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Solid-state transformer based on modular multilevel converters

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Abstract: A new highly compact topology for solid-state transformers is presented. It is based on modular multilevel converters and, therefore, has their usual advantages such as superior voltage shape, high reliability, and scalability. It utilises arm inductors for the isolated energy transfer between two converters and thereby allows for a more compact build compared to the design that uses separate transformers.

1 Introduction

The future of electrical distribution is widely seen to be based on microgrid structures [1]. Interconnecting the microgrids smart transformer technology is needed. This need is filled by solid-state transformers (SSTs).

An SST is an inverter-fed transformer. As such, it can actively control the power flow between its terminals. Also, reactive power can be provided independently to both sides. This enables reliable decoupling of microgrids from each other. The iron utilisation in the transformer can be optimised by choosing the frequency appropriately.

This paper presents a new topology for SSTs based on modular multilevel converters (MMCs).

MMCs are a class of converter in which many identical cells (see Fig. 1) are connected in series to reach high voltages [2]. This leads to a voltage shape containing many levels and, therefore, little distortion. Also, the cells can be fitted with bypass switches to increase the fault tolerance of the system.

1.1 Basic idea

MMCs consist of arms, which themselves consist of cells and an inductor. The cells as shown in Fig. 1 contain capacitors and can present the positive capacitor voltage, the negative capacitor voltage or a short-circuit at their terminals. The series connection of the cells can be modelled as a controllable voltage source.

The inductors can either be separate or coupled. The coupling of the inductors has been used for the reduction of the output impedance of the inverter [3, 4].

The basic idea of the new concept is the magnetic coupling of the arm inductors of not only one but two MMCs. This enables galvanically separated energy transfer between the coupled inverters.

1.2 Configurations

The coupled inductors are chosen in such a way that only the internal currents of the MMCs result in a magnetic field in the core.

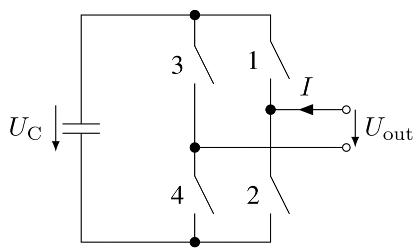

Fig. 1 *Full-bridge cell*

This enables the arbitrary choice of the frequency used to transfer the energy. Therefore, an optimal frequency, based on, e.g. transformer cost or cell utilisation, can be chosen.

The coupled MMCs can be of different types (e.g. DC → AC, 3AC → 3AC statcom). Two DC → 3AC converters can be coupled with all six inductors by using a three-phase transformer with four windings per leg. Since the energy is transferred with a three-phase system, the transferred power can be constant. A drawback is the fact that both internal currents of both inverters are coupled and cannot be chosen independently in both inverters.

The inner currents not being independent is a problem because these currents are needed for the balancing of the energy stored in the arms.

Another configuration of interest is two delta statcoms with all six windings on a common core. This is a simple way to connect two three-phase AC systems with this method. It has the same drawback as here too, all inner currents are coupled. Additionally, only a single phase is used to transfer energy. This means that the transferred power cannot be constant.

For rail supply applications, the coupling of a delta statcom and a single-phase statcom might be interesting: Rail often uses a different frequency from the main grid. This alleviates the problems with coupled internal currents.

For smart-grid applications, the most promising configuration is the coupling of two DC → 3AC converters, further called 'M2C', with four of the inductors per converter being coupled. This topology is described in the rest of this paper.

2 Topology

Fig. 2 shows the new SST topology with the cell modelled as voltage sources. The SST contains two M2Cs with full-bridge cells [5]. The AC terminals of both M2Cs are connected to one grid each. The link terminals ($\{A, B\}_{\{1,2\}}$) are unconnected. To allow an energy exchange between both M2Cs, four arm inductors of each inverter are coupled magnetically.

2.1 Theory of operation

MMCs have internal currents that do not appear at the terminals. Therefore, these internal currents can be arbitrarily controlled. For the M2Cs, these currents are a truly internal current i_i and the coupling current i_c:

$$i_i = i_{a,3} + i_{a,6} - \frac{i_{a,2} + i_{a,5} + i_{a,1} + i_{a,4}}{2} \tag{1}$$

$$i_c = i_{a,2} + i_{a,5} - i_{a,1} - i_{a,4} \tag{2}$$

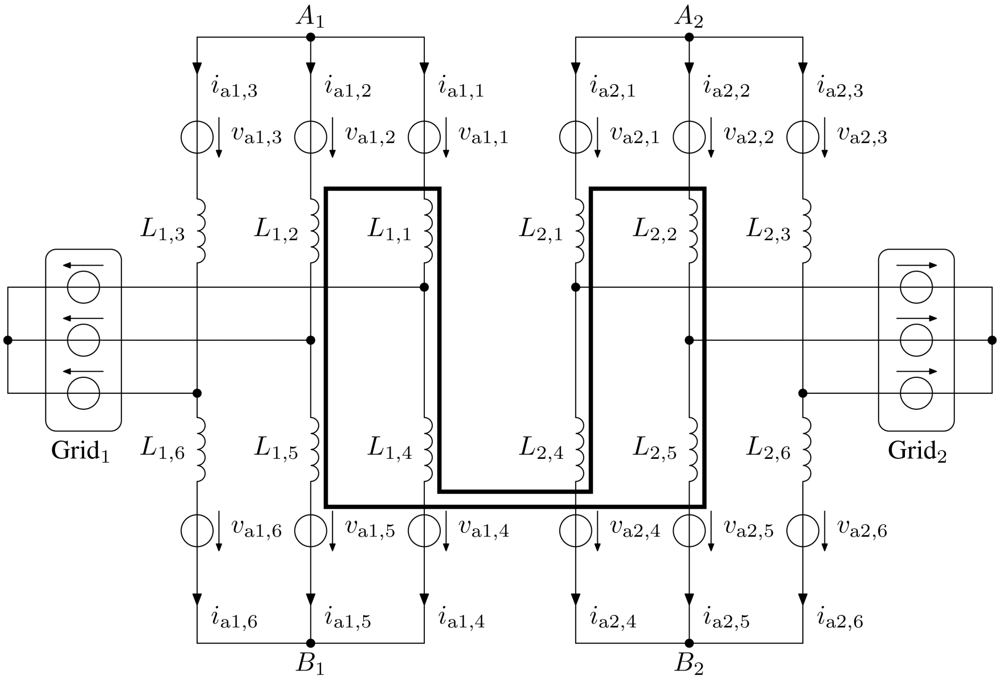

Fig. 2 *New solid-state transformer topology consisting of two M2Cs with magnetically coupled inductors*

By coupling the inductors as shown in Fig. 2, the magnetic field in the transformer core is only created by the currents that flow equally in inductors L_1 and L_4 and in the reverse direction in L_2 and L_5. This is i_c. Therefore, the flux in the magnetic core can be arbitrarily controlled.

This means that the coupling frequency can be chosen independently from the grid frequencies. Thereby, a frequency that is optimal for the used core material can be used.

Since both MMCs use the same magnetic core, both can exchange energy through it.

3 Control scheme

A major problem for all MMC designs is the symmetrisation of the stored energy. Each of the arms stores energy. This energy fluctuates with the electrical cycles. The energy levels of all arms need to be kept similar to prevent the cells from exceeding their operating range. As with all MMCs, active symmetrisation is needed.

In the usual MMC designs, the internal currents are used for this purpose [6]. Here, one of the two internal currents is already used for the energy transfer and, therefore, cannot be used for symmetrisation in the usual way. Therefore, a new symmetrisation strategy has to be found.

Usually, symmetrisation is done with the internal currents having the same frequency as the grid voltage. For the coupling current, this cannot be done because this current cannot be chosen independently for both MMCs. This means that a current that removes imbalances in one MMC is liable to create one in the other. Therefore, any balancing that is done with the coupling current must be careful to only influence one of the M2Cs.

Instead of using the grid voltages for balancing, additional AC voltages with different frequencies are introduced for the common-mode voltages $v_{\{1,2\},0}$ of the grids and the voltages $v_{\{1,2\},\mathrm{AB}}$ between the points $A_{\{1,2\}}$ and $B_{\{1,2\}}$. This control is detailed in Section 3.2.

3.1 Current control

To control the grid currents, the symmetrisation and the energy exchange, it is useful to first look at a single M2C in isolation: By applying the transformations described in [7], it is possible to separate the inverter into six independent virtual circuits, as shown in Fig. 3 (only the topologically different three are shown).

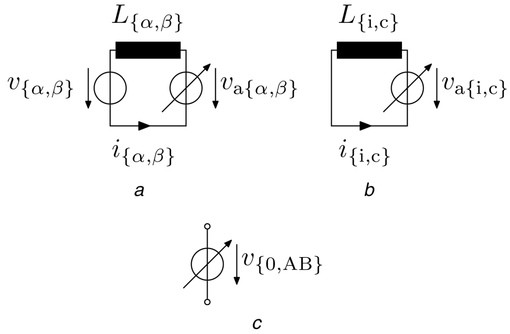

Fig. 3 *Transformed circuits*
(a) External currents, ***(b)*** Internal currents, ***(c)*** Voltages

Each of those contains a controllable voltage source. Two of these circuits control the grid current (Fig. 3*a*). These also contain an inductor and an external voltage source representing the grid voltage. The grid voltages are a space vector representation of the actual grid voltages. The values of the inductors are also the result of the transformation.

Another two circuits control the two internal currents of the M2C (Fig. 3*b*). These contain just the inductors. Here, care must be taken when choosing the transformation so that one of the internal currents is the coupling current.

The last two circuits control the voltage between points *A* and *B* and the common-mode voltage v_0 of the grid (Fig. 3*c*). Since neither of these is connected, there can be no current and the circuits contain only the controllable voltage source.

Due to simplicity of these circuits, the currents in these circuits can be controlled through the variable voltage with a variety of methods. The values of these voltages can then be transformed back into the actual system to find the necessary values for the v_{an}'s. To design proper controllers, it is necessary to know the values of the inductors in the transformed circuits.

A high quality of the current control, especially for the internal currents, is necessary because the energy control as described in Section 3.2 necessitates currents containing several frequencies. For each of these frequencies, the amplitude and phase of the current must be controlled independently.

When the coupling between the two M2Cs is introduced, the two circuits that describe the coupling currents (both Fig. 3*b*) merge into one. It has a transformer between the voltage sources,

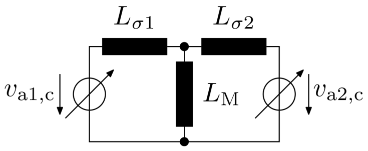

Fig. 4 *Transformed circuits for coupled currents*

as shown in Fig. 4. By controlling both voltage sources, the energy transfer can be realised.

To design a basic controller for the transferred energy, it is useful to assume that the current through the main inductance L_{M} is negligible. Then, the circuit is identical in structure to Fig. 3*a* and a similar controller can be used. One of the sources, e.g. $v_{\mathrm{a1,c}}$, is then used to output a sine with a constant amplitude, and the other one controls the current.

With these methods, all currents of the inverters can be controlled.

3.2 Energy control

The energy control of the inverters comprises two aspects: the total energy stored in all arms must be kept constant by drawing energy from an energy source and the energy that is stored in the arms must be distributed equally among them.

One of the M2Cs will use its grid connection to source needed or sink excessive energy. The other one will use the transformer for this purpose.

These controls are straightforward and can be implemented by controlling the active part of the grid and respectively the coupled current.

There are five ways in which the energy can be distributed unequally in the six arms. Therefore, it is necessary to identify five independent powers each of which controls an imbalance. A power in this sense is the product of one of the transformed currents with one of the transformed voltages. In general, it will not be possible to keep the energies perfectly balanced. Instead, only the averages of the energies can be balanced. Therefore, independence here means that the averages of the powers can be independently controlled.

Since the currents into the grid $i_{\{\alpha,\beta\}}$ are given, either by overarching controllers or by the total energy control, they cannot be independently controlled and, therefore, cannot be used for symmetrisation. This leaves only the two internal currents $v_{\{\mathrm{i,c}\}}$ and the two controllable voltages $v_{\{0,\mathrm{AB}\}}$ for this purpose.

While it is in principle possible to use the product of the controllable voltages and the grid current for symmetrisation, this has a major drawback: symmetrisation is always needed, so the operating point with no grid current would not be possible. Therefore, these voltages are controlled to sines with constant amplitudes and frequencies to have them available for creating powers with the inner currents. The frequencies of both voltages are chosen to be different from the grid frequency and from each other. This means that the average of the product of the grid current, which is assumed to have the same frequency as the grid voltage, and these voltages are zero.

In general, both grids will have the same frequency and an arbitrary phase shift relative to each other. Therefore, it is not possible to use the product of the coupled current and the grid voltage for symmetrisation because the coupled current will create powers with non-zero average in both M2Cs. These powers will in general not be advantageous for both M2Cs.

The following powers will be used for the symmetrisation:

$$i_{\mathrm{i}}v_{\mathrm{AB}},\, i_{\mathrm{i}}v_0,\, i_{\mathrm{i}}v_\alpha,\, i_{\mathrm{c}}v_{\mathrm{AB}},\, i_{\mathrm{c}}v_0 \tag{3}$$

The average of the products of the coupled current i_{c} with v_{AB} and v_0 need to be controlled independently in each M2C. This means that each M2C needs to have these voltages shifted by 90° relative to the other one.

To enable a simple design of the balancing controllers, the energy stored in the arms is transformed. This transformation creates separate components for the total stored energy and for five imbalances per M2C. These imbalances must then be controlled to stay around zero. By choosing the transformation properly, each of the powers in (3) directly controls one of the imbalances. The general method to do so is described in [7].

Since the controlled values are decoupled, it is possible to use simple proportional-integral (PI) controllers for the energy control. The outputs of the energy controllers are the setpoints for the current controllers. If a current is used by more than one energy controller, its setpoint is the sum of all corresponding energy controllers.

The balancing control is based on averages. Due to this, there are instantaneous deviations from perfect balancing. The total energy of one M2C can also not be controlled to a constant value because the transformer is single phase and, therefore, cannot transfer a constant power. Feedforward of these deviations can be used to improve the control quality.

3.3 Overall control

Both M2Cs work with different control regimes: The first one controls its grid current to a given setpoint and controls the coupled current to keep its total arm energy constant. The other one controls the grid current to keep its stored energy and outputs a quasi-constant sine voltage to the transformer.

For energy balancing, both M2Cs create their own inner current. The coupled current is also needed for balancing by both M2Cs. The M2C controlling the coupling current injects balancing components for both M2Cs into this current. This necessitates a common central controller for both M2Cs.

4 Simulation results

To prove the viability of the proposed design, simulations have been performed. For the simulations, a model of the proposed design has been created in Modelica. To run the simulations, OpenModelica 1.13 has been used.

For the purpose of the simulation, the cells are replaced by ideal voltage sources. The transformer is modelled as an ideal flux tube with leakage at each winding. A resistor was added to each arm to model the losses of the arms. At both grids, additional grid inductances are placed.

The two M2Cs and their connected grids are indexed by their control method: The M2C whose grid current is controlled by a setpoint has the index ‘I’. The M2C whose grid current is controlled by the energy controller has the index ‘E’. This convention is used throughout this section.

The parameters used for the simulation are shown in Table 1.

Fig. 5 shows the grid voltages and currents of both grids in the steady-state operation. To simplify the figure, only one phase per grid is shown. The other phases correspond to a symmetrical three-phase system. It can be seen that the power in both grids is equal but opposite.

Fig. 6 shows the energy distribution in the arms of both M2Cs over time. At $t = 0$ s, all arms are pre-charged to the nominal energy of 133 J. At $t = 0.5$ s, an energy imbalance is purposefully introduced to show the controllability of the energy distribution. At $t = 1.0$ s, the setpoints for the energy distribution are set to equal distribution again.

It can be seen that the imbalance is removed after ∼2 s. This shows that the energy distribution in the arms can be controlled. It can also be seen that the average energy in the arms stays constant. This shows that the energy transfer through the transformer works as expected.

5 Advantages

By using MMCs, all advantages of MMCs also apply to this type of SST. For usage in smart grid applications, there are several important ones: Compared to the SST concept based on two- or three-level inverters, this concept offers lower harmonics of the output voltage, redundancy and scalability. The output voltage is very low in harmonics. This enables a grid connection with little to no filtering. By fitting the cells with bypass switches and installing

Table 1 Parameters for the simulation

Grid	
voltage_{E} (amplitude)	200 V
voltage_{I} (amplitude)	100 V
$\text{frequency}_{E,I}$	50 Hz
inductance	100 µH
Arms	
arm energy setpoint	133 J
arm capacitance	880 µF
arm resistance	1 mΩ
Transformer	
turns per winding	10
per winding leakage inductance	125.7 µH
Control	
sampling frequency	1 kHz
power factor_{E}	1
power factor_{I}	−1
current_{I} (amplitude)	10 A
coupling frequency	500 Hz
common-mode frequency	150 Hz
frequency_{AB}	100 Hz

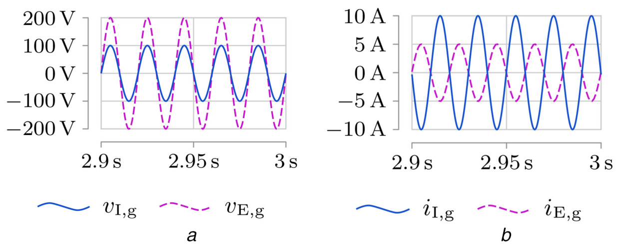

Fig. 5 *Grid currents and voltages in the steady-state operation. Only one phase is shown*
(a) Phase voltages, ***(b)*** Phase currents

additional cells, redundancy and thereby high fault tolerance are possible. The design easily scales to different grid voltage by choosing the number of cells and the winding ratio appropriately.

Compared to other cell-based SST designs [8], this concept has the advantage of using only a single transformer instead of one per cell. The single stage design has the advantage of using fewer cells than multi-stage SST designs.

6 Challenges

6.1 Black start

To be used in microgrid applications, the SST should be able to create the secondary grid without depending on other power sources on the secondary side. This is not simple and needs a specialised control regime.

A rough sketch of the possible black-start control is the following.

It is assumed that the primary-side M2C is connected to a powered grid while there is no power on the secondary grid. The primary-side M2C can be pre-charged normally but must use a different balancing strategy: the coupled current cannot be used for balancing because the secondary M2C cannot deliver a defined voltage to the coupling circuit, and therefore, the coupled current cannot be controlled easily. Instead, the balancing must be done with the one internal current and possibly with reactive grid current.

The secondary M2C can then be pre-charged with the coupled current. Since only four of the six arms are part of this current, the missing two arms will not be pre-charged. The controller for the secondary M2C must then move energy from the pre-charged arms to the still unpowered arms. As soon as all six arms are being powered, the normal control strategy can start.

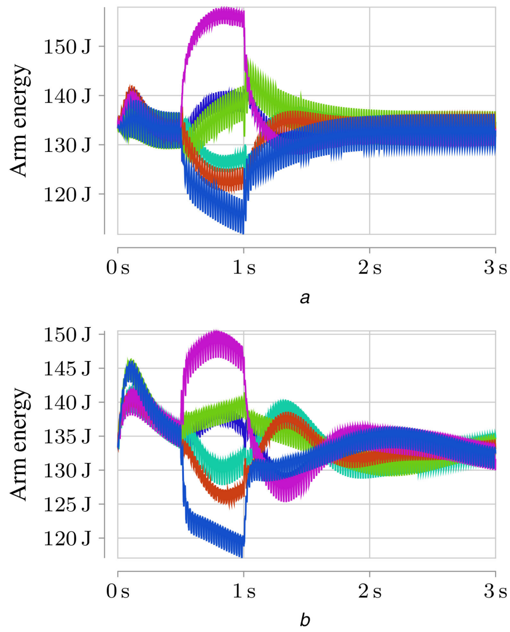

Fig. 6 *Energy stored in the M2C arms*
(a) M2C_{E}, ***(b)*** M2C_{I}

6.2 Realisation of the transformer

The transformer needs eight windings on a common core. This is unusual and might lead to complications: While the exact values of the per winding leakage inductances are not critical, unequal coupling between the windings might be.

The leakage inductances are needed to control the currents. Therefore, the leakages must have minimum values. This might necessitate a special high-leakage design for the transformer or additional external inductors.

7 Conclusion

In this paper, a new concept for solid-state transformers has been presented. It is based on MMCs and confers all of the associated advantages. The energy transfer is realised with the inductive coupling of the arm inverters. It has been shown that the internal currents of MMCs can be used to transfer energy between two converters. A control strategy has been described that enables a stable operation of the presented transformer. The viability of the approach has been shown through simulations.

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