SWAT-EM

Specific Winding Analyse Tool for Electrical Machines

Martin Baun

September 15, 2019

Contents

1 Overview

SWAT-EM is a software for designing and analyzing of windings systems for electrical machines. Currently supported are rotating field windings (permanent-magnet motors, induction motors, synchronout reluctance motors) with any number of phases. This can be distributed full pitch winding, distributed fractional slot winding or tooth-coil winding. The design can be done by

- Generating with manual allocation of the coil sides to stator slots
- Defining individual number of turns for each coil
- Automatic winding generators
- Tables of possible winding systems for slot/pole combinations

Analyzing features

- Calculation of the winding factor based on the voltage star of slots
- Plot of the winding layout
- Plot of stator ampere-conductor distribution and the magnetomotive force (MMF)
- Plot of the slot voltage phasors
- Plot of the winding factor
- Max. possible number of parallel circuit connection of coils

2 Installation

There are two recommended ways to install SWAT-EM.

2.1 Installer on Windows

SWAT-EM is based on python3 interpreter and some additional libraries. If you haven't this on your computer the easiest way is to download the SWAT-EM installer from: `https://sourceforge.net/projects/swat-em/` Start the installer and follow the instruction. No further work is necessary. After installation the program can be startet by double-clicking the Desktop-Icon or with the entry in the start menu.

2.2 PIP

Use this install method if you are on LINUX or macOS or if you still have an python3 environment with pip on your computer. SWAT-EM is hosted on the Python Package Index (pip). To install open a terminal on your computer and type

```
pip install swat-em
```

pip will install all necessary dependencies.

3 Usage

SWAT-EM comes with an QT based graphical user interface (GUI). The layout of the main window consists of the

1. Workspace
2. Winding information's
3. Graphical analysis of the winding

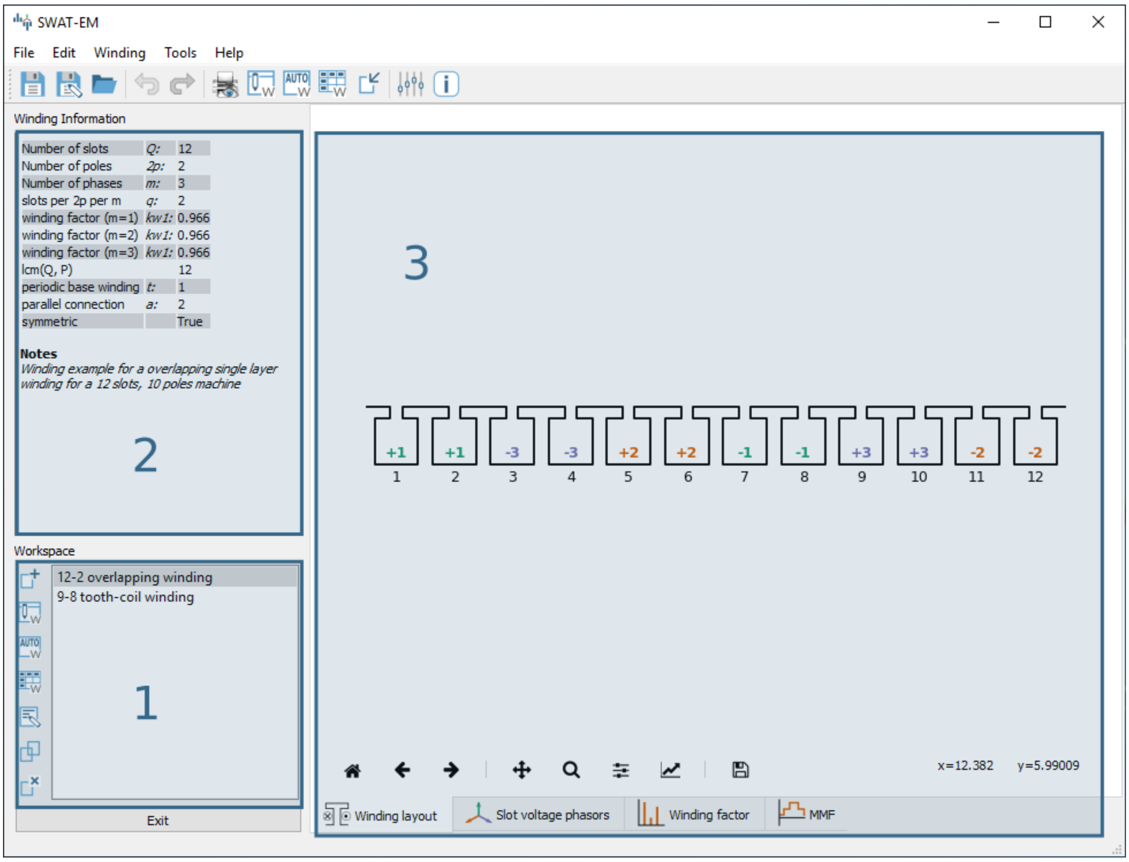

Figure 3.1: Main-window

3.1 Workspace

A SWAT-EM project, that can be saved as *.wdg file can contain several different windings system. So, one can define and compare these windings in the same window. The workspace shows all the windings of the project. By clicking of the name all outputs (text and plots) gets updated. The buttons on the left of (1) in figure 3.1 modifies the windings in the workspace

New winding Opens a dialog with all existing winding generator (see section 3.4). One can choose any of these generators to create a winding layout.

Manual winding layout Define the position of all coil sides by hand. (Not very comfortable but full control)

Auto winding layout Generates the winding automatically by number of slots, poles, ... (easy to use, almost every symmetric winding is possible)

Winding table Shows table slot/pole combinations (a good overview of possible combinations)

Notes If there a many windings in the project it might be a good idea to add some notes to the different layouts.

Clone For modifying windings one can clone/duplicate an existing one. So a switch-back to the initial state and a comparison is possible.

Delete Deletes the selected winding.

While saving the project to file (File → save) all windings of the workspace are saved.
Note: Renaming of windings is possible by double-click or by pressing F2 on keyboard.

3.2 Winding information

The text field (2) in figure 3.1 shows a summary of actual winding.

Q	Number of stator slots
$2p$	Number of pole pairs
m	Number of phases
q	Number of slots per pole per phase $q = \frac{Q}{2pm}$
$kw1$	Fundamental winding factor (for separate for each phase)
$lcm(Q, P)$	Least common multiplier of number of slots an pole pairs. For permanent-magnet machines this is the first harmonic number of the cogging torque
t	Periodicity of the base winding. $t = gcd(Q, p)$
a	Number of possible parallel winding circuit. (In most cases a is equal to t)
$symmetric$	True, if all phases are identically and shifted by a constant angle
$Notes$	User defined description

3.3 Winding layout plot

Many analyzing function results in plots which are shown on(3) in figure 3.1. Every plot has a toolbar on the bottom for zooming, panning and saving the figure to file.

3.3.1 Winding layout

The winding layout plot shows sketched slots and coil sides. The number and color defines the number of phase the coil side belongs to. The sign (+ or -) defines the winding direction (+ means that the wire goes into the plain and - out of the plain)

3.3.2 Slot voltage phasors

The impact of the coils can be represented by the star of slot. The theory behind this is described in [1] for example. Every coil side S_i gets a phasor assigned with the angle

$$\alpha_i = \frac{2p\pi S_i}{Q} \tag{3.1}$$

The angle of the phasors can also be determined for the harmonics by adding the electrical ordinal number ν_{el}

$$\alpha_{i,\nu} = \frac{2\nu p\pi S_i}{Q} \tag{3.2}$$

with p pole pairs and the number of stator slots Q. If the coil side has a negative winding direction π is added to $alpha_i$ (turning down the phasor). With this the phasers E_i can be generated in the complex plain

$$E_i = e^{j\alpha_i} \tag{3.3}$$

All phasors of a phase are getting grouped a vectorial summed up which is shown as (1) in figure 3.2. The dotted line represents the vectorial sum. The amplitude and the phase of this is shown in (2). Options:

harmonic The star of slots can be drawn for any harmonic number by using (3.2).

force phase 1 on x-axis The angle of the sum of phasors depends on the location of the coil sides in the slots. If the whole winding is shifted by some slots the winding is still the same winding. However the phasors are getting a phase shift. To compare different windings and for having an unified diagram one can set this checkbox.

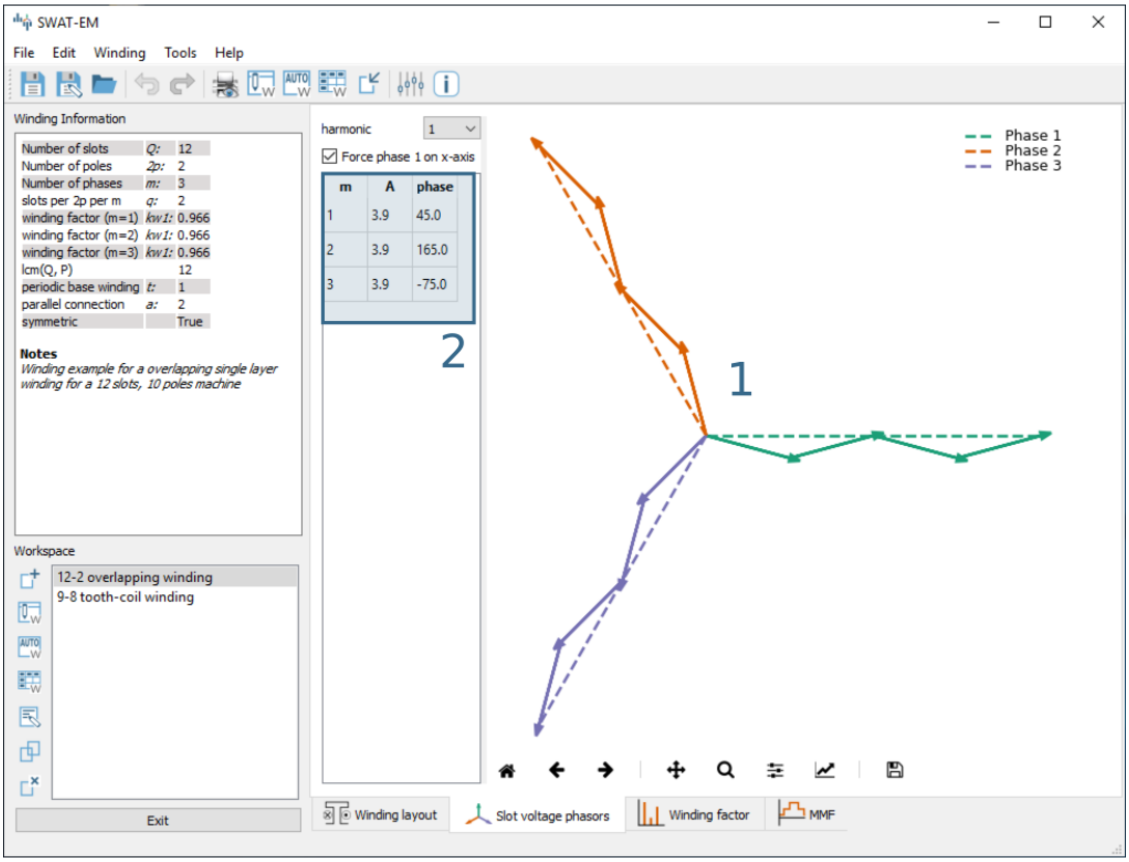

Figure 3.2: Phasors plot

3.3.3 Winding factor

The winding factor k_w describes the coupling of the winding with the existing field in the stator. It depends on the ordinal number ν (electrical or mechanical ordinal number possible). There are many methods for calculating the winding factor, for example from the MMF 3.3.4. Unfortunately there are limitations of this method because for three-phase windings the factor k_{w3} can't be determined. Further calculation methods derives specific equations based on the winding zones. However theses equation are not universal, so there are many equations for different winding systems. To be general SWAT-EM uses the phasors of the star of slots. The absolute value of the winding factor is defined by

$$|k_w| = \frac{|\sum E_i|}{\sum |E_i|} \tag{3.4}$$

and for all harmonics with

$$|k_{w,\nu}| = \frac{|\sum E_{i,\nu}|}{\sum |E_{i,\nu}|} \tag{3.5}$$

It can be seen in figure 3.2 that the winding factor gets the maximum value of 1 if all phasors of a phase have the same phase angle. Typically the winding factor is specified with a sign. This indicates the direction of the magnetic field wave, that is generated by the winding in the airgap. SWAT-EM determines the sign by generating the phasors plot for every harmonic number and detecting the sequence of the phases. Figure 3.3 shows the values in (1) as a table and the absolute values as a bar plot in (2). Both can be displayed

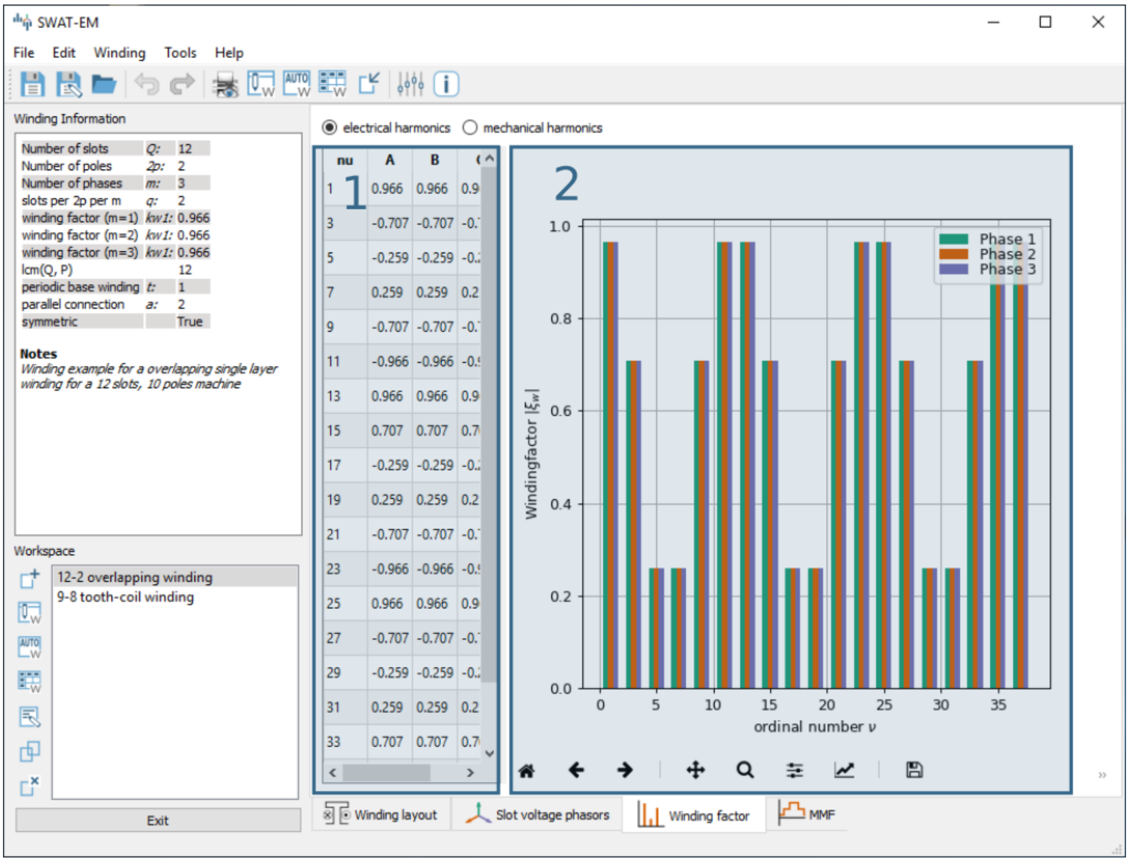

Figure 3.3: Winding factor plot

with respect to the mechanical ν or the electrical ν_{el} ordinal number by the radio buttons on the top of the table.

Mechanical harmonics This representation is useful to detect all possible rotor pole numbers, which can be combined with the winding. Especially tooth-coil windings have many harmonics and so there are many pole-pairs per winding layout is possible.

Electrical harmonics If one have chosen a winding and a number of pole-pairs of the rotor it's a good idea to switch to the electrical ordinal numbers. Here the numbers describes influence of the winding of the waveform of the back-emf for permanent-magnet machines for example. If the winding factor for the harmonics is low, the waveform is more sinusoidal.

3.3.4 Magnetomotive force (MMF)

For evaluation of the winding the so called "‘Magnetomotive force"’ or short MMF is a useful tool. It is based on the the ampere-conductor distribution. This is shown for time $t = t_1$ with respect to the AC current system of m phases. For every slot the winding

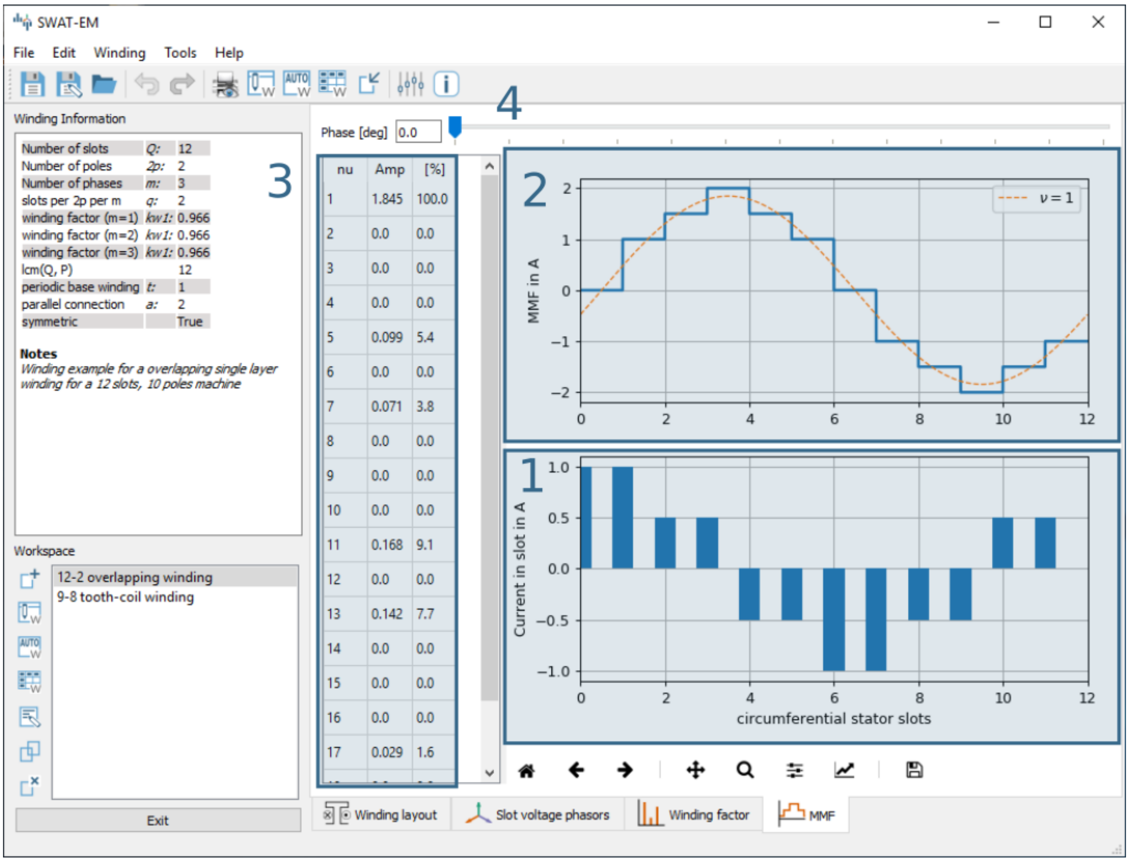

Figure 3.4: Plot of the ampere-conductor distribution and the Magnetomotive force (MMF)

direction ($d = \pm 1$), number of turns N_c the current i gets summed up

$$\Theta_{slot} = \sum d \cdot iN_c. \tag{3.6}$$

Therefor the distribution of ampere-turns is coupled with number of slots. (1) in Figure 3.4 shows this for a winding example with $Q = 12$ slots, so there are 12 bars. In reality the distribution has a width per bar which corresponds to the slot opening. However in theory (in this program) the distribution can be interpreted as infinitely thin peaks. The integral of this leads to the MMF

$$MMF(\alpha) = \int_0^{2\pi} \Theta d\alpha, \tag{3.7}$$

which is shown in (2) in figure 3.4. The waveform of the MMF corresponds to the magnetic field, that is generated in the airgap by the winding. For further information consider the literature (eg [2]). The plot also shows the fundamental and some of the harmonics. The number of harmonics which are plotted can be defined relative to the fundamental. Please consider the "‘Tools"’ → "‘Settings"’ dialog. The table (3) in the window displays the harmonic analyses of the MMF. With the slider (4) one can define the phase angle of the AC current system for the MMF plot. Note that the phase angle has no effect on the harmonic content of the MMF, so the harmonic analyses is independent from it.

3.4 Winding Generators

SWAT-EM comes with many different winding generators. Each of them have different features.

3.4.1 Manual layout

The manual layout generator (figure 3.5) is the most basic generator in SWAT-EM. One can define the position and the number of turns for each coil side by hand. With this every winding layout can be sketched and analyzed. The price of this is the comparatively large manual effort.

Button "‘edit machine data"’ Use this dialog if you want to change the number of slots Q, of phases m, of poles $2p$ or layers.

definition of the coil sides Use the table to define the phase for the layers in each slot. The number describes the phase number. The color is added automatically for overview. The sign defines the winding direction (+ into the plane, - out of the plane)

number of turns If radio button is set to "‘fix number of turns for all coil sides"’ one can type the number of turns in the edit field apart from that. While choosing "‘individual number of turns"’ one can define this for each coil side. Use the table below

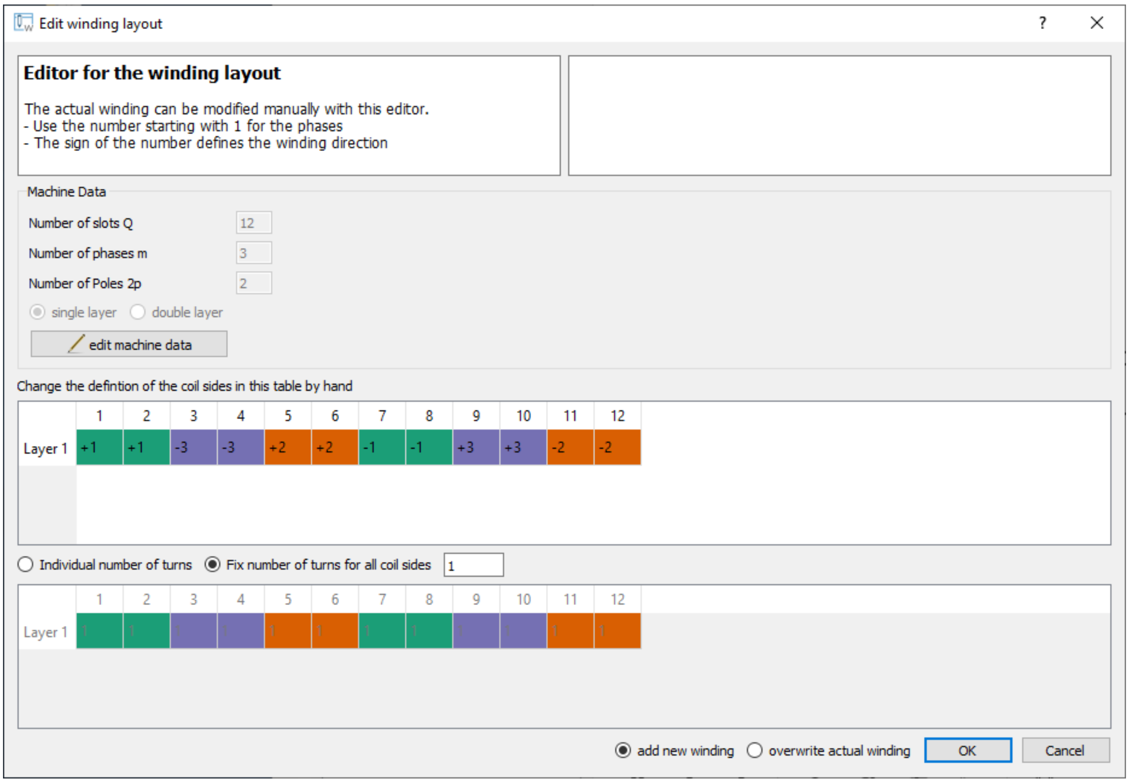

Figure 3.5: Manual winding generator

info On the upper right there is an info field. While the user defines the winding there is a live-analysis. If there is an unsymmetrical winding or if the sum of all winding turns is not zero for example, the user get an info.

overwrite winding There are two different possible action while exiting an generator dialog with the ok button. If the radio button "‘add new winding"’ is selected, the winding in the generator winding is added to the workspace in the main window. If "‘overwrite"’ is selected, than the actual selected winding of the workspace getting overwritten. Be relaxed, if you have overwritten your winding accidentally, there is an undo function in the main window.

3.4.2 Automatic layout

With the automatic winding generator it is possible to generate almost every symmetric winding system, except "‘dead coil windings"’ (where some slots are empty). This includes

- overlapping full pitch winding
- overlapping fractional slot winding
- tooth coil winding
- all above as single-layer or double-layer

This generator uses the star of slots to for defining the coil sides in the slots, based on the theory of [3].

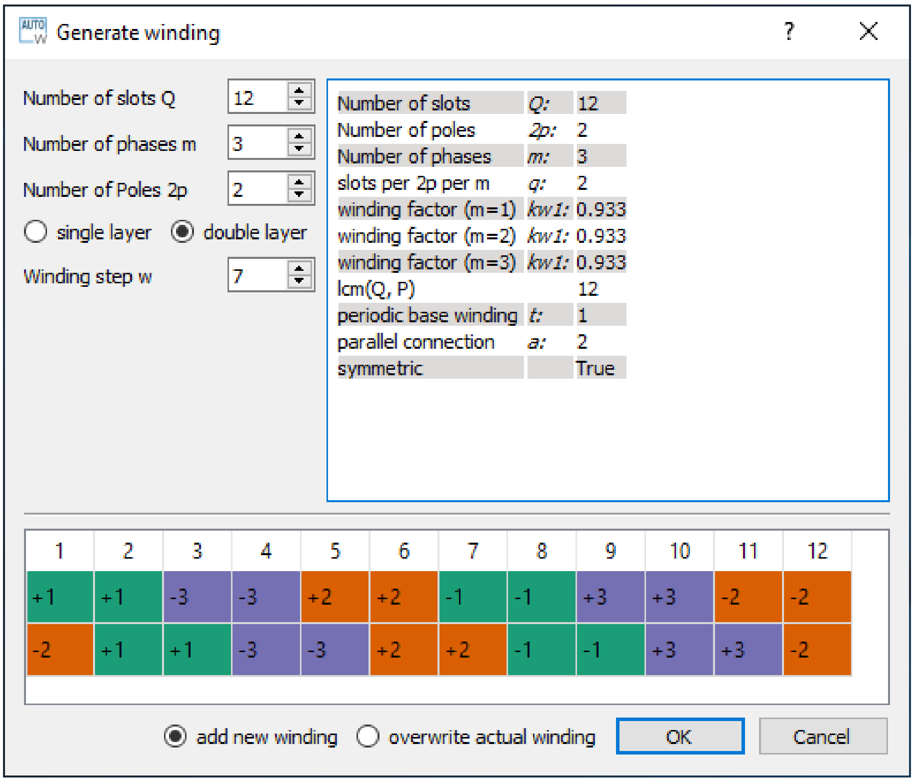

Figure 3.6: Automatic winding generator

Machine data Number of slots Q, phases m and poles $2p$

layer Double layer winding means, that in every slot there are two coil sides (from the same or from different phases)

winding step Every coil has an "‘in"’ and an "‘out"’ conductor, which are connected via the winding overhang. The winding step defines the distance between "‘in"’ and "‘out"’ in slots. If winding-step is 1 a tooth-coil winding will be created. Note: For single layer windings there are some restriction to accommodate all coil sides, so in this case the winding step can’t be influenced.

overwrite winding There are two different possible action while exiting an generator dialog with the ok button. If the radio button "‘add new winding"’ is selected, the winding in the generator winding is added to the workspace in the main window. If "‘overwrite"’ is selected, than the actual selected winding of the workspace getting overwritten. Be relaxed, if you have overwritten your winding accidentally, there is an undo function in the main window.

layout table The lower table shows the actual defined winding. Note, that layout can’t changed here by hand. If you want to change, than accept the winding with OK to the workspace in the main window and use the manual generator (section 3.4.1). The winding will be transmitted.

3.4.3 Winding table

This generator gives an overview about possible slot/poles combinations. So it's generator with a broad but not very deep view on windings. It can be useful in the early state of designing electrical machine, for example to define the appropriate number of slots and poles.

While clicking on a item in the upper table, the winding characteristics shown on the left side and the winding layout is shown on the bottom table. As with the other generators the selected winding can be transferred to the workspace in the main window.

For some slot/pole combinations there are many winding system possible where this generator shows the winding with the highest fundamental winding factor $k_{w,1}$. At this time there is no way to modify the windings (changing winding steps for example). For more control you have to use other generators like 3.4.1 or 3.4.2.

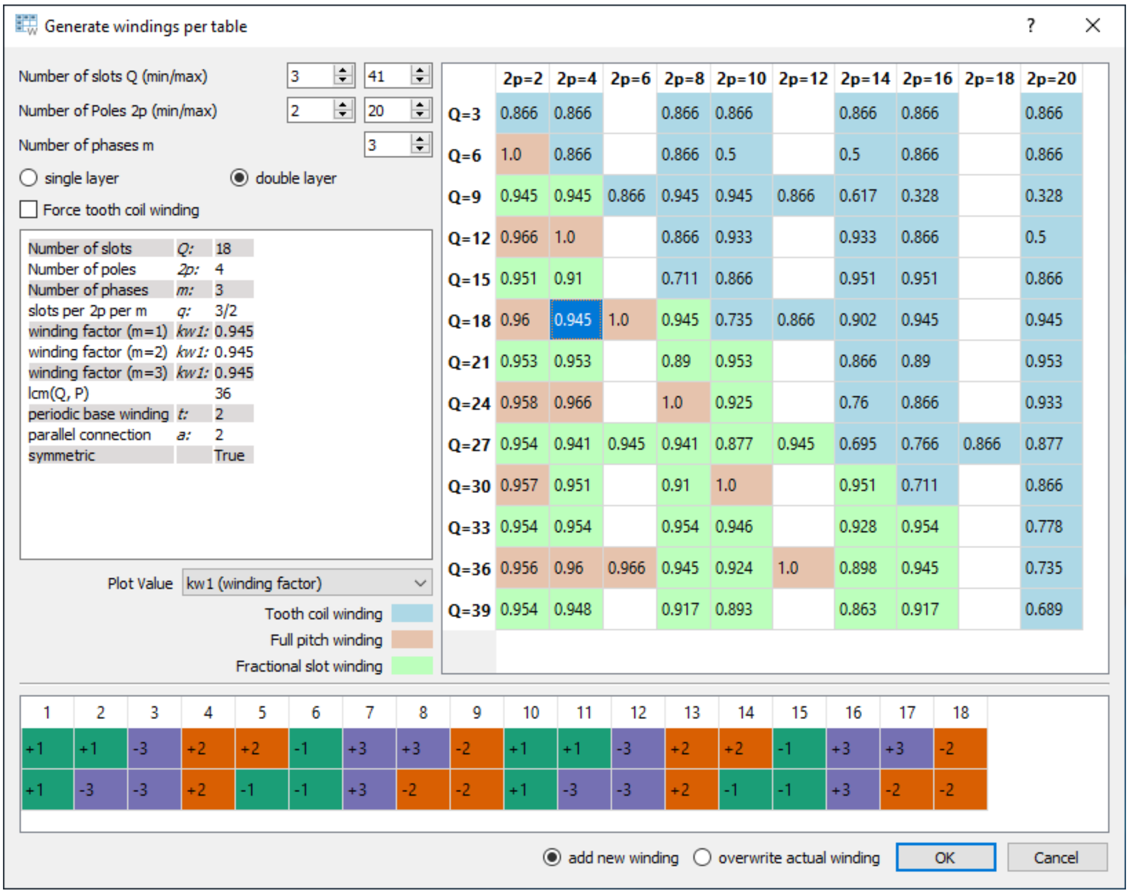

Figure 3.7: Table of possible windings for diffrent slot/pole combinations

Number of slots Defines the range of number the number of slots Q for them table. For symmetric windings the number of slots must be a integer multiple of the number of phases m.

$$Q = k \cdot m, \text{ with } k = 1, 2, 3... \tag{3.8}$$

For single layer windings (without dead coil windings) the number of slots must be doubled

$$Q = 2 \cdot k \cdot m, \text{ with } k = 1, 2, 3... \tag{3.9}$$

Number of poles The number of poles $2p$. Only even integer values ≥ 2 are valid.

Number of phases The number of phases m in the machine. Every integer value > 1 is valid.

layers Defines the number of layers for the table. At this time only single layer and double layer windings are possible.

Force tooth coil winding In some cases you may want to realize tooth coil windings, even when the winding factor isn't very high. In this case the winding step is set to $w = 1$.

plot value Defines the number which is shown in the upper table.

- **kw1** The fundamental winding factor. A big number (near to "1") means a high-torque.
- **q** The number of slots Q per pole $2p$ per phase m. It characterized the winding system.

$$p = \frac{Q}{2p \cdot m} \tag{3.10}$$

- **t** The number of the periodic sequence of identical "base-" windings.
- **a** The number of possible parallel circuits of coil groups in the winding. In most cases it's the same as t. But for some windings it's possible to connect coil groups in parallel while changing the start and end of the coils.
- **lcm(Q,2p)** Means the least common multiple of the number of slots Q and number of poles $2p$. For permanent-magnet machines this is the first ordinal number of the cogging torque. Tends to be true: The higher the ordinal number the lower the amplitude of the cogging torque.

overwrite winding There are two different possible action while exiting an generator dialog with the OK button. If the radio button "'add new winding"' is selected, the winding in the generator winding is added to the workspace in the main window. If "'overwrite"' is selected, than the actual selected winding of the workspace getting overwritten. Be relaxed, if you have overwritten your winding accidentally, there is an undo function in the main window.

3.5 Import winding

As in 3.1 described you can have many winding system in the workspace. In some cases you may want to have a winding in your workspace which is saved as a *.wdg file on the hard disk. This can be done by the import function. For import a window opens with

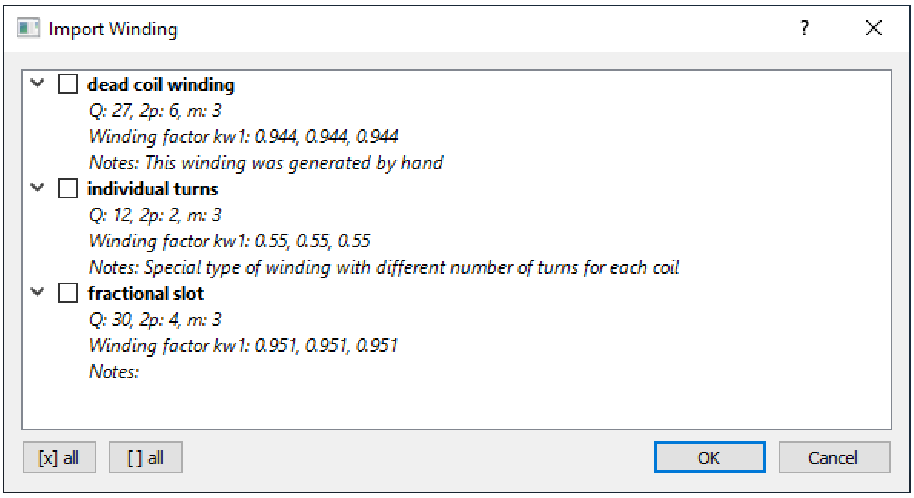

Figure 3.8: Import winding from file

the file dialog. Navigate to an existing *.wdg file. After that you get a list of all windings systems of the file (figure 3.8). Choose all windings you want to import into the workspace.

Bibliography

[1] G. Müller and K. Vogt. *Berechnung elektrischer Maschinen*. VCH, 1996.

[2] J.R. Hendershot and T.J.E. Miller. *Design of Brushless Permanent-magnet Machines*. Motor Design Books, 2010.

[3] N. Bianchi and M. Dai Pre. Use of the star of slots in designing fractional-slot single-layer synchronous motors. *IEE Proceedings - Electric Power Applications*, 153(3):459–466, May 2006.