdot\pi/3) & cos(4\cdot\pi/3) & -cos(\sigma) & -cos(2\cdot\pi/3+\sigma) & -cos(4\cdot\pi/3+\sigma) & 0 & 0 & 0 \\ 0 & sin(2\cdot\pi/3) & sin(4\cdot\pi/3) & -sin(\sigma) & -sin(2\cdot\pi/3+\sigma) & -sin(4\cdot\pi/3+\sigma) & 0 & 0 & 0 \\ 1 & cos(2\cdot\pi/3) & cos(4\cdot\pi/3) & 0 & 0 & 0 & -cos(2\cdot\sigma) & -cos(2\cdot\pi/3+2\cdot\sigma) & -cos(4\cdot\pi/3+2\cdot\sigma) \\ 0 & sin(2\cdot\pi/3) & sin(4\cdot\pi/3) & 0 & 0 & 0 & -sin(2\cdot\sigma) & -sin(2\cdot\pi/3+2\cdot\sigma) & -sin(4\cdot\pi/3+2\cdot\sigma) \\ c & c & c & -c & -c & -c & 0 & 0 & 0 \\ c & c & c & 0 & 0 & 0 & -c & -c & -c \\ c & c & c & c & c & c & c & c & c \end{bmatrix} \quad (1)$$

A. Harmonic Mapping

As it has been mentioned earlier, the auxiliary subspaces are not mutually orthogonal in the novel transformation, given with (1). This is obvious since all of them share information about the reference three-phase system (here the system number 1). In the case of VSD, all the transformed subspaces are mutually orthogonal and so each harmonic will be mapped (projected) into one single subspace, as shown in Fig. 1. In Fig. 1, each phase voltage is taken as being composed of a fundamental and certain odd harmonics, all with 1 per-unit amplitude, as shown in the uppermost part of Fig. 1.

With the novel transformation, the harmonic mapping will no longer be unique and some of the harmonics will be mapped into more than one auxiliary subspace, as illustrated in Fig. 2. It is important to note that the mapping of the fundamental and all the torque ripple producing harmonics (e.g. the 17^{th} and 19^{th}) does not change, compared to the VSD transformation, since these components still appear only in the first subspace.

An important observation from Fig. 2 is that the amplitudes of the harmonics that map in multiple auxiliary subspaces are different (lower) than the original values introduced by the source (1 p.u.). On the contrary, it can be seen in Fig. 1 how the 5^{th} harmonic projection in the subspace $x1$-$y1$ of the VSD transformation had the same amplitude as introduced by the source. This issue can be explained with the help of Fig. 3, which represents a simplified representation of the nine-dimensional space as a two-dimensional one for the ease of visualization. As the 5^{th} harmonic has the same amplitude in the x-y subspace as the original source harmonic (for VSD transformation), it means that the harmonic is fully contained within said subspace. If a different, non-orthogonal, subspace is used (as the case is in the novel transformation), the projections of the 5^{th} harmonic will be smaller than the original one and the values will depend on the relative angle between the two subspaces.

B. Current Sharing Coefficients

By defining the current sharing coefficients (k_{di}, k_{qi}) as

$$\begin{aligned} i_{d1} &= k_{d1} \cdot i_d \\ i_{q1} &= k_{q1} \cdot i_q \\ i_{d2} &= k_{d2} \cdot i_d \\ i_{q2} &= k_{q2} \cdot i_q \\ i_{d3} &= i_d - i_{d1} - i_{d2} \\ i_{q3} &= i_q - i_{q1} - i_{q2} \end{aligned} \quad (2)$$

where i_d and i_q are the total desired flux and torque producing currents of the complete machine, and where i_{di} and i_{qi} (i = 1,2,3) are the flux/torque producing currents of individual three-phase windings, the values for the currents in the auxiliary subspaces can be calculated to obtain the desired current sharing:

$$\begin{aligned} i_{d12} &= (k_{d1} - k_{d2}) \cdot i_d \\ i_{q12} &= (k_{q1} - k_{q2}) \cdot i_q \\ i_{d13} &= (2 \cdot k_{d1} + k_{d2} - 1) \cdot i_d \\ i_{q13} &= (2 \cdot k_{q1} + k_{q2} - 1) \cdot i_q \end{aligned} \quad (3)$$

It has to be noted that in a machine with k three-phase systems, when controlling the main subspace (α-β or d-q after rotational transformation application), only (k–1) of the three-phase systems can be controlled independently, so that only 2·(k–1) current sharing coefficients are required.

III. Simulation Studies

A triple three-phase permanent magnet machine model is generated in the Simulink © SimPowerSystems blockset from Matlab ©. The machine model can be configured to reproduce the behaviour of any kind of a nine-phase machine with any spatial phase shift between the three-phase systems. The parameters of a permanent magnet machine from a previous project within Ingeteam (Table I) have been adopted in order to examine the behaviour of a control algorithm based on the novel transformation.

In order to focus on the transformation influence on the control loop behaviour, digital current control loops have been implemented in the synchronously rotating frame for the main subspace current components, while stationary reference frame is used for current control in the auxiliary subspaces. The outputs of the current loops, which provide voltage component references, are further transformed to produce stator phase voltage references that are impressed through a linear amplifier which resembles the power electronic devices in an ideal implementation, where no commutations (and hence switching harmonics) are present.

The current control algorithm includes the *d-q* axis cross-coupling decoupling terms, as shown in Fig. 4. The expressions for the decoupling terms can be easily obtained from the machine model and can be expressed as:

$$K_{dVSD} = -\omega_r \cdot (L_{ls} + \frac{9}{2} \cdot L_{mq}) \cdot i_q$$
$$K_{qVSD} = \omega_r \cdot (\psi_{pm} + (L_{ls} + \frac{9}{2} \cdot L_{md}) \cdot i_d) \quad (4)$$

where ω_r is the rotor speed of the machine and ψ_{pm} is the permanent magnet flux.

Once when the current references for the *d-q* subspace have been calculated to satisfy the torque and flux requirements for the entire machine, the current references for the auxiliary subspaces need to be determined with the help of (3). These references are in a rotating frame. Hence an inverse rotational transformation needs to be subsequently applied to refer them to the stationary reference frame, so that they can be used in stationary frame current regulators. The structure of the stationary frame current regulators is simple since no cross-coupling terms appear. Fig. 5 shows the block diagram of the entire current regulation scheme programmed in the C code.

The machine model is an implementation of the VSD equations for a nine-phase machine. Its equations are:

$$v_d = r_s \cdot i_d - \omega_r \cdot \psi_q + \frac{d\psi_d}{dt}$$
$$v_q = r_s \cdot i_q + \omega_r \cdot \psi_d + \frac{d\psi_q}{dt}$$
$$v_{xi} = r_s \cdot i_{xi} + \frac{d\psi_{xi}}{dt}$$
$$v_{yi} = r_s \cdot i_{yi} + \frac{d\psi_{yi}}{dt} \quad (5)$$
$$\psi_d = (L_{ls} + 9/2 \cdot L_{md}) \cdot i_d + \psi_{pm}$$
$$\psi_q = \left(L_{ls} + 9/2 \cdot L_{mq}\right) \cdot i_q$$
$$\psi_{xi} = L_{ls} \cdot i_{xi}$$
$$\psi_{yi} = L_{ls} \cdot i_{yi}$$

It can be configured to represent both symmetrical and asymmetrical machines with any phase shift.

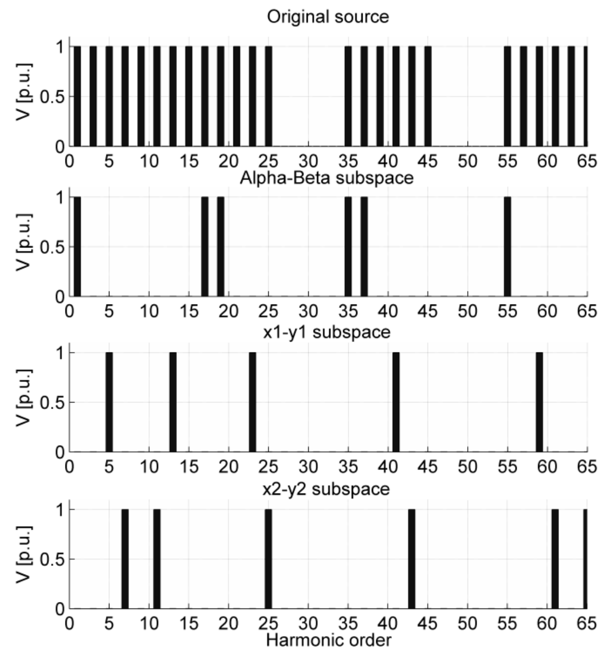

Fig. 1. Harmonic mapping using VSD transformation for the triple three-phase (nine-phase) winding with 20º shift between first phases.

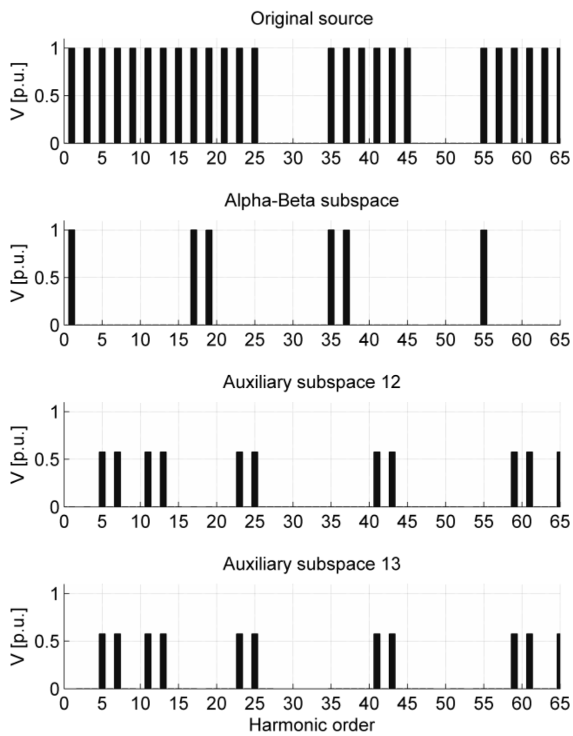

Fig. 2. Harmonic mapping using novel transformation (1) for the triple three-phase (nine-phase) winding with 20º shift between first phases.

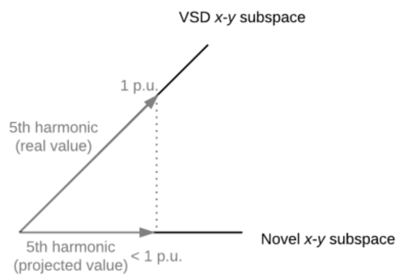

Fig. 3. Harmonic mapping using the novel transformation (1).

TABLE I. PARAMETERS OF THE MACHINE AND OTHER SIMULATION DATA

Machine	
Parameter	**Value**
Pole pairs	4
Rated Power	6000 kW
d-axis magnetising inductance (L_{md})	1.6 mH
q-axis magnetising inductance (L_{mq})	2.4 mH
Leakage inductance (L_{ls})	0.15 mH
Phase winding resistance (R_s)	9e-3 Ω
Nominal frequency (f_{nom})	73 Hz
No-load voltage (V_0) at f_{nom}	3294 V (line-to-line)
Nominal voltage (V_n)	3300 V (line-to-line)
Number of phases (n)	9
Spatial shift angle (σ)	π / 9
Control	
Parameter	**Value**
Simulation type	RMS model, no commutations
Controller nature	Digital, sample time 434 µs
Control type	Field-oriented control (FOC)
d-q current controller	Dual PI controller
Auxiliary subspaces current controllers	Proportional resonant controller (PR)
Machine mechanical input	Speed (750 rpm), infinite inertia
Initial *d-q* reference current setting	i_d = 0 A i_q = 300 A

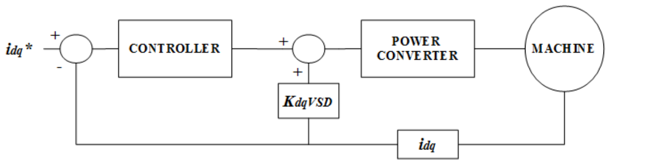

Fig. 4. Block diagram representation of the current regulators in the *d-q* subspace.

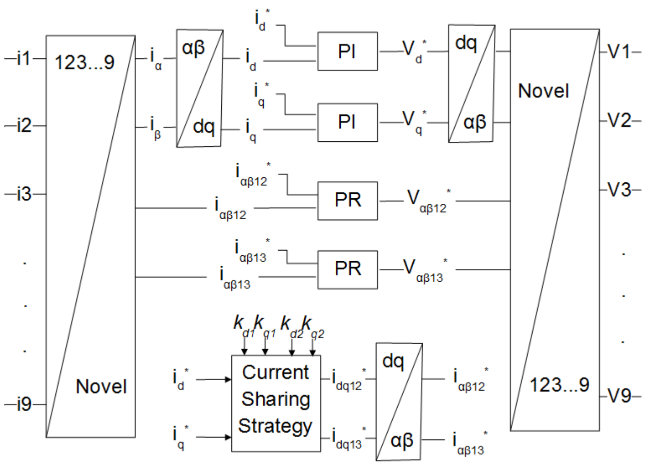

Fig. 5. Block diagram representation of the current regulators used in the simulations.

Fig. 6 shows the simulation blocks as used in Simulink. All the control algorithms are coded in C and integrated in the simulation by means of an S-function block (Control block in Fig. 6).

Simulation results, illustrating phase voltages and currents, are shown in Fig. 7. Initial operating condition is with equal power (current) sharing between the three three-phase windings. Total flux current reference i_d is kept at zero value throughout the simulation, as indicated in Table I. At time instant t = 1s, the currents of the three-phase systems number 1 and 2 are driven towards zero (k_{q1} and k_{q2} are set to 0), which thus become virtually disconnected. The remaining three-phase system (the number 3) needs to compensate for the disconnection of the other two by means of increasing its currents to keep the same torque (and, in general, flux) level as before the disconnection. This is so because the current references in the main subspace (*d-q*) remain constant.

In Fig. 8, the same transient operation is shown but the transformed current components (by means of the novel transformation) are plotted. It can be seen how, at t = 1s, there appear fundamental frequency currents in the auxiliary subspace 13 representing the imbalance between the three-phase systems number 1 and 3. The perturbation observed in Fig. 8 in the *d*-axis currents of each individual three-phase system is due to the transients associated with the current regulators in the auxiliary subspaces when a sudden change in the references is commanded (a step change in this simulation). During the said transient, the currents in the auxiliary subspaces have not reached the desired values yet; therefore a different current sharing between the three-phase systems results during the transient. This transient can be eliminated by avoiding the step reference change and using a ramped reference change profile instead.

Fig. 9 shows the currents in the auxiliary subspaces when VSD approach is followed under the same conditions as in Fig. 8. It can be seen how the projections in this case appear in both auxiliary subspaces in contrast to what happened when the novel transformation is used (Fig. 8).

With the novel transformation, the fundamental frequency projections in the auxiliary subspaces appear only in those whose related three-phase system currents differ from the

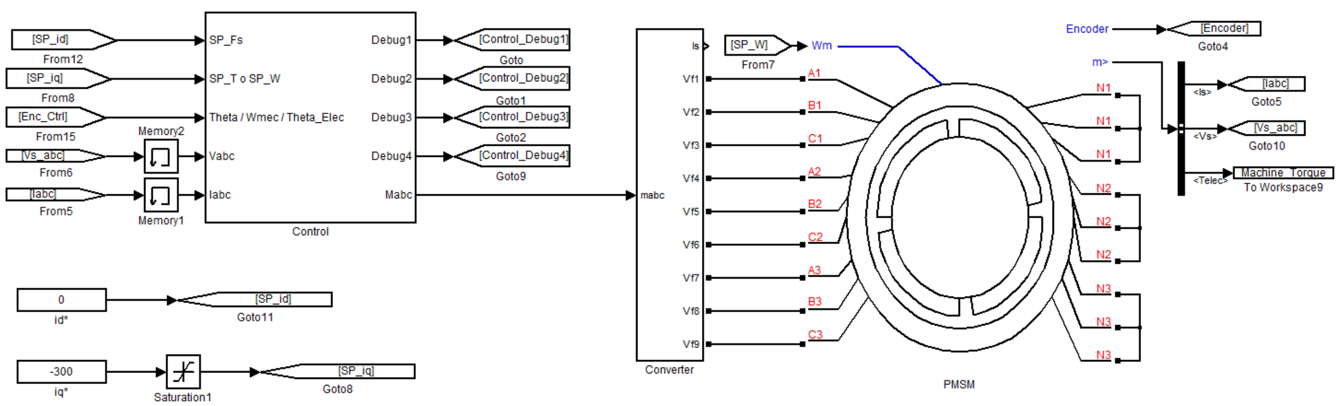

Fig. 6. Simulation model diagram. The block Control performs the sampling of all the measurements and executes the algorithms yielding the stator voltages references. The block Converter is a unitary gain.

currents in the reference system. With this, it can be concluded that each of the auxiliary subspaces in the novel transformation reflects the current sharing between the reference three-phase system and each of the other systems in the machine.

IV. Conclusion

A novel transformation for triple three-phase machines, especially aimed at easing the current (power) sharing between the three-phase systems, has been presented. It has been applied to a nine-phase machine but its extension to any number of phases, which is a multiple of three, is rather simple. Its main benefit with regard to the existing VSD approach is that each of the auxiliary subspaces is related to the current sharing between the reference three-phase system and each of the other ones within the machine. This facilitates the sharing strategy as with algebraic parameters (current sharing coefficients) any desired sharing can be easily achieved by simply generating adequate current references for the corresponding auxiliary subspace. Properties of the developed transformation are studied and verified by simulations.

V. References

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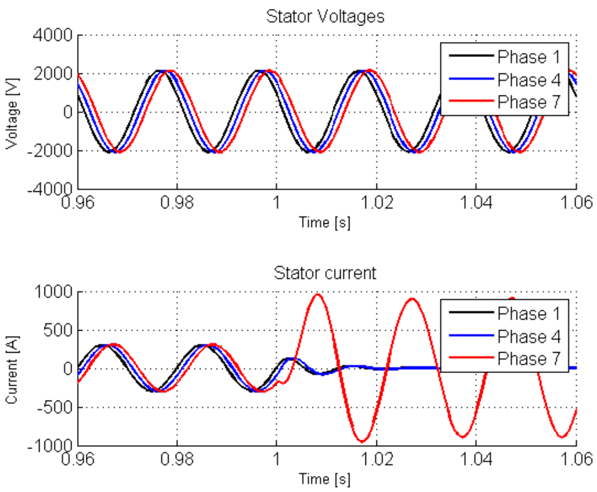

Fig. 7. Simulation of a nine-phase permanent magnet synchronous machine with data and conditions specified in Table I. Initial operation is with equal power (current) sharing. Then, at instant t = 1s, current sharing coefficients k_{q1} and k_{q2} are set to zero. Stator phase voltage and current of the first phase of each three-phase winding are shown.

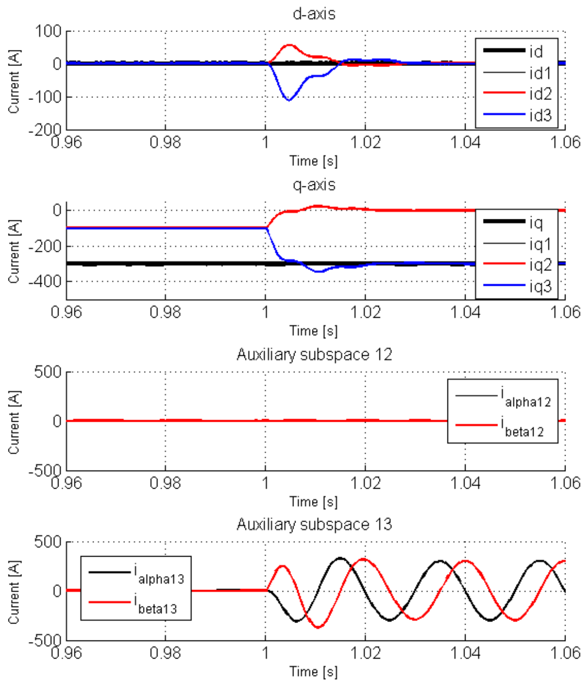

Fig. 8. Current components with the transformation (1) for the scenario described in conjunction with Fig. 7. Top two plots show current components of the main subspace, while the bottom two plots illustrate auxiliary subspace current components (indices *alpha* and *beta* stand for α and β, respectively).

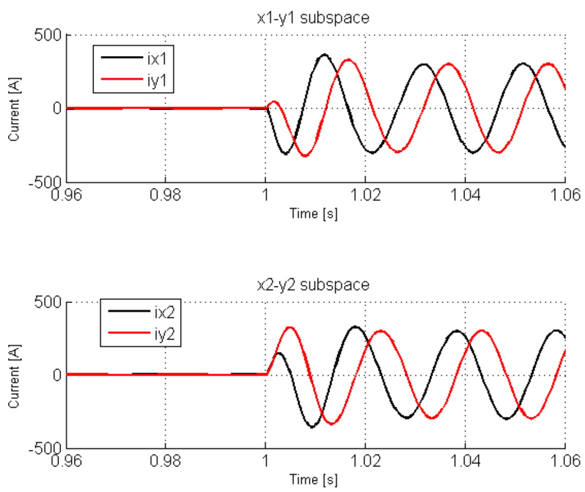

Fig. 9. Current components obtained with the VSD transformation approach in the auxiliary subspaces for the same conditions as in Figs. 7 and 8.

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