Design of a three-phase 100 A linear amplifier for power-hardware-in-the-loop machine emulation

Manuel Fischer\(^1\), Robert Malić\(^1\), Nathan Tröster\(^1\), Johannes Ruthardt\(^1\), Jörg Roth-Stielow\(^1\)

\(^1\)Institute for Power Electronics and Electrical Drives University of Stuttgart, 70569 Stuttgart, Germany

E-mail: fischer@ilea.uni-stuttgart.de

Abstract: Here, the setup of a three-phase 100 A linear amplifier is proposed. This work focusses on the use of this linear amplifier as power element for machine-emulation. In contrast to common power electronics, a linear amplifier avoids ripple content in the output current caused by switched-mode operation.

1 Introduction

In order to offer safely running drive systems, developers have to test all components of the drive system consisting of an electric machine and a three-phase inverter. Therefore, a machine test bench is typically used. A load machine is mechanically coupled to the surveyed machine to set several mechanical operating points. The device under test inverter is connected to a constant voltage source at the input clamps and to the machine at the output clamps. To do a revealing test, it is necessary to set as many as possible operating points and analyse if the whole drive system runs as desired. Such machine test benches are quite expensive and complex to implement.

An alternative way to test the drive inverter is the emulation of the machine's electrical behaviour [1, 2, 3]. Instead of connecting the device under test inverter to the real surveyed machine, it is now connected to the power-hardware-in-the-loop (PHIL) machine emulator, which has the same electrical characteristic at the connecting terminals as the surveyed machine.

To emulate the electrical behaviour of electric machines, two essential components are required. On the one hand, a detailed machine model is indispensable. The machine model replicates the machine's behaviour in software and controls the power electronic device. On the other hand, it is necessary to utilise a power electronic device which transfers the demands of the machine model as exactly as possible. A main problem by using common power electronics is their switched-mode operation, which leads to a ripple content in the output current. This differs from the current which will occur if real electric machines are driven. Several concepts to minimise the ripple content in the output current are already reviewed. In [4, 5, 6], a concept of multiphase inverter with an interleaved modulation technique is presented. The higher effective switching frequency leads to less ripple content.

A different approach is the use of an additional LC-filter after the inverter which, however, leads to a lower cut-off frequency and worse dynamic [7].

Here, the use of a linear amplifier as power electronic device for a PHIL machine emulator for machines with maximum voltages up to 12 V is proposed. Due to a special concept of parallelisation, the amplifier can drive output currents up to 100 A without any ripple content caused by switched-mode operation. In addition to the setup of the amplifier, measurement results of crossover distortions’ investigation and frequency response are shown. Finally, the operation as PHIL machine emulator is presented.

2 Setup of the amplifier

The proposed class AB linear amplifier consists of two stages: a pre stage and a final stage. The pre stage can be divided into a circuitry of operational amplifiers and a driver stage, which facilitates the base current for the final stage's transistors. In Fig. 1, the setup of the three-phase linear amplifier is depicted.

2.1 Pre stage of one amplifier's phase

The pre stage has two tasks. On the one hand, it has to offer a high resistive input. Typically, controller units, like microcontrollers, only drive quite low currents. So it is necessary that the amplifier can be controlled by a voltage signal with almost no current flow. On the other hand, the pre stage has to generate currents, which serve as base currents for the final stage. In Fig. 2, the schematic of the pre stage is shown. The differential amplifier provides the demanded high resistive input. The ratio between the resistors \(R_1\) to \(R_4\) defines the amplification factor of the linear amplifier. If \(R_1 = R_3\) and \(R_2 = R_4\) are valid, the amplification factor \(A_V\) calculates to

\[
A_V = \frac{R_1}{R_f} \tag{1}
\]
To avoid crossover distortion at the output by higher cross currents in the final stage, an additional offset is generated for the drive voltages. The absolute values of the offset voltages $V_{\text{offset}}^{+}$ and $V_{\text{offset}}^{-}$ have to be greater than the sum of threshold voltages of the following transistors.

The following driver stage's task is to amplify the output current of the operational amplifiers OP2 and OP3. Due to the added offset voltages, the transistors $T_{\text{dr}1}$ and $T_{\text{dr}2}$, respectively, $T_{\text{dr}3}$ and $T_{\text{dr}4}$ would start to conduct without any input signal. To limit the cross currents through these transistors, the resistors $R_9$ and $R_{10}$ are added. Being able to drive base currents into the final stage's transistors, the driving voltage $V_{\text{dr}}$ is 10 V greater than the DC-link voltage $V_{\text{DC}}$ of the final stage.

2.2 Final stage of one amplifier's phase

The final stage has to drive output currents up to 100 A. Therefore, 12 transistor branches are parallel-connected. Every branch consists of one NPN- and one PNP transistor and of two symmetric resistors $R_{\text{sym}} = 220 \, \text{mΩ}$. The symmetric resistors $R_{\text{sym}}$ are needed because of the transistors' negative temperature coefficient to ensure a symmetric division of the load current on the 12 branches. Otherwise, an asymmetric division of the load current could lead to a positive feedback between transistor current and junction temperature and finally to a destruction of the transistors. Moreover, base resistors $R_b$ are added to force a symmetric division of the base currents driven by the pre stage. In Fig. 3, the schematic of the final stage is shown.

3 Measurement results

3.1 Crossover distortion

In order to analyse the intensity of crossover distortion, the amplifier is directly controlled by a rapid prototyping system which generates a sine-signal for the amplifier's input. The amplitude of the sine-signal is 2.5 V, the frequency is 40 Hz. The amplification factor of the linear amplifier is set to $A_{V} = 1$.

Fig. 4 shows the measurement results of the output voltage. In Fig. 5, a detailed view of the red-marked area is depicted. Crossover distortion at the zero-crossing are in evidence but there are only short-time impulses with amplitudes less than 0.3 V. In use as PHIL machine emulator, the linear amplifier is coupled by a coupling inductor to the device under test inverter. The coupling inductor filters these short-time impulses so that they are insignificant for the PHIL emulator application.

In general, the output voltage follows the input signal quite accurate. Even the steps of the input signal, caused by the digital-analogue-conversion of the rapid prototyping system, are visible.

3.2 Frequency response

For the purpose of analysis of the amplifier's frequency of behaviour, the frequency response is recorded. The amplifier's input of one phase is connected to a sine frequency generator which varies the frequency between 10 Hz and 50 kHz. The amplitude of the input voltage is constant $v_{\text{in}}^\sim = 5 \, \text{V}$, the amplification factor of the linear amplifier is set to $A_{V} = 1$. The amplifier's output is open-circuited. By measuring the corresponding amplifier's output voltage in comparison with the input voltage, the frequency response can be calculated. The results of one phase are depicted in Fig. 6.

Up to 26 kHz, the amplifier has a constant amplitude ratio $V_{\text{out}} / V_{\text{in}} = 98.4\%$. The cut-off frequency is about 35 kHz.

Up to 5 kHz, there is no phase shift $\phi$ visible between the output and the input voltage. At 5 kHz, a small drop and, at 26 kHz, a strong decrease are visible.

In order to investigate the influence of a load connected to the output terminals, a further frequency response is recorded. The amplifier's input of one phase is connected to a sine frequency generator which varies the frequency between 10 Hz and 50 kHz. The amplitude of the input voltage is constant $v_{\text{in}}^\sim = 5 \, \text{V}$, the amplification factor of the linear amplifier is set to $A_{V} = 1$. The only difference in comparison with the measurement setup before is an additional load resistance $R_L = 110 \, \text{mΩ}$ connected to the output terminals.
currents, the partial currents cause a voltage drop across every resistor and the load current. If the load current is measured, the voltage drop in a control system, these voltage drops across the symmetric resistors and the load current. If the load current is measured, the voltage drop across the symmetric resistors will act as a disturbance value. As seen in (2), the voltage drops depend on the known resistance value of the symmetric resistors and the load current. If the load current is measured, the voltage drop will be considered as known disturbance variable as a function of the load current. With the objective of eliminating the influence of the voltage drop, it can be respected in the calculation of the actuating variable by disturbance feedforward control or an integral element in the current controller.

At 5 kHz, the course of the amplitude ratio decreases more strongly than in the case with open-circuit output. This behaviour is caused by parasitic inductances in the setup of the amplifier and especially in the link between the amplifier and the load. The parasitic inductances’ influence rises according to a higher frequency in the case of load current flow.

The phase shift’s course is traced back to the same explanation. According to a higher frequency, the influence of parasitic inductances rises and thereby the phase shift’s absolute value.

All in all, the measurement of the frequency response reveals that the linear amplifier’s bandwidth is high enough not only to emulate the fundamental component of the electrical behaviour of machines but also harmonic components. Even in case of load connected to the output, it has an acceptable frequency response up to \( f_{\text{max}} = 10 \text{ kHz} \). The numbers of harmonic components \( v_{\text{harm}} \), which are able to be emulated by the linear amplifier, are calculated with (3) dependant on the maximum rotational speed \( n_{\text{max}} \) of the emulated machine and its pole pair number \( z_p \).

\[
v_{\text{harm}} = f_{\text{max}} \times 60 \text{ s/min} / z_p \times n_{\text{max}} \tag{3}
\]

4 Operation as PHIL machine emulator

4.1 PHIL machine emulator setup

In order to operate the linear amplifier as PHIL machine emulator, a common three-phase MOSFET inverter is connected by dint of three coupling inductors \( L_c \) to the amplifier's output clamps. An overview of the machine emulator setup is shown in Fig. 8. The inverter is controlled by a pulse width modulation (PWM) with a switching frequency of \( f_{\text{PWM}} = 20 \text{ kHz} \). The inverter's output voltages are measured and transmitted to a software machine model. The machine model's duty is the calculation of all electrical and mechanical values in the operating point according to the inverter's output voltages and the initial conditions before the operating point. Especially the currents, which are going to flow into the machine, are calculated and transferred as reference values to the amplifier's current controller. Both machine model and current controller are executed on a rapid prototyping system. The current controller is implemented as a common PI controller. Besides the reference values, it has the currently measured values of the three-phase currents as an input. The actuating variable is the input voltage of the amplifier. Hence, the amplifier adjusts output voltages that the same waveforms of the three-phase currents occur as in the setup with the real corresponding electric machine.

4.2 Machine model

The aim of machine models is the calculation of all electrical and mechanical values for all operating points. An indispensable requirement on the machine model is its real-time capability. The higher the accuracy and the level of detail of the model, the more time required for computing in general. For operating the amplifier as a PHIL machine emulator, a simple fundamental component model for a permanent-magnet synchronous machine (PMSM) was chosen [6, 8]. Its block chart is depicted in Fig. 9.

The measured inverter’s output voltages \( v_{\text{U,inv}}, v_{\text{V,inv}} \) and \( v_{\text{W,inv}} \) are transformed into the dq reference frame. The parameter \( K_R \) depends on the windings’ resistance \( R_S \) of the machine, the parameters \( K_{Ld} \) and \( T_{Ld} \) respectively, \( K_{Lq} \) and \( T_{Lq} \) on its inductances \( L_d \) and \( L_q \) in d- and q-direction. The permanent-magnets’ flux is represented by the parameter \( K_{\psi M} \).

The electrical angular frequency \( \omega_{\text{el}} \) can be calculated by the rotational speed \( n \) of the machine and its pole pair number \( z_p \) according to (4).
However, the model can be expanded easily by a mechanical part comparison between the measured load current coupling inductor is higher than the inductances the inverter's output voltage. Since the inductance measurement results exemplarily for the phase U in this operating course of the amplifier's output voltage time-averaged over each switching period. The electrical part. The mechanical part is omitted because the following measurements are made at a constant rotational speed. The presented simple machine model consists only of an electrical part. The model can be expanded easily by a mechanical part [6].

4.3 Measurement results

The operation of the amplifier as PHIL machine emulator is made with the parameters in Tables 1 and 2.

For the following measurement, the emulated machine rotates virtually with a constant rotational speed \( n = 100 \text{ min}^{-1} \). The inverter's output voltage time-averaged over each switching period has a \( d \)-component \( v_d = 0 \text{ V} \) and a \( q \)-component \( v_q = 1.5 \text{ V} \). The measurement results exemplarily for the phase U in this operating point are depicted in Fig. 10.

The upper plot shows the sinusoidal course of inverter's output voltage \( v_{U_{inv}} \) time-averaged over each switching period. The amplitude is exactly the absolute value of the \( q \)-component. The course of the amplifier's output voltage \( v_{U_{amp}} \) is inversely phased. That means the voltage across the coupling inductor is higher than the inverter's output voltage. Since the inductance \( L_C \) of the coupling inductor is higher than the inductances \( L_d \) and \( L_q \) of the emulated machine, a higher voltage is required to set the demanded current slope.

The reference currents calculated by the machine model have a \( d \)-component \( i_d = 3.04 \text{ A} \) and a \( q \)-component \( i_q = 32.79 \text{ A} \). A comparison between the measured load current \( i_L(t) \) and its reference value \( i_{L \text{,ref}}(t) \) is shown in the lower plot of Fig. 10.

### Table 1 Parameters of the setup

| Parameter | Value |
|-----------|-------|
| Amplifier's DC-link voltage | \( V_{DC} = 20 \text{ V} \) |
| Amplification factor | \( A_V = 1 \) |
| Inverter's DC-link voltage | \( V_{DC,inv} = 10 \text{ V} \) |
| Inverter's switching frequency | \( f_{PWM} = 20 \text{ kHz} \) |
| Coupling inductance | \( L_C = 78 \mu\text{H} \) |

\[
\omega_d = 2\pi \times \frac{z_p \times n}{60 \text{s/min}}
\]  

The electrical position \( \phi_d \) can be calculated by integrating the electrical angular frequency with respect to the time.

The presented simple machine model consists only of an electrical part. The model can be expanded easily by a mechanical part [6].

### Table 2 Parameters of the emulated PMSM

| Parameter | Value |
|-----------|-------|
| Pole pair number | \( z_p = 4 \) |
| Resistance of the windings | \( R_S = 32.5 \text{ m\Omega} \) |
| Inductance in \( d \)-direction | \( L_d = 56 \mu\text{H} \) |
| Inductance in \( q \)-direction | \( L_q = 72 \mu\text{H} \) |
| Flux of permanent-magnets | \( \varphi_{PM} = 10.2 \text{ mVs} \) |

### 5 Conclusion

In order to avoid ripple content in PHIL machine emulator's current affected by switched-mode operation of commonly used power electronics a design for a three-phase linear amplifier is proposed. Due to a parallelised structure, the amplifier can drive currents up to 100 A. The setup of the pre stage and a concept to connect several transistor branches in parallel in the final stage are presented. Further measurement results which investigate the crossover distortion and the frequency response are shown. They prove the ability for the use as power electronic device in PHIL machine emulators. Finally, the operation as machine emulator is presented by dint of an overview of the setup and further measurement results.

### 6 References

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