Direct Power Control for a Grid Connection of a Three Phase Z-Source Inverter

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1. Abstract

The Z-Source inverter (ZSI) has proven to be a robust and easy to control inverter. As a drawback it has increased requirements towards the PWM modulator to insert the shoot through states that are necessary for the boost operation. To overcome that restriction a novel direct power control (DPC) scheme that does not require a PWM has been developed and successfully validated by experiment. It works similarly to the well-known direct torque control (DTC) with the difference that the output voltage of the inverter does not directly control the flux and the torque of an electrical machine but the active and reactive power fed into the grid. In addition, the DPC control had to be extended to also manage the shoot through states i.e. the boosting of the ZSI.

2. Introduction

In many research works, the ZSI has shown to be a good and robust power electronic converter. Its modified DC link enables the unique feature of the Z-source inverter that combines the properties of a buck and of a boost converter in one inverter stage. Thus, a short circuit in one inverter leg is no longer a catastrophic failure; moreover, it is necessary for enabling the boost operation of the Z-source inverter. Since the ZSI delivers a constant voltage even if fed from sources of variable voltage and it has increased immunity to short circuits in the legs of the inverter, it can be considered for distributed electric power generation in the lower power range e.g. in remote areas. Therefore, the single-phase ZSI was investigated in previous works and presented as low cost, easy to control and robust solution [1] - [4]. On the other hand, it has a reduced efficiency if compared with standard two stage concepts.

If the amount of harvested energy is increased or if a grid connection is considered, a single-phase concept is no longer suitable, instead a three-phase topology should be chosen. For the control of the three phase ZSI many concepts have been presented in the literature [5] - [7]. To cope with the requirements of remote and rugged areas, a simple, low-cost solution should be the aim. Nevertheless, the PWM features of standard microcontrollers are limited and not suitable for this task. In particular, the PWM – units implemented in microcontrollers are usually not able to generate the pulses as they are required in the well-known control strategies of ZSIs. On the other hand an additional processing unit (e.g. CPLD) would increase the cost and the complexity of the system that becomes less attractive and not suitable for harvesting energy in remote and rural areas.

In the following, a DPC control structure for a three phase ZSI without any PWM-unit is proposed that can be used to feed the generated power into a grid.

3. Z-Source inverter

Fig. 1 shows the structure of the three phase ZSI as it is used in the present work. Instead of a regenerative source of variable voltage a variable transformer connected to a rectifier is used to provide the input voltage and to operation the inverter in defined conditions for the investigation. The output is connected to the grid. Between the input rectifier and the output inverter the special DC - link with Z-topology is shown. The explanation of the principle of operation of the ZSI can be found in previous papers or in the standard literature [1][5]. Compared to a conventional voltage source inverter, the ZSI exhibits an additional switching state (shoot through) that has to be included in the generation of the switching patterns. The short circuiting of the DC link, which is necessary for the boost operation, has the same effect on the inverter side like a zero voltage vector of a standard VSI. Therefore, any zero voltage vector can be replaced by a shot through vector without influencing the modulation scheme of the output voltage.

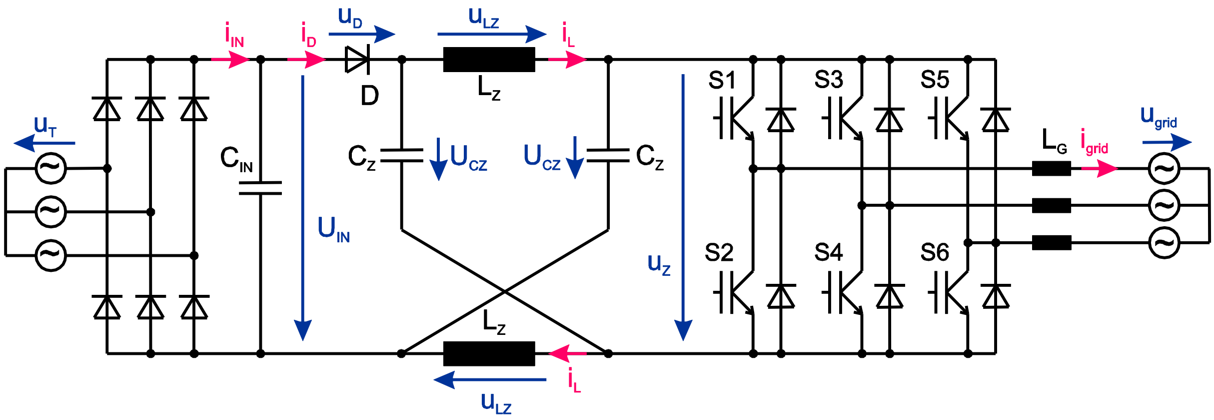

Fig. 1: Proposed setup of a three phase ZSI for grid connection

4. Direct Power Control for ZSI

The principal scheme of DPC is similar the well-known DTC which is widely used in motor drives. In comparison to DTC, where the stator flux and torque of the motor are controlled, the DPC is designed to control the active and reactive power fed into the grid. At every sampling time, the instantaneous active and reactive power are calculated and the algorithm chooses the right switching state, to manipulate the system into the right direction [8].

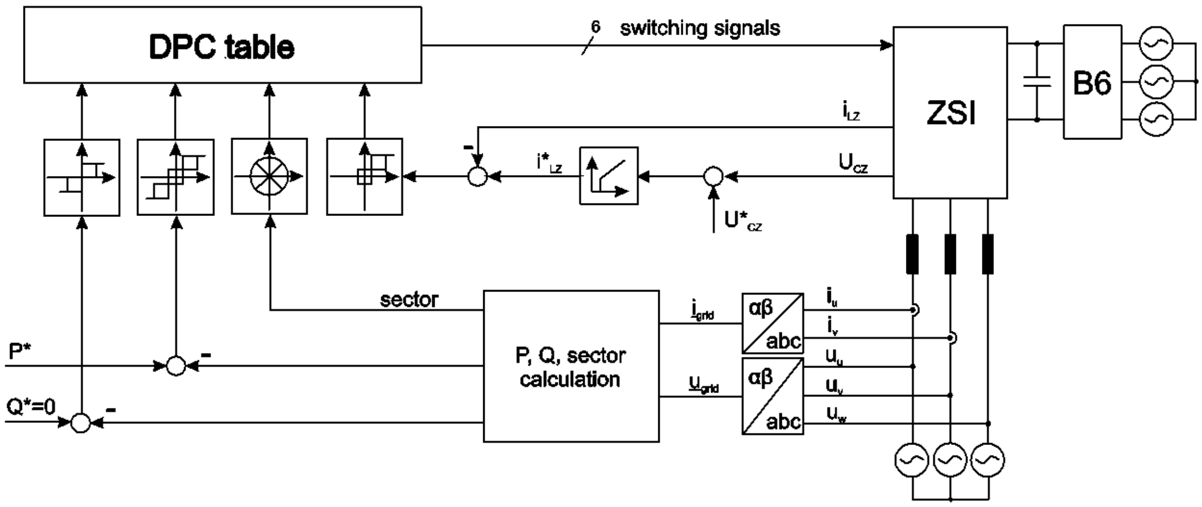

Fig. 2: Proposed PDC control structure for a three phase ZSI

In the proposed setup, as depicted in Fig. 2, the grid voltage and the currents injected into the grid are measured. After transforming both voltage and current into the α-β-coordinate frame, the space phasors $\underline{u}_{grid}$ and $\underline{i}_{grid}$ are obtained and the instantaneous active and reactive power are calculated as:

$$P = u_{grid,\alpha} \cdot i_{grind,\alpha} + u_{grid,\beta} \cdot i_{grid,\beta} \tag{1.1}$$

$$Q = u_{grid,\beta} \cdot i_{grind,\alpha} + u_{grid,\alpha} \cdot i_{grid,\beta} \tag{1.2}$$

The set point for the control of the active power P* is obtained from a superimposed control according to the available power of the source. The set point for Q* is set to zero in order to have a unity power factor. For the control of the active power a three level hysteresis control is used, while the reactive power is controlled by a four level hysteresis controller.

For the control of the output voltage of the ZSI in boost operation a cascaded control structure with an underlying inner current control loop is used. For that purpose the measurement of the voltage of the ZSI capacitors U_{CZ} and of i_{LZ}, the current through one of the main inductors are required. The reference value for the capacitor U_{CZ}^{*} has to be set according to the control requirements. The current control is performed by a three level hysteresis controller with a reference value obtained from the outer control loop i.e. from the PI-voltage controller. The manipulated variable of the current controller determines how the shoot through states are inserted into the pulse pattern of the inverter.

If the output of the current controller is zero (mode 0), it indicates that the level of U_{CZ} is sufficient and no boosting is required. In this case, the switching of the ZSI is performed like in the case of a standard VSI and no special provisions are required.

If the voltage $U_{CZ} < U_{CZ}^{*}$ it has to be boosted and the control demands a higher current I_{LZ}. As a result, the current controller will switch to the operation mode 1. In this mode of operation the zero vectors are replaced by the shoot through vector and the capacitor voltage U_{CZ} is boosted. Like DTC, DPC is a non-deterministic control and it is not possible to predict, which switching pattern is chosen next. In case of a high load of the inverter or of a low DC link voltage, it might happen that only very few zero states are available to be replaced by shoot through states. If that happens, the whole control algorithm can become unstable and cannot properly function. This situation is worsened because the amount of available zero states decreases under high load or at low DC link conditions. This case would correspond to the case of higher modulation index in PWM.

To overcome this problem, a third stage (mode 2) at the output of the current controller is implemented that inserts the shoot through states in a deterministic way. From previous papers it is known that the theoretical maximum boost (infinity) occurs at a shoot through duty cycle of 0.5 corresponding to a DPC operation in which every second switching state is a shoot through. Based on previous experiences, a shoot through duty cycle of 0.333 < 0.5 shows good results and was chosen for the implementation. In every third DPC cycle a shoot through state is introduced. Between two shoot through states the normal DPC operation (mode 0) is applied. In this way, the shoot through that is necessary for the boost operation of the ZSI can be achieved even under heavy load or at low DC-link voltage.

Fig. 3 shows the single-phase equivalent circuit of an inverter connected to the grid across an inductor. Fig. 4 shows the resulting phasor diagram. As mentioned the angle φ is controlled to zero to achieve unity power factor and to completely inject the available energy into the grid. The phase and the amplitude of the current $\underline{i}_{grid}$ and can be controlled by manipulating $\underline{u}_{Lgrid}$ by applying the proper voltage space phasor $\underline{u}_{Inv}$ delivered by the inverter. If the voltage $\underline{u}_{Lgrid}$ has a component in direction of $\underline{i}_{grid}$, the amplitude of $\underline{i}_{grid}$ will change. If

$\underline{u}_{Lgrid}$ has a component orthogonal to $\underline{i}_{grid}$, the phase of $\underline{i}_{grid}$ can be influenced. The angle φ has an impact on Q while the amplitude of the current $|\underline{i}_{grid}|$ determines P. During operation $\underline{i}_{grid}$ is rotating with line frequency, yet the available six active space phasors as depicted in Fig. 6 do not move. At every control cycle the states of the three hysteresis controllers are evaluated and the right switching state is chosen from a table in a way that $\underline{i}_{grid}$ follows the desired trajectory.

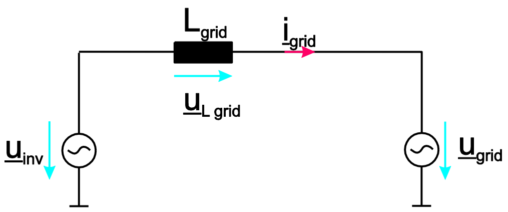

Fig. 3: Simplified equivalent circuit

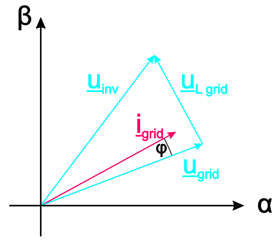

Fig. 4: corresponding phasor diagram

Table 1 lists the available switching states and gives the effect of each of the voltage spaces phasors on P and Q. “+” indicates an increase of the value of the corresponding variable, “-” indicates a decrease and finally a “0” indicates no change.

space phasor	$\underline{u}_1$	$\underline{u}_2$	$\underline{u}_3$	$\underline{u}_4$	$\underline{u}_5$	$\underline{u}_6$	$\underline{u}_7$	$\underline{u}_8$	$\underline{u}_9$
$\lvert\underline{i}_{Grid}\rvert \approx P$	+	+	-	-	-	-	-	-	-
$\varphi \approx Q$	-	+	+	+	-	-	0	0	0
boosting	no	no	no	no	no	no	no	no	yes

Table 1: Available inverter states and their effect on the active power P, on the reactive power Q and on the boosting of the ZSI for sector 0

The effect of the vectors on $\underline{i}_{grid}$ depends on the sector in which $\underline{i}_{grid}$ is located. The influence of the six active vectors changes circular. If $\underline{i}_{grid}$ moves from sector 0 to sector 1, $\underline{u}_2$ has the effect $\underline{u}_1$ had in sector 0. The plane is divided into six sector as it can be seen in Fig. 5. The knowledge of the sector in which $\underline{i}_{grid}$ is, is also necessary for the evaluation of the DPC algorithm

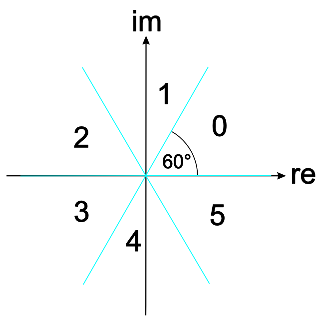

Fig. 5: Arrangement of the sectors used for the DPC

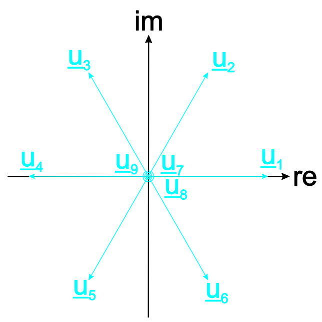

Fig. 6: Available voltage space phasors utilized in the DPC

5. Dimensioning of the main inductance L_Z

The dimensioning of the main inductance L_Z has in the case of DPC a higher importance than in PWM based control schemes and has to be examined with some detail. As previously mentioned, the inductance current I_{LZ} is increasing during the shoot through. In PWM based control schemes the duration of the shoot though can be finely adjusted and as a consequence the current increase can be limited. In the proposed control method, the states of the inverter will be applied for at least the duration of one DPC cycle. During that time I_{LZ} will constantly increase. For a voltage U_{CZ} = 560V, as it is required to feed a grid with a line to line voltage of 400V with a DPC sampling frequency of 40 kHz i.e. a sampling time of 25µs and for an inductance L_Z = 1.2mH the current will increase by

$$\Delta i_{LZ} = \frac{\Delta t_{DPC} \cdot U_{LZ}}{L_Z} = \frac{25\mu s \cdot 560V}{1{,}2mH} = 11{,}7A \qquad (1.3)$$

during one DPC cycle. The design of the inductance has to take this high current ripple into account. If a high fluctuation of the current is not acceptable, a solution would be to increase the DPC sampling frequency or the inductance or both. For the proposed setup, the frequency was therefore increased to 66 kHz. That reduces the current ripple but still gives enough time for the microcontroller to calculate the required data. The real switching frequency of each MOSFET is not necessarily increased by this measure. The real switching frequency mainly depends on the values of the inductances and on the choice of the hysteresis levels.

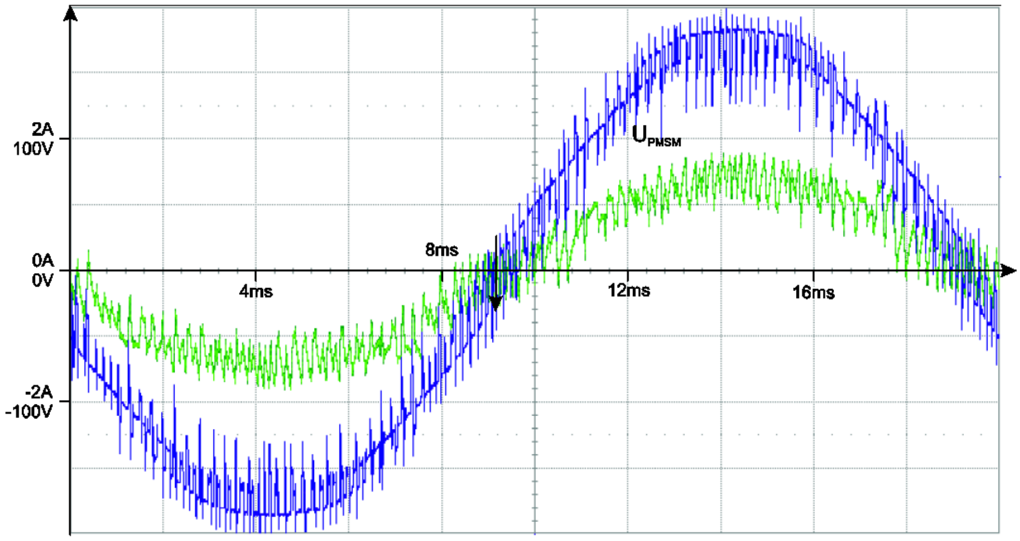

Fig. 7: Grid voltage u_{grid} (blue, phase voltage) an injected current i_{grid} (green).

6. Experimental Results

For the experimental validation of the proposed control scheme the inverter was connected to grid with a voltage of 230V RMS line to line. In order to be able to inject a current into the grid the DC link voltage U_{CZ} was set to 350V. The main inductance was L_Z = 1.2mH, the gird coupling inductance was L_{GRID} = 18mH. Fig. 7 shows the grid voltage $\underline{u}_{grid}$ (phase voltage) as well as $\underline{i}_{grid}$, the current injected into the grid. The current exhibits a ripple characteristic for the DPC and the hysteresis control keeps it within a tolerance band around the reference value. The RMS value of $\underline{i}_{grid}$ is 1A and approximately 400W are fed into the grid. The power control algorithm keeps the power factor λ= 1 so voltage and current are in phase.

Fig. 8 gives a general view of the functioning of the DPC. The current I_{LZ} is shown by the green trace. Every time the voltage U_{CZ} (yellow trace) drops below the threshold shoot through states are applied. This is clearly visible as the current I_{LZ} increases. The shoot through is activated until the level of U_{CZ} is sufficient again. This procedure repeats periodically to keep U_{CZ} at level.

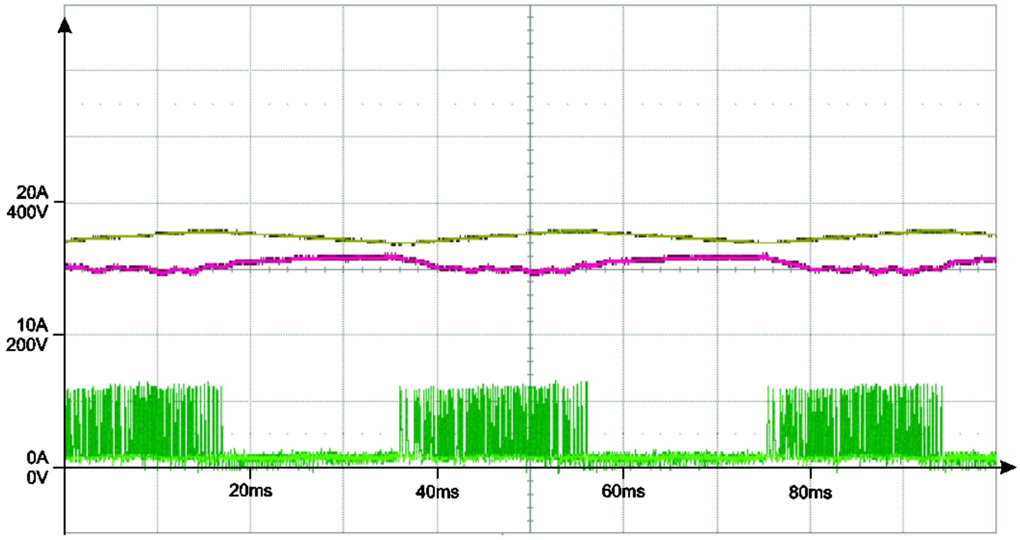

Fig. 8: View of the boosting behavior of the DPC; U_{IN} (red), U_{CZ} (yellow), I_{LZ} (green)

Fig. 9 shows the same context but with a zoom into the boosting (same color coding as above). It can be seen that the current increases for the duration of one DPC cycle, after that it falls back to zero. Within the 15µs it increases by more than 5A. This can be calculated according to (1.3) but the line to line voltage of the grid is only 230V so U_{CZ} of only 350V is sufficient resulting in a smaller current peak. The voltage U_{CZ} is increased above the level of U_{IN} (red trace), indicating a boosting. Discontinuous mode as it is described in [1] is not a problem, because it is automatically corrected by the control.

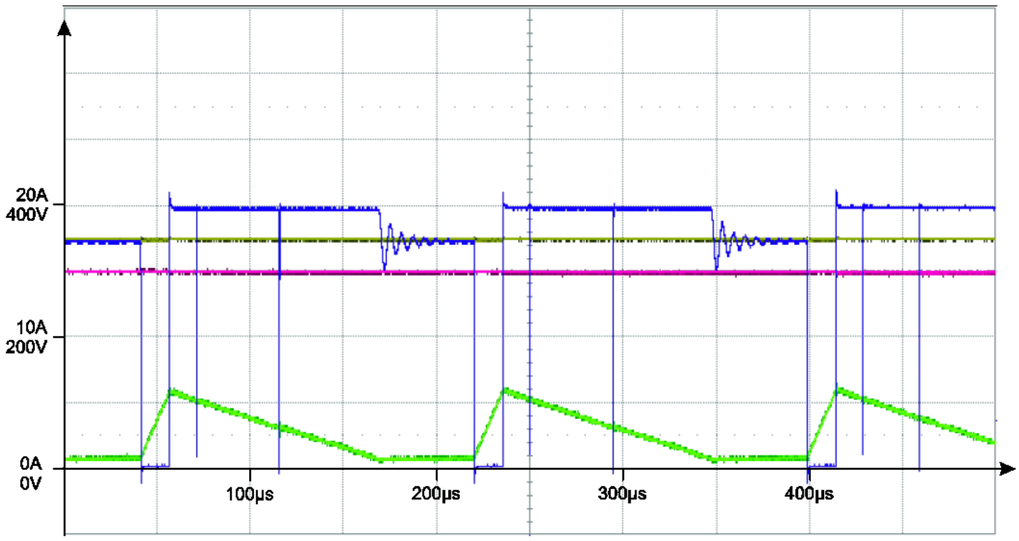

Fig. 9: Detailed view of the boosting behavior of the DPC; U_{IN} (red), U_{CZ} (yellow), U_Z (blue), I_{LZ} (green)

7. Conclusion

This paper presents a novel PDC control structure that is based on the idea of DTC. The proposed control method extends the well-known DPC scheme and includes the boosting operation of the ZSI. The appropriate switching states of the inverter are selected from a table in order to control the instantaneous values of P and Q in a way that only active power is fed into the grid. The advantage of this method is that it does not require a PWM modulator that can cause problems in other control schemes. One main advantage of the proposed scheme is the low computational effort: in fact it could be implemented on a simple dsPIC µController platform with a sampling time of 15µs. For validating the proposed control method by experiment active power was injected into the grid by successfully including the boosting of the ZSI.

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