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The Application of Average Voltage Estimation Models in Simulation of Permanent Magnet AC Electric Motor and Generator Drive Systems

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***Abstract*— This paper explores the application, development and potential benefits of using Average Voltage Estimation techniques in Matlab/Simulink modelling of Permanent Magnet AC (PMAC) electric motor and generator drive systems. These models can include all elements of a multi-technology system; electrical circuits, power electronics, digital control, electro-magnetic machine, dynamic mechanical loads, and in the case of wind turbines also time varying aerodynamic subsystems. The paper compares the performance of an average voltage model against the standard switching converter approach for both PMAC motor and generator drives to ensure the accurate prediction of key operating parameters throughout the complete operating range. The result is that the averaging model performs well for both motor and generator systems but with the significant advantage of greatly accelerated simulation times thus making this technique attractive for system level modelling which also requires detailed modelling of mechanical and possibly aeronautical systems.**

Keywords—permanent magnet machine drives; power electronic inverters; voltage averaging techniques

I. INTRODUCTION

The Matlab/Simulink simulation platform is used extensively in the modelling of electrical machines and associated drive circuits. These models allow the designer to determine and optimise the electrical machine performance for a given application, and also to develop and evaluate the associated control systems within the electronic drive. These models will include some form of power electronic converter which compared with other types of circuits have unique features such as high-frequency switching and large size and complexity that make the simulation particularly challenging in terms of intensive computation time and complex control circuitry. These factors result in notably long simulation times and convergence problems when used for power electronic circuit simulation and become even worse as power converter systems grow in size and complexity and as the operating frequency increases. Solving the convergence problem requires a good understanding of the device models, experience with the software, and, to some extent, trial and error [1]. One solution to decreasing simulation times is the use of averaging models for the power converters. These averaging techniques have been widely used either by applying to the state-space equations or to the switches [2-4]. In general terms, in order to define the system's specifications such as stability, response time and etc., the equivalent circuit is used to simulate the response of the system. Simulink incorporates such averaging models for specific machine drives but these models are fixed for the given control strategy and also the background theory in the support documentation is limited. This paper, therefore, presents a detailed outline of a generic and flexible voltage averaging model which can be applied to any three phase PWM control strategy. As can be seen in the paper the averaging block simply replaces the switching converter, using the same electrical machine and digital controller blocks, and therefore can be easily introduced into standard switching converter based models for situations which require accelerated simulation times while still maintaining important detail within the drive model. This work follows on from and further develops previous studies in the application of averaging models using the Portunus simulation platform [5].

II. PERMANENT MAGNET MOTOR DRIVE SYSTEMS

Permanent Magnet AC (PMAC) motor drives, traditionally used in high performance servos, have also seen development over the last number of years for a range of applications ranging from automotive power steering to aircraft actuation. This is primarily due to their high power density and low torque ripple characteristics. Using Matlab/Simulink the standard method to model the complete drive system is using power electronic switching converter topologies as outlined in Fig. 1.

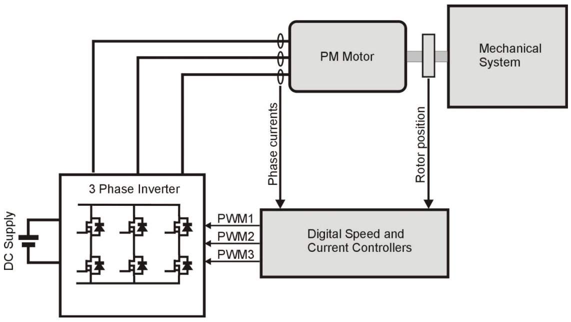


Fig. 1. Switching PMAC motor drive model.

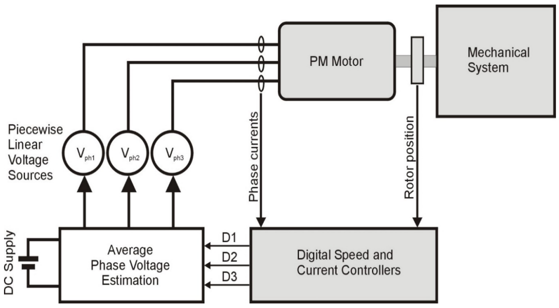


Fig. 2. Averaging PMAC motor drive model.

This approach allows the designer to determine the detailed drive performance including; machine torque vs speed curves, drive efficiency, optimising control algorithms, torque ripple etc. This is clearly a very useful tool to the designer but there is a cost and that cost is the time it takes to simulate even a few seconds worth of operation. This becomes a big problem when this approach is incorporated into complete system models including mechanical and possibly also aeronautical components where time constants are longer and simulation lengths are in the order of minutes if not hours. One solution to this, while still retaining a lot of the detailed drive performance data, is to replace the power electronic switching converter with an averaging model. The details of one simple yet flexible implementation will now be outlined.

III. AVERAGING PMAC MOTOR DRIVE MODEL

The proposed averaging model is outlined in Fig. 2. As can be seen, it uses identical PMAC motor model and digital controller blocks thus retaining its ability to accurately model a number of key drive parameters but replaces the power electronic switching converter with three piecewise linear voltage sources controlled by the average voltage estimators.

The averaging operation begins with the three phase PWM duty cycles output from the digital current controllers, an example PWM output being shown in Fig. 3. Before describing the subsequent averaging process it is worthwhile noting that this process is completely independent of the digital current controller topology and so can be applied to any control algorithm, e.g., Space Vector Control, PI control etc., thus making it a generic and flexible technique. It is also worth noting that the control block can also include outer speed and/or position control algorithms. Observing Fig. 3 it can be seen that the PWM period can be divided into four time zones, $t_0 - t_3$ with the corresponding motor phase connections during each of these time zones shown in Fig. 4.

Further investigation shows that there are six particular duty cycle sectors with unique average voltage equations for each sector, therefore the first requirement of the average voltage estimation block is to determine which of the six possible sectors the PWM switching pattern is currently in by interrogating the three phase duty cycle values, the implementation of which is shown in Fig. 6. The basic requirement is to determine the order of duty cycles, i.e., D1 > D2 > D3, and from that 'enable' the relevant Sector voltage example of which is shown in Fig. 7.

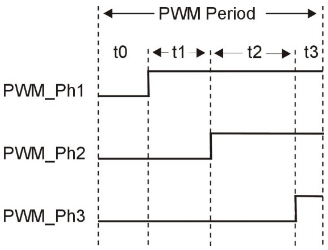
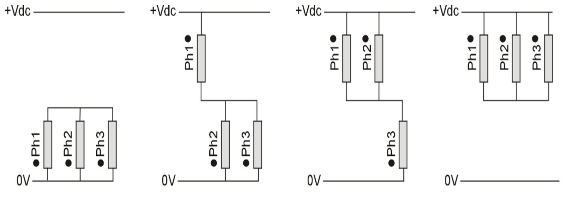


Fig. 3. Example PWM switching periods.



t0 Phase connections
t1 Phase connections
t2 Phase connections
t3 Phase connections

Fig. 4. Phase connections during time zones t_0 - t_3.

Time Zone	V_{ph1}	V_{ph2}	V_{ph3}
t0	0	0	0
t1	$\frac{+2.Vdc}{3}$	$\frac{-1.Vdc}{3}$	$\frac{-1.Vdc}{3}$
t2	$\frac{+1.Vdc}{3}$	$\frac{+1.Vdc}{3}$	$\frac{-2.Vdc}{3}$
t3	0	0	0

$$V_{av\_ph1} = \frac{(2.t1 + 1.t2).Vdc}{3.T}$$

$$V_{av\_ph2} = \frac{(-1.t1 + 1.t2).Vdc}{3.T}$$

$$V_{av\_ph3} = \frac{(-1.t1 - 2.t2).Vdc}{3.T}$$

Fig. 5. 'Average' voltage calculations.

The final requirement is to determine the 'average' DC Link current during every PWM switching period based on the instantaneous motor phase currents and the calculated sector, and then combine these to determine the actual mean DC Link current over a complete revolution. With reference to Fig. 5, during the t_1 time zone all the DC link current flows in a positive direction through phase one and during the t_2 period all the DC link current flows in a negative direction through phase three.

The 'average' DC link current during the complete PWM period (T) is therefore given by the equation:

$$I_{dc\_ave} = \frac{\left(\left(t_1.I_{ph1}\right) - \left(t_2.I_{ph3}\right)\right)}{\mathrm{T}} . \qquad (1)$$

Once again this equation is only valid for one of the six sectors so there is a separate calculation block for each sector, an example of which is shown in Fig. 8, and then these are combined to determine actual mean DC Link current.

IV. PMAC MOTOR DRIVE SIMULATION RESULTS

Two Simulink models were developed using an identical PMAC motor model and digital PI current controllers, and the switching inverter model was based on ideal switches and default diodes.

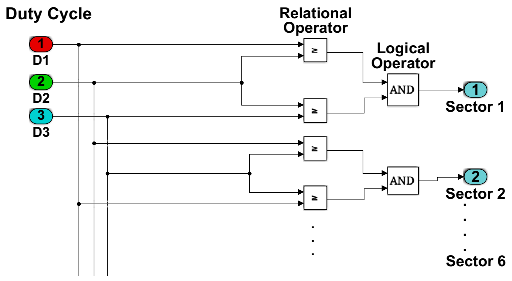


Fig. 6. Averaging model sector block.

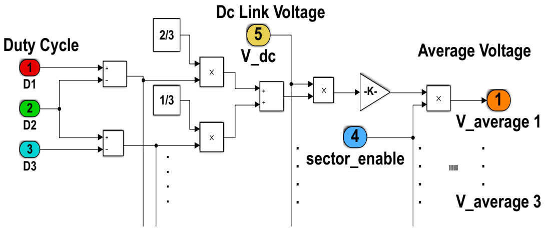


Fig. 7. Example sector average voltage calculations.

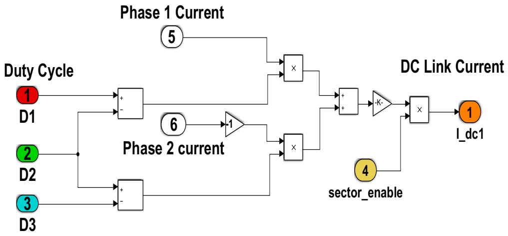


Fig. 8. 'Average' DC link current sector calculation block.

The PI current regulators are based on a tried and tested design implemented in a number of practical laboratory drive systems at the University of Glasgow. The six inverters switches are controlled with 10 kHz PWM signals output from the current controller block. Basic simulations were carried out at a constant current reference of 1 A peak and 100 V DC Link over the complete operating speed range of the particular motor.

The key requirements of the averaging model are to accurately reproduce torque vs speed performance, calculate average input current and correctly predict instantaneous phase current waveforms (excluding switching current ripple) over the complete operating range of the motor, including the high speed field weakening region. Simulation results for these are shown in Fig. 10 with plots of torque vs speed and DC Link current vs speed for both the switching and averaging models. As can be seen there is near identical results for both simulation models (the torque curves actually lie on top of each other), with both models indicating that the current controllers can no longer maintain sinusoidal currents above 2000 rpm and as a result, the motor torque quickly falls to zero above this speed.

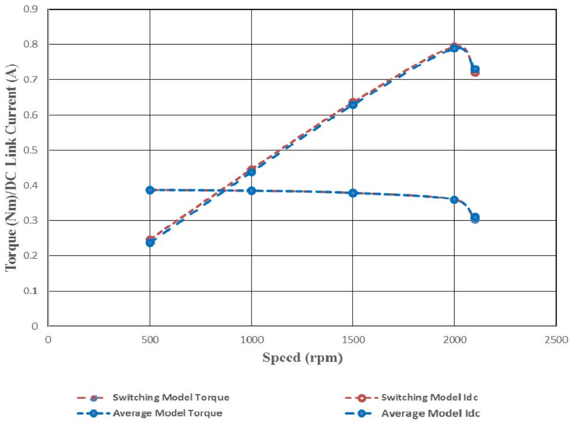


Fig. 10. PMAC motor drive simulation results.

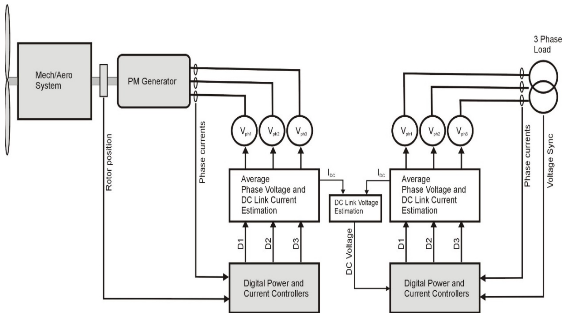


Fig. 11. Average voltage model for PM generator with back to back converters.

Given these comparable results, the key question now is long did each model take to execute for a simulation length of 5 seconds?

Results: Switching Model = 5 mins 45 secs and the Averaging Model = 24 secs thus the Averaging model has a significant advantage when it comes to simulation time as hoped.

V. PMAC GENERATOR SYSTEMS

Given these encouraging results, a logical next step would be to develop the concept for a variable speed PM generator connected to a three phase fixed frequency load via back to back converters, a block diagram of the averaging model implementation being shown in Fig. 11. A three phase six switch/ six diode converter (MSC) connects the PM generator to the intermediate DC Link and then a further three phase six switch/ six diode converter (GSC) connects the DC link to the fixed frequency three phase load or grid. The control requirements are such that the MSC controls the amount of power taken from the mechanical system driving the generator, this power being put into the intermediate DC Link capacitor. The GSC is then required to maintain constant DC Link voltage by controlling the currents/power taken from the DC Link and output onto the three phase load/grid.

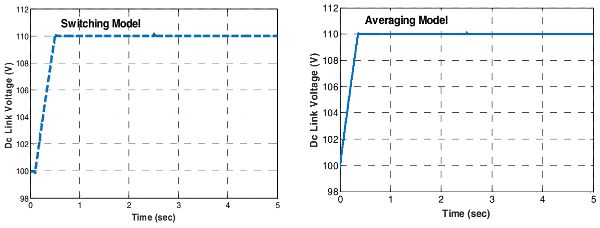


Fig. 12. DC link voltage.

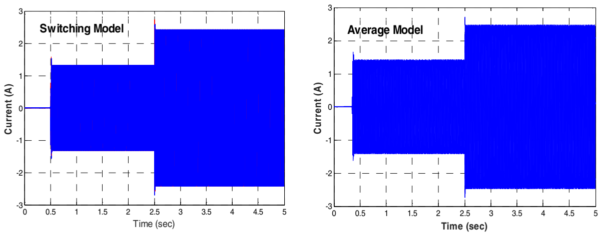


Fig. 13. Three phase load currents

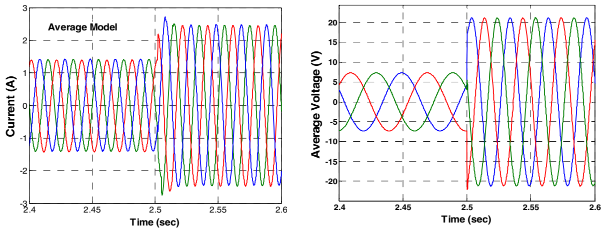


Fig. 14. Zoomed plot of three phase load currents and average voltage.

The additional requirements for the generator model compared to the motor drive averaging model is the additional three phase converter stage and also a DC Link voltage estimation block based on the net difference in charge from the current being supplied to the DC Link capacitor from the MSC and the current flowing to the load through the GSC.

VI. PMAC GENERATOR SIMULATION RESULTS

Once again two models were developed to implement the PM generator with back to back converter connection to a three phase load, one implementing a standard switching converter topology and the other based on the average voltage technique. A simple step change in generator speed from 500 rpm to 1000 rpm was implemented with the sinusoidal generator currents being fixed at 3A peak, and the DC Link voltage regulated at 110V. Simulation results from the two models were recorded for the DC Link Voltage and three phase load currents and are shown in Fig. 11 and 12 respectively. As can be seen in Fig. 11 the DC Link voltage is accurately regulated at 110 V for both models with each showing a slight transient at 2.5 seconds when there is a step change in generator speed from 500 rpm to 1000 rpm. This increase in generator speed results in an increase in mechanical power and subsequently an increase in the current suppled to the DC Link from the generator. This increase in generator power results in a corresponding increase in the three phase load currents (power) as can be seen at 2.5 seconds in Fig. 12. Once again given these comparable results the question is how long did each model take to execute for a simulation length of 5 seconds? Results: Switching Model = 17 mins 45 secs and the Averaging Model = 18 secs thus the averaging model has an even greater advantage when it comes to simulation time due to the fact that the switching model now consists of two 3 phase converters.

VII. CONCLUSIONS AND FUTURE WORK

The most important results from both the motor drive and generator models indicate that the averaging model has a significant advantage in terms of simulation execution time compared with the equivalent switching model, this advantage increasing as the number of switching converters increases. The averaging model accurately predicts a number of key parameters as a summary of these along with the standard switching model approach are given in Table 1. The result is that the only areas where the switching model gives additional detail are being in converter ratings/efficiency and current ripple.

Future work will further develop the single machine models with one particular application to incorporate the averaging model into a complete wind turbine model, thus allowing detailed generator performance analysis in a dynamic wind regime. In addition given the increasing benefits in terms of execution times as the number of converters increases is proposed to investigate the use of the averaging technique in multi-machine/converter systems.

TABLE 1. COMPARISON OF PERFORMANCE.

Areas of Study	**Switching Model**	**Averaging Model**
Torque vs speed performance	Yes	Yes
Field weakening operation	Yes	Yes
DC Link current/power	Yes	Yes
Machine efficiency	Yes	Yes
Digital control loops optimisation	Yes	Yes
Machine current ripple	Yes	No
Power Converter losses	Yes	No

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