Arbitrary $d$–$q$ current sharing in three-phase winding sets of multi-phase machines

Ivan Zoric$^1$, Martin Jones$^1$, Emil Levi$^1$
$^1$Department of Electronics and Electrical Engineering, Faculty of Engineering and Technology, Liverpool John Moores University, Liverpool, United Kingdom
E-mail: E.levi@ljmu.ac.uk

Abstract: This study proposes a technique for arbitrary current sharing between winding sets of any multiple three-phase machine by using a decoupled control in two-dimensional orthogonal vector space decomposition subspaces. With ability to arbitrarily set the $d$–$q$ currents in all winding sets, both active and reactive power of each winding set can be separately overlapped in $d$–$q$ and $x$–$y$ subspaces. Normally, this behaviour requires machine model in multi-stator variables where control implementation may be challenging due to the cross-coupling between winding set variables. On the contrary, in this study, the correlation between multi-stator and the vector space decomposition modelling has been used so that benefits of both modelling approaches are fully utilised: a decoupled control feature thanks to vector space decomposition and an ability to individually control winding set currents, a feature of the multi-stator modelling approach.

1 Introduction

Use of multi-phase machines in high-power variable-speed drives is becoming more widespread due to their advantages over three-phase alternatives, which include an inherently improved fault tolerance, smaller current and power per phase for the same total power rating, lower torque ripple at higher frequencies, and the possibility to use the additional degrees of freedom for various application specific purposes [1, 2]. Target applications include wind energy conversion systems (WECS) [3], more-electric aircraft [4], ship propulsion and generation [5], and other high-power industrial applications where variable-speed drives are used.

The most widely investigated and used multi-phase machines are the ones with multiple three-phase winding sets [6, 7]. The main benefit of these types of machines is that they can be supplied by widely available three-phase voltage source inverters (VSIs). In the case of a machine with isolated neutral points, there is a galvanic isolation between VSIs, resulting in an ability to connect the machine to multiple independent sources, such as for example micro-grids [8]. Regardless of the type of the micro-grid, i.e. whether the WECS supplies an ac or dc micro-grid (Fig. 1), such a topology requires independent current control of each three-phase winding set, so that the supply current of each source can be arbitrarily controlled.

For this control requirement, an obvious choice would be to model machine by use of multiple three-phase Clarke's transformation, the so-called multi-stator (MS) modelling approach [9], and apply independent control of $d$–$q$ currents in each winding set [10]. MS modelling would then enable arbitrary current control in each winding set [4]. However, a price to pay is the more demanding control due to the heavy cross-coupling between winding set equations [11].

Another common approach of controlling multi-phase machines is to use vector space decomposing (VSD) to decouple a machine into multiple orthogonal two-dimensional subspaces where flux and torque producing currents are mapped only in a single $d$–$q$ subspace [12, 13] for machines with near-sinusoidal magnetomotive force (mmf), while others $x$–$y$ subspaces can be used for different purposes, e.g. low-order harmonic elimination [14] or on-board vehicle charger design [15]. Benefit of VSD modelling is an easy implementation of flux and torque control [1], whereas disadvantage is a loss of information of individual winding set currents. This limitation has been circumvented by relating individual winding set flux/torque producing currents available in the MS model to $x$–$y$ currents of the VSD model in the case of 6-phase [3, 8] and 12-phase [16, 17] machines, where currents in the $x$–$y$ subspace have been imposed in order to control power flow in each winding set.

More general approach has been reported in [18] where the relation between MS and VSD flux/torque producing currents has been found in general case applicable to any multiple three-phase machine. This has enabled the implementation of decoupled control in VSD variables, while information on individual winding set flux/torque producing currents is still available. Implemented current sharing is restricted in a sense that both $d$-axis and $q$-axis currents of each winding set are always changed to the same extent. The goal of this paper is to extend the work of Zoric et al. [18] by providing an algorithm for arbitrary and independent sharing of $d$- and $q$-currents between three-phase winding sets of multiple three-phase machines.

2 Relationship between VSD and MS flux and torque producing currents

The relationship between VSD and MS flux/torque producing currents of multiple three-phase machines, developed in [18], is
need to be imposed in order to produce desired current sharing. Therefore, besides the $i_{dq}$ current controller pair, ($l−1$) additional current controller pairs are needed. It should be noted that $x−y$ subspaces are non-flux/torque producing ones for machines with near-sinusoidal mmf, so the total flux and torque remain unaffected. Nevertheless, the constraint set by the first equation in (3) has to be respected. On the other hand, when all coefficients are equal to 1, the machine is balanced and $x−y$ currents are zero.

These considerations are illustrated by randomly varying the current-sharing coefficients. Amplitudes of the VSD currents $i_{d}$ and $i_{q}$ are equal to 1, while the frequency is 50 Hz, i.e. $i_{dq}=e^{2π50t}$. The current-sharing coefficients have been randomly varied in three time intervals as follows:

- 00 s−25 ms – all coefficients are equal to 1
- 25 s−50 ms – coefficients take the first random value
- 50 s−75 ms – coefficients take the second random value
- 75 s−100 ms – coefficients take the third random value
- 100 s−125 ms – all coefficients are equal to 1.

Since current sharing is implemented in the rotational reference frame, $θ_{dq}$ is defined as $2π50t − π/6$. Angle $π/6$ is taken as a random value so that flux/torque producing currents $i_{dq}$ are both non-negative; thus, current sharing can be properly demonstrated. Cases up to 15 phases (6, 9, 12, and 15) have been simulated. A block diagram of the simulated system is shown in Fig. 2. It should be noted that the coefficients are limited here to positive values. However, there is no limitation to set them to negative value as well. For example, a negative coefficient for the $i$th winding set torque producing current $k_{qi}$, depending on the operating point, may set corresponding winding set in a different operating mode than the whole machine in the motoring/generation sense.

Fig. 3 shows simulation results, where the first column shows VSD currents measured at the output. Total VSD flux/torque producing currents $i_{dq}$ are shown in the first plot (yellow trace – $i_{dq}$; purple trace – $i_{di}$) together with $i_{di}/i_{dq}$ currents (blue trace – $i_{di}$; red trace – $i_{dq}$). Since current-sharing coefficients define values in the rotational reference frame, phase currents within each winding set are balanced (the second column). The third column shows that references for winding set $d−q$ currents (dashed yellow trace – $i_{dq}$; dashed purple trace – $i_{q}$) are overlapped with actual $d−q$ currents (solid blue trace – $i_{di}$; solid red trace – $i_{di}$) of the winding sets confirming validity of the developed equations. It should be emphasised that total flux/torque producing VSD current $i_{dq}$ is not changed throughout the simulation, despite variation in the flux/torque production in each winding set. This behaviour can be seen in the first plot of each figure. Consequently, machine operation regarding the mechanical output at the shaft is not changed during current sharing.

Although the simulated configurations are asymmetrical with single neutral point, the results would be similar for any other configuration, with the only difference being in the phase shift of phase currents. This follows from the fact that the developed current sharing is independent of the machine configuration when the VSD matrix, used in [18], is applied.

3 Simulation results

The developed technique is tested on an asymmetrical nine-phase IM with three isolated neutral points. Machine flux and torque control have been implemented by using the standard IRFOC with an outer speed control loop [1]. Since VSD flux/torque producing current references $i_{dq}$ are readily available from the flux/torque control, e.g. IRFOC, (3) governs currents in the $x−y$ planes that
A schematic of the implemented control is shown in Fig. 4. Current control is implemented in the decoupled two-dimensional subspace systems using VSD variables ($\alpha-\beta$ and $x-y$). Apart from a pair of PI regulators for flux/torque control in the $\alpha-\beta$ plane, it is only necessary to add two pairs of PI regulators to gain full control over flux/torque production in each of the winding sets (blocks in grey in Fig. 4). The total number of current controllers is the same as it would have been had the MS modelling approach been used. However, in this case, current control is much simpler, since the machine is decoupled into multiple orthogonal subspaces.

IM, with parameters given in Table 1, is used in the simulation. It is supplied by ideal two-level nine-phase VSI, where carrier-based pulse-width modulation at 5 kHz is used to provide gating signals for the VSI switches. The machine has one pole pair ($P$) and is rated at 230 V, 50 Hz, and 2.2 kW. Although targeted microgrid applications require independent supply of each winding set by individual three-phase VSIs, using a single nine-phase inverter does not make any difference in implemented control nor does it affect validity of the results.

Two test scenarios have been considered in order to verify the operation of the developed current-sharing control. In the first test scenario, d-axis currents of all winding sets are kept equal ($k_{d1} = k_{d2} = k_{d3} = 1$) so that all winding sets equally contribute to the rotor flux production, while the torques producing q-axis currents are varied in five time intervals as follows:

- $[0.0 - 0.1]s$  \quad $k_{q1} = 1.0$,  \quad $k_{q2} = 1.0$,  \quad $k_{q3} = 1.0$;
- $[0.1 - 0.3]s$  \quad $k_{q1} = 0.4$,  \quad $k_{q2} = 1.2$,  \quad $k_{q3} = 1.4$;
- $[0.3 - 0.5]s$  \quad $k_{q1} = 0.7$,  \quad $k_{q2} = 1.8$,  \quad $k_{q3} = 0.5$;
- $[0.5 - 0.7]s$  \quad $k_{q1} = 1.5$,  \quad $k_{q2} = 0.0$,  \quad $k_{q3} = 1.5$;
- $[0.7 - 0.9]s$  \quad $k_{q1} = 0.0$,  \quad $k_{q2} = 3.0$,  \quad $k_{q3} = 0.0$;
- $[0.9 - 1.0]s$  \quad $k_{q1} = 1.0$,  \quad $k_{q2} = 1.0$,  \quad $k_{q3} = 1.0$.

In the second test scenario, both d-axis and q-axis currents of all winding sets are varied. Torque producing currents are varied in the same manner as in the first test, while the flux producing currents are varied in five time intervals as follows:

- $[0.0 - 0.2]s$  \quad $k_{d1} = 1.0$,  \quad $k_{d2} = 1.0$,  \quad $k_{d3} = 1.0$;
- $[0.2 - 0.4]s$  \quad $k_{d1} = 1.5$,  \quad $k_{d2} = 0.0$,  \quad $k_{d3} = 1.5$;
- $[0.4 - 0.6]s$  \quad $k_{d1} = 0.0$,  \quad $k_{d2} = 3.0$,  \quad $k_{d3} = 0.0$;
- $[0.6 - 0.8]s$  \quad $k_{d1} = 1.3$,  \quad $k_{d2} = 0.5$,  \quad $k_{d3} = 1.2$;
- $[0.8 - 1.0]s$  \quad $k_{d1} = 1.0$,  \quad $k_{d2} = 1.0$,  \quad $k_{d3} = 1.0$.

The first test scenario is obviously more realistic since all winding sets equally contribute to the rotor flux creation (reactive power), while torque producing q-axis currents govern active power of each winding set, enabling power sharing between winding sets.

Fig. 4 Schematic of the implemented control

$$
\begin{align*}
\dot{i}_{d1y} &= \frac{1}{6} \left[ 2(k_{d1} - k_{d2} - k_{d3}) \sqrt{3}(k_{q1} - k_{q3}) \right] \frac{i_d}{i_d} \\
\dot{i}_{q1y} &= \frac{1}{6} \left[ 2(k_{d1} - k_{d2} - k_{d3}) \sqrt{3}(k_{q1} - k_{q3}) \right] \frac{i_q}{i_d} \\
\dot{i}_{d2y} &= \frac{1}{6} \left[ 2(k_{d1} - k_{d2} - k_{d3}) \sqrt{3}(k_{q2} - k_{q3}) \right] \frac{i_d}{i_d} \\
\dot{i}_{q2y} &= \frac{1}{6} \left[ 2(k_{d1} - k_{d2} - k_{d3}) \sqrt{3}(k_{q2} - k_{q3}) \right] \frac{i_q}{i_d} \\
\dot{i}_{d3y} &= \frac{1}{6} \left[ 2(k_{d1} - k_{d2} - k_{d3}) \sqrt{3}(k_{q2} - k_{q3}) \right] \frac{i_d}{i_d} \\
\dot{i}_{q3y} &= \frac{1}{6} \left[ 2(k_{d1} - k_{d2} - k_{d3}) \sqrt{3}(k_{q2} - k_{q3}) \right] \frac{i_q}{i_d}
\end{align*}
$$

(4)
second test scenario is aimed at demonstrating the ability to arbitrarily change both $d$- and $q$-axis currents of each winding set. In both test scenarios currents are changed to random values and to the extreme cases, where either $q$- or $d$-axis currents are zero in one or two winding sets. Results are shown in Figs. 5 and 6. It can be seen that, in both test scenarios, $d$- and $q$-axis currents of all winding sets are changing as per set sequences. Since current sharing is implemented only by imposing currents in flux/torque non-producing $x$-$y$ subspaces, total machines flux and torque producing VSD currents $i_d$ and $i_q$ are not affected. Hence, there is no change in machine speed or torque, which confirms the validity of proposed control.

4 Experimental results

Experimental verification is performed on a custom-made asymmetrical nine-phase IM with the same parameters as given in the previous section. The machine is supplied by two custom made two-level seven-phase VSIs based on Infineon FS50R12KE3 IGBT modules, while dc link (600 V) is provided by four-quandarat linear amplifier Spitzenger & Spies PAS2500, equipped with resistive load RL4000. The machine shaft is coupled to the dc machine which operates in constant torque mode by using dc power supply Sorensen SG1600/25. Mechanical torque is measured by Magtrol TM210 torque meter. Control and measurements have been realised by use of rapid prototyping system dSPACE based on ds1006 processor board. Additional current and voltage measurements are available by use of Tektronix DPO/MSO 2014 oscilloscopes, complemented with current (TCP0030A) and high voltage differential (P5205A) probes. The experimental setup is show in Fig. 7. The implemented control structure is identical to the one used for simulations. However, due to the VSI dead time (6 μs) and non-ideal machine construction, it was found necessary to use additional resonant controllers for low-order harmonic elimination, as explained in [14]. This, of course, does not have any impact on the implemented current sharing.

The same test scenarios used in the simulations are repeated here. The results are depicted in Figs. 8 and 9 for the first and second test scenarios, respectively. It can be clearly seen that the $d$−$q$ currents of the winding sets are changed in the same manner as shown in the simulation results (Figs. 5 and 6), i.e. $d$−$q$ currents are changed as imposed by the current-sharing coefficients provided by the selected test scenario. Once again, there is no change in the total flux and torque producing VSD currents $i_d$ and $i_q$, so that the machine torque and speed are unaffected. It should be noted that scenarios tested here are the extreme cases of very fast change of current-sharing coefficients, which demonstrate high dynamic capability of the system. In normal operation rapid current change within 0.1 s interval would not be required.

Currents in the first phase of each winding set are only shown for the second test scenario (Fig. 10), since it represents more extreme case in terms of imposed imbalance. Amplitude of the phase currents is governed by the imposed winding set $d$−$q$ currents, and it can be seen that its value is greatly increased for a certain combination of current-sharing coefficients due to the absence of current limiting (in a real-world application, care should be taken to ensure that phase current does not exceed maximum allowed value). It should be noted that currents within each winding set are always balanced. This behaviour is a consequence of implemented rotational transformation, where the $d$−$q$ current vector of each winding set always travels along the circular path.

### Table 1

| Parameter   | Value |
|-------------|-------|
| $P$         | 1     |
| $R_s$       | 5.3 Ω |
| $L_m$       | 520 mH|
| $L_s$       | 24 mH |
| $L_r$       | 11 mH |

This is an open access article published by the IET under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0/).
A technique for arbitrary d–q current sharing between winding sets of multiple three-phase winding machines is presented. It enables independent control of both active and reactive powers of individual winding sets. Such control can be of importance when a multi-phase machine is connected to multiple independent sources or networks. Developed control is based on the correlation between MS and VSD variables, so that the best features of both modelling approaches are exploited: decoupled control of the VSD and access to individual winding set variables of the MS. The concept is applicable to any multiple three-phase winding machine, regardless of the type (induction or synchronous). It is tested here by simulation and experimentally using an asymmetrical nine-phase machine. A good agreement between simulation and experimental results, even in the most demanding scenarios, confirms the validity of the theoretical development.

6 References
[1] Levi, E., Bojoi, R., Profumo, F., et al.: ‘Multiphase induction motor drives – a technology status review’, IET Electr. Power Appl., 2007, 1, (4), pp. 489–516
[2] Levi, E.: ‘Advances in converter control and innovative exploitation of additional degrees of freedom for multiphase machines’, IEEE Trans. Ind. Electron., 2016, 63, (1), pp. 433–448
[3] Che, H.S., Levi, E., Jones, M., et al.: ‘Operation of a six-phase induction machine using series-connected machine-side converters’, IEEE Trans. Ind. Electron., 2014, 61, (1), pp. 164–176