Operation Method for AC Grid powered PMSM with Open-End Winding in Dual-Inverter Topology for Power Factor Maximization

F. Ludwig, A. Möckel †*

**TU Ilmenau, Germany, florian.ludwig@tu-ilmenau.de, †TU Ilmenau, Germany, andreas.moeckel@tu-ilmenau.de*

Keywords: PMSM; Dual Inverter; Power Factor; Open-End Winding; AC

Abstract

The paper proposes a new operation method of permanent magnet synchronous machines in single phase AC grids by using a dual-inverter topology. The proposal is targeting on the reduction of current harmonics and maximization of the power factor of the drive system. This can be achieved without additional energy storing inductors, like filter- or PFC-chokes. This new operation method can be considered as a combination of an active PFC and inverter operation.

1 Introduction

Drive systems with permanent magnet synchronous machines are well suited for the use in DC power supply applications, like auxiliary drives in cars or battery powered handheld power tools. AC grid operations, especially in single phase powered devices, are an exception. The reasons therefor are manifold. Common control strategies require a constant input voltage at the inverter stage. Thus, a high amount of energy storing capacitors is needed to compensate the power gap in singe phase AC supplies. To consider the requirements for power quality with regards to power factor and current harmonics, an additional filter stage is necessary. This is commonly implemented by a large and heavy passive PFC choke, or an expensive active PFC circuit. At this point, the advantages of the PMSM compared to a classic universal motor are often nullified. Another operation strategy is to reduce the DC link capacitance to a minimum by using film capacitors and adapting the control loop for voltage fluctuations [1]. Smaller DC link capacitance leads to the beneficial effect of smaller current pulses. However, some disadvantages with respect to power quality, especially at higher drive power occur [2,3]. Furthermore a constant torque operation of the machine is not possible.

The idea of the proposed operation method is to use the inductance of the machine for the DC link charge process and to spare an additional filter inductor. Therefore the dual inverter topology with isolated DC links is used. To form a sinusoidal input current with a power factor near 1, an adjusted control strategy for the drive system operation was developed.

2 Inverter topology comparison

To overview the common AC inverter topologies and the proposed dual-inverter topology for AC operations with its advantages and disadvantages, a short topology comparison is given in the next section.

2.1 Conventional inverter topology with active PFC stage

The most prevalent inverter topology for single phase AC operation of a PMSM represents the conventional inverter with an active power factor correction stage. A typical design with one inductor and one switch-diode pair is shown in Figure 1. Furthermore a wide range of other PFC designs are present in different applications, for example the interleaved PFC or the bridgeless PFC design [4].

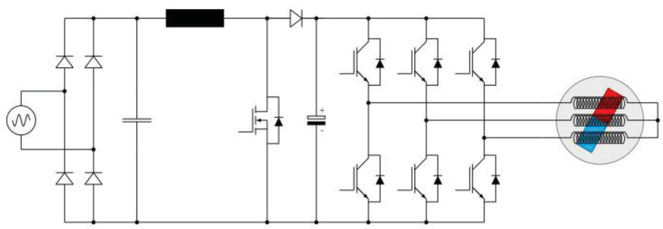

Figure 1: Example for AC inverter with active PFC stage

This topology offers the possibility for a constant power operation of the machine with a sinusoidal input current waveform and a power factor of almost one (typical 0.99) [4]. The control algorithm for the machine operation does not differ from control strategies of DC applications, because DC link voltage fluctuations are moderate compared to the voltage level.

Disadvantages of this topology are the additional components for the PFC circuit with its large installation spaces, especially for the PFC inductor. Combined with a large DC link capacitor, the size of the inverter and PFC electronics exceeds the machine size by far. Drive systems for mobile or handheld applications are therefore difficult to realize.

2.2 Inverter topology with small DC link capacitor

This simplest hardware design for a single phase AC PMSM inverter is a standard machine inverter with an additional diode rectifier and a small film capacitor, as shown in Figure 2. To avoid power factor distortion and high input current harmonics, caused by capacitor charge currents, the capacitance of the DC link is reduced to a minimum, which is required for commutation overvoltage limitation.

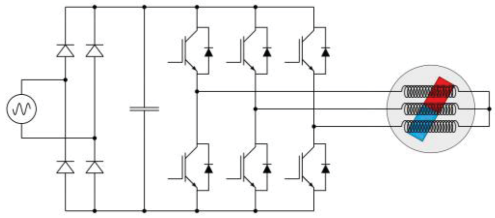

Figure 2: AC inverter with small film capacitor

Depending on the PCB layout and the grid inductance, only a few µF of capacitance are required in the DC link. In contrast designs with electrolytic capacitors, several hundred µF are required due to high ESR values [1]. This leads to small installations spaces for the inverter electronics.
Because of the lack of energy storing capabilities, a constant power operation of the machine is not possible at single phase AC operation. An adapted control strategy for power factor maximization is also required, because the actual input power and the actual machine power are coupled within this design.

2.3 Dual-Inverter topology for AC operations

The proposed dual-inverter topology for single phase AC operations constitutes a combination of an inverter with small film capacitor at the AC side, and an inverter with large electrolytic capacitors on the isolated side. Both are connected through an open-end winding of the PMSM (shown in Figure 3) [5]. Thus, high charge currents from the AC grid can be avoided and energy for constant power operation of the machine can be stored.

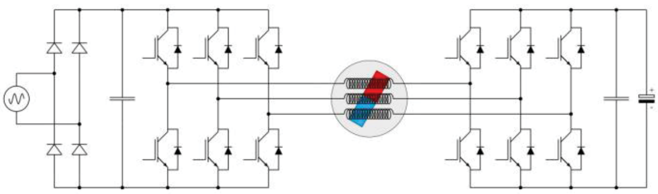

Figure 3: AC dual-inverter topology with isolated DC links

The AC side of the inverter is also called the primary side, the other is called the secondary side. Within this design, the PFC inductor can be spared, because the machine inductance is used for current limitation. Especially for higher power regions of the drive system, costs and installation space of an additional compact three-phase bridge module may undercut the amounts compared to an additional PFC circuit. With an adapted field oriented control algorithm, it is possible to impress a sinusoidal input current and reach high power factors (see measurements in section 5). The disadvantage of this topology is the number of active switching devices in the current path. Therefore a reduced efficiency of the inverter electronics has to be expected. Also a special winding layout of the machine is required.

3 Control strategy

The applied control strategy for the dual-inverter is based on the field oriented control algorithm. Nevertheless there are many differences to common dual-inverter control strategies. Figure 4 shows the block diagram of the control algorithm.

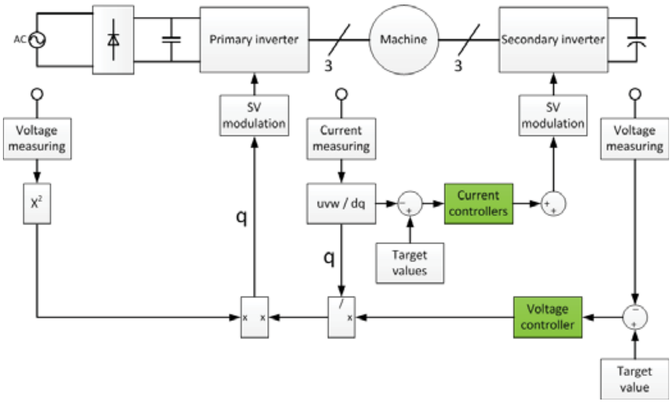

Figure 4: Dual-inverter control scheme

Three fundamental controllers are included in the control scheme, two current controllers for the d- and q-axis current of the machine and a voltage controller for the floating DC link voltage of the secondary side. The voltage inverter of the secondary side is controlled from the two current controllers, while the voltage inverter of the primary side is controlled by the voltage controller of the secondary DC link voltage.
To create a sinusoidal input current with a high power factor, the output power of the primary inverter has to oscillate with a $\sin^2$ function synchronous to the AC grid. This condition has to be applied, because a sinusoidal grid current in phase to the impressed sinusoidal grid voltage results in a $\sin^2$ shaped grid power. Due to the small DC link capacitance of the primary side, the grid power and the output power of the primary inverter are coupled.

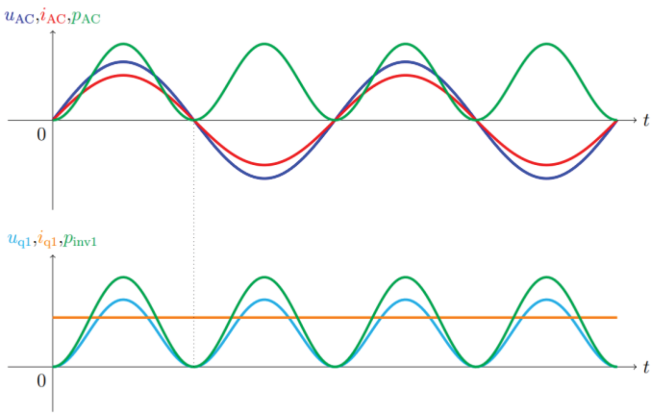

Figure 5: Exemplary progressions of voltage, current and power at AC input and primary inverter output

To generate this output power progression at the primary inverter, the q-axis voltage has to swing with a $\sin^2$ shape as well, while the machine is operating with a constant q-axis current under normal circumstances, as shown in Figure 5. Thus the shape of the output power of the primary inverter is fixed and synchronous to the grid voltage. To control the voltage level of the secondary DC link, the amplitude of this output power is controlled by the voltage controller. If the voltage level drops, the voltage controller increases the output power by increasing the q-axis voltage at the primary inverter. The d-axis voltage of the primary side is forced to zero.

The control scheme for the current controllers is identical to the common field oriented current controllers including one exception. The impressed voltage of the primary inverter is added to the decoupling network, so that voltage and current controllers does not affect each other [6].

For this control strategy a q-axis current through the machine is necessary. For *no load conditions* or *standstill events*, a precharge functionality for the secondary DC link with d-axis current is possible.

To perform the proposed control strategy, the actual values of the machine currents, the AC grid voltage and the secondary DC link voltage have to be measured.

4 Winding layout

To realize the rated output power of the PMSM with this dual-inverter topology, the winding layout of the machine has to be adapted. It can be determined by creating the power balance of the drive system. The average input power and the average mechanical output power are connected by the efficiency of the power electronics and the machine, as shown in equation (1).

$$\overline{P}_{\text{input}} = \frac{\overline{P}_{\text{mech}}}{\eta_{\text{inverter}} \cdot \eta_{\text{machine}}} \tag{1}$$

The mechanical output power of the PMSM is composed by the product of speed and torque. The torque of the machine can be approximately expressed by the q-axis current, the number of poles p and the stator flux linkage of the permanent magnets, if the d-axis current is controlled to zero [6].

$$\begin{aligned} \overline{P}_{\text{mech}} &= 2\pi \cdot M \cdot n \\ \overline{P}_{\text{mech}} &= 2\pi \cdot \frac{3}{2} \cdot \frac{p}{2} \cdot i_q \cdot \Psi_{\text{PM}} \cdot n \\ \overline{P}_{\text{mech}} &= \frac{3}{2}\pi \cdot p \cdot i_q \cdot w \cdot \phi_{\text{PM}} \cdot n \end{aligned} \tag{2}$$

Because the primary inverter does not have major energy storing capabilities, the input current and the current of the machine are coupled by the drive level M_1 of the primary inverter. The maximum drive level of the inverter is reached at maximum input voltage, because the machine is fully driven by the primary side and the capacitor of the secondary DC link has to be charged. By assuming a $\sin^2$ shaped input power progression, the maximum input power is twice the average input power. The following relation can be drawn for the event of maximum input voltage:

$$\begin{aligned} 2 \cdot \overline{P}_{\text{input}} &= \hat{U}_{\text{AC}} \cdot \hat{I}_{\text{AC}} \\ 2 \cdot \overline{P}_{\text{input}} &= \hat{U}_{\text{AC}} \cdot \hat{M}_1 \cdot \frac{i_q}{\sqrt{3}} \end{aligned} \tag{3}$$

If the equations (2) and (3) are inserted to (1), the required number of windings w can be calculated as follows:

$$w = \frac{\hat{U}_{\text{AC}} \cdot \hat{M}_1 \cdot \eta_{\text{inverter}} \cdot \eta_{\text{machine}}}{3\pi \cdot \sqrt{3} \cdot p \cdot \phi_{\text{PM}} \cdot n} \tag{4}$$

The variable n represents the speed, at which the machine should establish its rated power. The efficiencies of inverter and machine have to be calculated or estimated. The maximum drive level depends on the design of the drive circuit. Electronics with bootstrap configuration normally use a drive level limitation of 0.9 - 0.95 [7]. These considerations apply for drive system operations with d-axis current equal to zero and therefore without regarding's to reluctance torque influences.

5 Measurement results

To verify the considerations and calculations and to proof the operation behaviours of the dual-inverter topology at the AC grid, a test setup of a PMSM with an adapted open-end winding in dual-inverter configuration was assembled. Table 1 shows the parameters of the test machine.

Parameter	***Value***
Phase resistance	75 mΩ
Direct axis inductance	250 µH
Quadrature axis inductance	360 µH
Poles	4
Rotor flux linkage	11 mWb
Windings	34

Table 1: Test machine parameters

The drive system was operating at a 230V AC power supply with a 50Hz grid frequency. Figure 6 shows the test bench with the eddy current brake, the test machine and the test inverter.

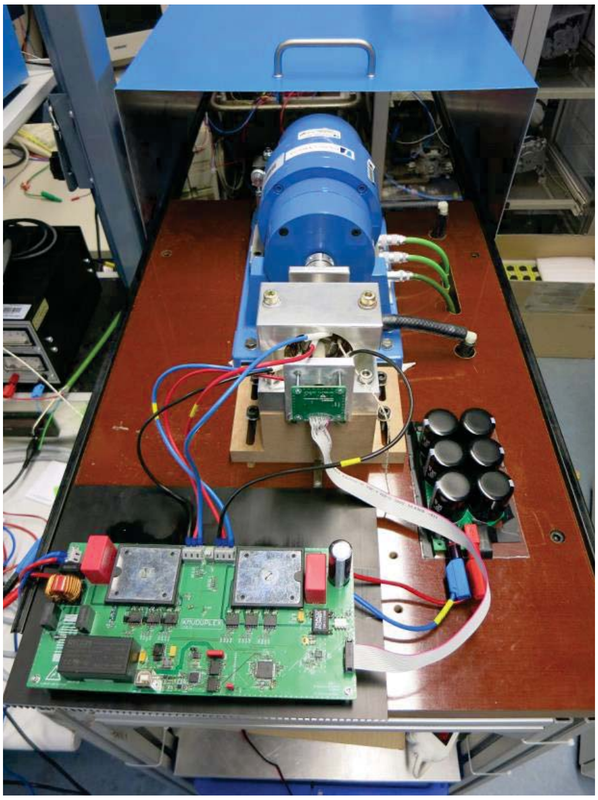

Figure 6: Test bench

The PMSM runs at an operating point of 20.860 rpm with a load torque of 0.813 Nm. This corresponds to a rated output power of 1.77 kW. Progressions of both DC link voltages, one phase current of the machine and the input current from this operating point are displayed in Figure 7.

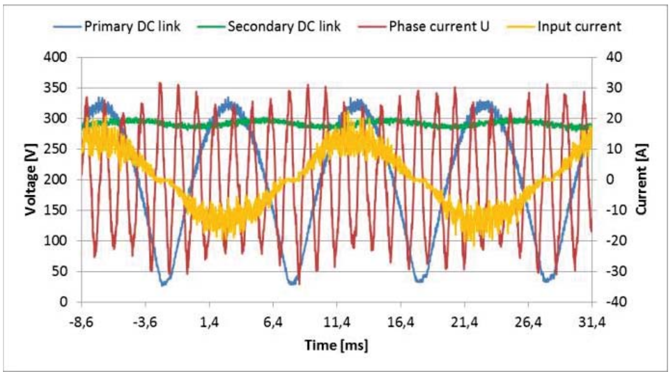

Figure 7: Progressions of the drive system at operating point

It can be seen, that the blue coloured curve of the primary DC link voltage correlates to the rectified AC voltage of the grid, due to the small DC link capacitance of the primary side. The yellow drawn input current is sinusoidal and in phase to the rectified grid voltage. The power factor can be ascertained to 0.96 . The green coloured secondary DC link voltage has a value of about 300V with a superposed ripple of 20-30V due to charge and discharge processes. The size of the secondary DC link capacitance of the test inverter amounts approximately 2800µF. The phase current in red shows a constant operation of the machine, even at zero voltage events of the AC grid. Some fluctuations in the amplitude of the machine current, which represents a pure q-axis current, can be lead back to the control limit of the drive system and a drive level near 1. The overall efficiency of the drive system at the operation point amounts 80.7%. This is comparable to an active PFC inverter topology with an efficiency of approximately 94% at the PFC circuit.

Figure 8 shows the harmonic analysis of the input current. The percentage of the total harmonic distortion is with 11.7% pretty low and comparable to advanced PFC solutions.

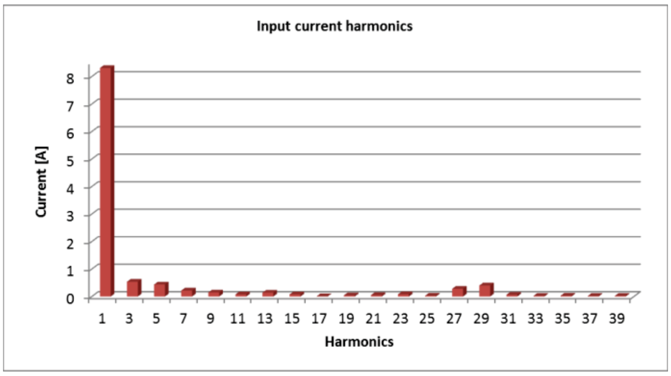

Figure 8: Harmonics of input current at operating point

6 Conclusion

As the prototype testing showed, the proposed operation method of the PMSM in dual-inverter topology at a single phase AC grid achieved performances, which are comparable to drive system solutions with an active PFC stage. The benefit of this solution is the displacement of additional PFC inductors. These inductors are responsible for a large percentage of costs and installation spaces in conventional topologies with active PFC circuits.

Instead an additional three-phase bridge is necessary, which slightly reduces the overall efficiency of the drive system [8]. Also an adaption of the winding is required, to reach the rated machine power. Due to the reduction of the number of turns compared to the normal design criteria and the resultant decreasing of the machine inductance, the phase current ripple increases.

Nevertheless the proposed operation method may achieve advantages in the matter of cost and installation space reduction of the drive system in various applications. The decision, which system design is to prefer depends on the circumstances of the drive task.

Another aspect is the safety reason concerning braking torques at failure states of the machine. In the case of a winding short-circuit event, machines with neutral point connections generate major braking torques which can harm the application requirements [9]. The dual-inverter topology offers the possibility of open-end phase connections and can therefore prevent braking torques in failure cases.

References

[1] H. Lamsahel, P. Mutschler. "Permanent Magnet Drives with Reduced DC-Link Capacitor for Home Appliances", *Industrial Electronics*, 2009. IECON´09. 35th Annual Conference of IEEE, pp. 725-730.

[2] M. Cacciato, S. De Caro, A. Testa, and A. Consoli. "Using the DC Bus Current to Improve the Power Factor in Low-cost Electric Drives." *IEEE International Electric Machines and Drives Conference* IEMDC 10637.pdf, Madison, Wisconsin 2003.

[3] S.-W. Kang, S.-I. Kim, R.-Y. Kim, D.-S. Hyun. „A Novel Power Factor Control for Synchronous Motor Drive System with Small DC-link Capacitor", *Vehicle Power and Propulsion Conference* (VPPC), 2013. IEEE.

[4] J.P.M. Figueiredo, F.L. Tofoli, and B.L.A. Silva. "A review of single-phase PFC topologies based on the boost converter", *Industry Application* (INDUSCON), 2010. 9th IEEE/IAS International Conference on.

[5] Y. Lee, J.-I. Ha. "Power Enhancement of Dual Inverter for Open-end Permanent Magnet Synchronous Motor", *Applied Power Electronics Conference and Exposition* (APEC), 2013, 28th Annual IEEE.

[6] N.P. Quang, J.-A. Dittrich. "Vector control of three-phase AC machines", Springer, Berlin, 2008.

[7] "Design and Application Guide of Bootstrap Circuit for High-Voltage Gate-Drive IC", *Application Note AN-6076*, Fairchild Semiconductor Corporation*, 2008.*

[8] U. Schwalbe, M. Protze, M. Scherf, T. Reimann, J. Petzoldt "Which is the best PFC stage for a 1KW application? Comparison of different PFC stage topologies under an identical design philisophy", *International Exhibition & Conference for Power Electronics Intelligent Motion Power Quality* (PCIM), 2011.

[9] S.A. Hossain, E.R. Oliveira. "Braking torque analysis of PMSM motor under stator winding failures", *Electrical Machines* (ICEM), 2012. 20th International Conference on.