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Grid-tied 15-level Cascade Inverter with Predictive Current Control

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***Abstract*—The paper presents a grid-tied cascade H-bridge inverter with predictive current control. The proposed 15-level cascade inverter consists of three H-bridge inverters with separated DC sources. At the output of the cascade inverter an L filter is used. The cascade inverter is controlled by the mean of RT-Lab. The predictive current regulator and one-phase synchronous reference frame PLL are designed with help of Rapid Control Prototyping. The proposed control method uses a discrete model of the load to predict the behaviour of the system for each of 15 voltage levels of inverter's output voltage. Verification on a laboratory model is described.**

***Index Terms*—current control, multilevel inverter, photovoltaics, predictive control.**

I. INTRODUCTION

The solar energy and especially photovoltaics is one of the fastest growing industries in the world. There is a demand for high quality electrical energy and thus the use of photovoltaics is almost impossible without modern power electronics. Whether it is a stand-alone PV electrical generator or a grid-connected system there is a demand to change the DC voltage to the AC voltage, to maximize the energy yield and to monitor the whole system. This is done by the mean of a PV inverter. There are several types of PV inverters according to the topology. However, there is little experimentation with alternative inverter topologies [1]. The most widely used topology employs full-bridge (H-bridge) voltage source inverter.

The cascade H-bridge inverter is an alternative to the single H-bridge inverter in photovoltaic systems. Its advantages over the single H-bridge inverter are lower THDi of the grid current and THDu of the output voltage, requirements of smaller filters, ability to transfer more power and smaller du/dt stresses. There is a need to increase the lifetime of photovoltaic inverters as well as their reliability. High voltage stresses decrease the lifetime of many electrical components [2]. Lower du/dt stresses of components in multilevel H-bridge inverter can help to meet these needs.

The lifetime of PV generators is in the range of 25 years and their reliability is high. However, the lifetime of typical inverter is in the range of 5–10 years (in 2006) [1]. It means that the inverter needs to be replaced several times during the lifetime of the PV generator. According to several biggest PV inverter producers, the PV inverter lifetime of 20 years cannot be achieved (mainly due to poor reliability of capacitors) and the price of the inverter is more important than its lifetime. On the other hand, the cost reduction and the reliability increasing can be achieved by using new topologies of PV inverters [1]. The topologies of utility scale PV inverters are moving towards multilevel structures mainly because of lighter filtering components and better harmonic spectra [1]–[7].

II. CASCADE H-BRIDGE INVERTER

Multilevel inverters have been used for many years in high-voltage, high-power applications. Their capability to divide the net voltage and power between several smaller cells and to produce higher quality voltage and current were the reason for their spreading in these areas. The most widely used topologies in industry are cascade inverter, diode-clamped NPC inverter and capacitor-clamped (flying capacitor) NPC inverter.

Multilevel inverters usually need several separated dc sources which is one of the biggest problems they have. However, in the area of photovoltaics, the separated dc sources with galvanic isolation are not a problem. Even though, not all above-mentioned multilevel topologies are suitable for PV inverter. The diode-clamped NPC inverter has a complicated active power control and the capacitor-clamped NPC inverter has low efficiency when it has to transfer the active power [3].

By using asymmetrical DC voltages at the cascade inverter input, where the next DC source voltage level is two-times the previous DC voltage level, the number of output voltage levels can be increased compared to symmetrical H-bridge inverter (d-number of DC sources)

$$n = 2^{d+1} - 1. \tag{1}$$

Each H-bridge inverter can create positive, negative or zero voltage on its output with magnitude equal to the DC source voltage. Thus there are 15 possible combinations for the cascade H-bridge inverter with 3 separated DC sources.

The measured partial voltages at the output of each H-

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bridge inverter are shown in Fig. 2.

It can be clearly seen that each H-bridge inverter is switching with different frequency, which is increasing as the voltage of the H-bridge inverter is decreasing (natural decrease of switching losses). There is discontinuous power transfer at the output of each bridge cell.

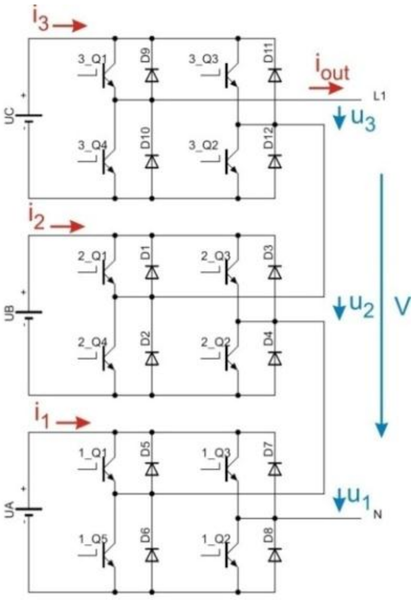


Fig. 1. Single-phase cascade H-bridge inverter with three separated DC sources (UA = 240V, UB = 120V, and UC = 60V), capable of creating 15 voltage levels at its output.

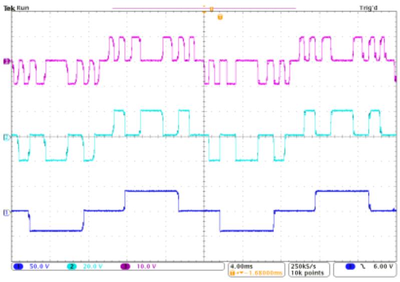


Fig. 2. Measured partial output voltages u_1, u_2, u_3 of the cascaded H-bridge inverter (amplitudes: 40, 20 and 10V), $m_a = 0{,}8$, $m_f = 2$.

III. DISTRIBUTED GENERATION SYSTEM

Small grid connected PV systems are usually connected to the low voltage grid. In Germany, which has more than 20 GW of grid connected PV systems installed, is approx. 80% of installed power fed to the low voltage grid [6].

Such installed power has significant influence over grid and thus there is a need to change PV grid connected systems from pure grid feeders to grid supporters. It can mean, for instance, that the increase in grid voltage can be compensated by grid connected PV system which is capable of consuming reactive power.

When considering the control structure for grid connected PV systems, there are two possibilities to choose from. Either voltage or current control can be chosen. With the current control, there is a fully independent control of reactive power.

The current regulation structure of a grid connected PV system is depicted in Fig. 3. One phase system is considered. The inputs to the regulation structure are two currents in synchronous reference frame: i_{dref} and i_{qref}. The synchronous reference frame is synchronized to the grid by mean of one-phase synchronous reference frame PLL. The PV system is current controlled. The output from the reference current generator is fed to the predictive current controller which is together with the coder responsible for generating gating pulses for the 15-level cascade inverter. The cascade inverter is connected to the grid through the grid filter which is for now just a simple L filter.

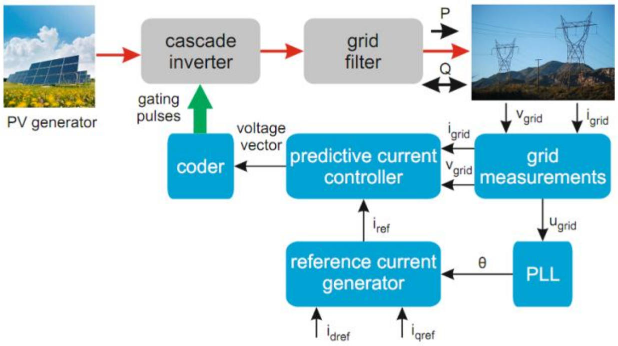


Fig. 3. Current control of grid connected PV system.

IV. CASCADE INVERTER CONTROLLER

The cascade inverter controller (Fig. 3) consists of several parts: grid measurements, PLL, reference current generator, predictive current controller and coder.

The PLL (Phase Locked Loop) is a mean how to synchronize the grid connected system to the grid voltage. The synchronization is needed for power factor control. The most widely used PLL technique in three-phase system is synchronous reference frame PLL (SF-PLL). The SF-PLL has good performance with the grid which is not highly distorted [8].

The SF-PLL is based on direct Clark transformation of the three-phase system into two-phase system and the subsequent Park transformation into synchronous reference frame. Thus two voltages v_d and v_q are produced. One of these voltages is by a mean of PI controller set to zero which results in the reference being locked to the grid. The output from the PLL is a phase angle which is used to generate the reference three-phase currents through reverse Park transformation (dq→αβ) and subsequent reverse Clark transformation (αβ→abc).

The SF-PLL can be used for one-phase systems as well. However, it is not possible to use the direct Clark transformation because only one voltage is presented. The solution is to create artificial two-phase system based on the one-phase grid voltage [8], [9].

The property of the stationary reference frame is that two voltages v_α and v_β are orthogonal. If the grid voltage corresponds to the v_β voltage, than the v_α can be created in a virtual two-phase generator as follows

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} v_{grid}(\omega t - \pi/2) \\ v_{grid}(\omega t) \end{bmatrix} = \begin{bmatrix} V_m \sin(\omega t - \pi/2) \\ V_m \sin(\omega t) \end{bmatrix} \cong$$

$$\cong \begin{bmatrix} -V_m \cos(\omega t) \\ V_m \sin(\omega t) \end{bmatrix}. \qquad (2)$$

The second-order low-pass filter is used to create the 90 degree phase shift [8], [9]. When the input voltage v_{grid}

passes through the second-order low-pass filter, where the damping ratio $\zeta = 1/\sqrt{2}$, the undamped natural frequency ω_n has the same value as the estimated frequency, a signal with a phase-angle difference of $\pi/2$ and amplitude of $V_m/\sqrt{2}$ is obtained [8]

$$u_\alpha = -\sqrt{2}\frac{V_m}{\sqrt{2}}\sin\left(\omega t - \frac{\pi}{2}\right) = V_m\cos(\omega t). \quad (3)$$

The one-phase synchronous reference frame PLL is shown in Fig. 4. The input is a grid voltage which passes through a low-pass filter. The amplitude and phase of that filter is compensated, as suggested in [8].

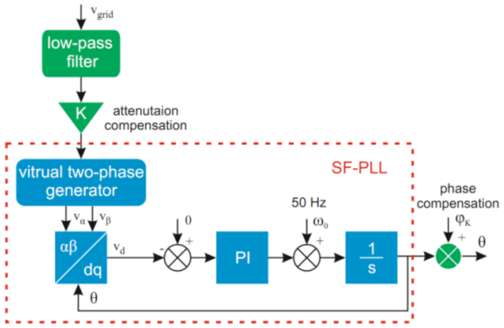


Fig. 4. One-phase synchronous reference frame PLL (virtual two-phase generator is 2nd order low-pass filter).

The reference current generator consists simply of direct Park transformation. The i_α is set as reference current i_{ref} for current regulator.

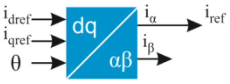


Fig. 5. Reference current generator.

When using the PWM control there is a need to linearise the model of the inverter and this control technique can lead to cascade regulation structure which has slow response time. The predictive control offers the possibility to control the inverter's output current and voltage with high dynamics without the need to face the problem of non-linear nature of semiconductor power converters [4].

In [5], authors use trajectory based predictive control for current control of three-level diode-clamped NPC inverter. This control technique has been adapted to the proposed 15-level cascade H-bridge inverter. The basic principle of used predictive control technique is that the cascade H-bridge inverter can create only limited number of voltage levels at its output.

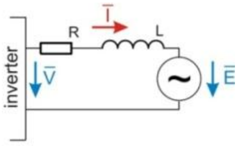


Fig. 6. The RL filter between the inverter's output and the grid used to decouple the output voltage and the grid and to filter higher harmonics.

The system shown in Fig. 6 can be described by

$$\mathrm{v} = \mathrm{Ri} + \mathrm{L}\frac{\mathrm{di}}{\mathrm{dt}} + \mathrm{e}. \quad (4)$$

The prediction of the load current is based on the discrete model, which can be easily implemented by computer. The derivative in (4) can be replaced by its discrete approximation (T_S is the sampling time)

$$\frac{\mathrm{di}}{\mathrm{dt}} \approx \frac{\mathrm{i(k+1)-i(k)}}{\mathrm{T_S}}. \quad (5)$$

By replacing (5) in (4), the discrete model of the system is obtained

$$\mathrm{i(k+1)} = \frac{\mathrm{T_S}}{\mathrm{L}}\big(\mathrm{v(k)} - \mathrm{e(k)}\big) + \mathrm{i(k)}\left(1 - \frac{\mathrm{RT_S}}{\mathrm{L}}\right). \quad (6)$$

The (6) is used to predict the future value of the load current. For the trajectory based predictive control there is a need to create the trajectory, which will the controlled variable follow. However, the future value of the reference current $i^*(k+1)$ is unknown. In order to determine the next value of the reference current, in [5] Lagrange quadratic extrapolation is used

$$\mathrm{i^*(k+1)} = 3\mathrm{i^*(k)} - 3\mathrm{i^*(k-1)} + \mathrm{i^*(k-2)}. \quad (7)$$

For predictive control, there is a need to create the cost function which will be evaluated in each sampling time and will define the behaviour of the system. The function can be chosen as a filter to remove certain harmonics and so on [4]. The cost function was chosen as

$$z(k) = |i^*(k+1) - i(k+1)|. \quad (8)$$

The cost function is evaluated for each of 15 voltage vectors that the cascade H-bridge inverter can create at its output and the voltage vector V that minimizes the cost function (8) is chosen and applied at the inverter's output. The controller structure is shown in Fig. 7. The inputs are grid voltage and current and the reference current from the reference current regulator. The discrete model of the system is calculated for each voltage vector and the voltage vector that minimise the cost function is chosen. The output of the predictive current regulator is the desired voltage vector which is fed to the coder. The coder is responsible for the control of switching states of H-bridges to create the desired voltage level at the inverter's output.

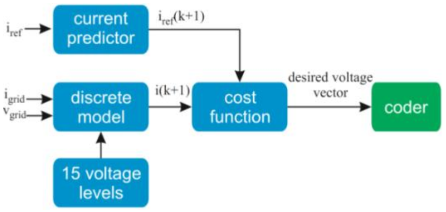
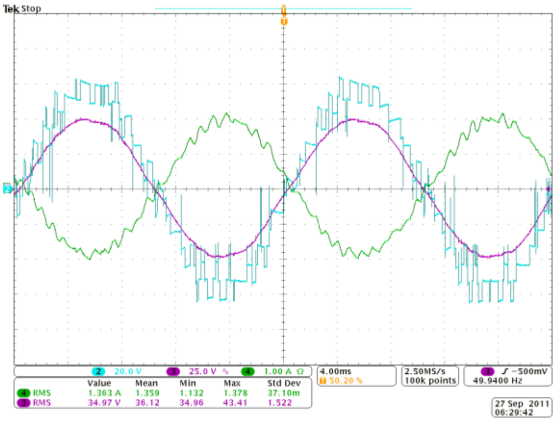


Fig. 7. The predictive current controller.

V. EXPERIMENTAL RESULTS

The laboratory model of 15-level cascade H-bridge inverter was build. The model was designed to verify the control technique, mainly tracking capability of the load current and the power factor control. The 3.6 kW/ ~230 V/50 Hz system is built. For measurements, the system parameters were lowered to: $R = 5\ \Omega$, $L = 7\ mH$, $T_S = 100\ \mu s$, $U_A = 40\ V$, $U_B = 20V$, $U_C = 10\ V$ (voltage sources). The inverter was connected to the single-phase grid ~35V/50Hz and controlled by RT-Lab with DAQ card.

The reference current was set as $i_{dref} = 2\ A$, $i_{qref} = 0\ A$, thus the power factor should be 1. The active and reactive power as well as phase shift was measured by power analyzer. The real phase shift was 2 degrees into inductive region thus the reactive power was consumed by the inverter (Fig. 8).



	Value	Mean	Min	Max	Std Dev
4 RMS	1.363 A	1.359	1.132	1.378	37.10m
3 RMS	34.97 V	36.12	34.96	43.41	1.522

Fig. 8. Output current of cascade inverter with current control: CH2: inverter voltage (inverted), CH3: grid voltage, CH4: grid current (T = 100μs, R = 5Ω, L = 7mH, U_A = 40V, U_B = 20V, U_C = 10V), THDi = 4%, P = 50 W, Q = -1,3 W, φ = 2° inductive, i_{dref} = 2 A, i_{qref} = 0 A.

The designed control technique works properly and is ready to by used with cascade inverter with full output power.

VI. CONCLUSIONS

In this paper the 15-level grid-tied cascade H-bridge inverter with predictive current control technique is presented. From the experimental results can be concluded that the proposed current regulator and PLL synchronisation work properly. One of the biggest challenges is connection to the PV generator and design of MPPT (Maximum Power Point Tracking) control, which is essential for a PV inverter. Also replacing the simple L filter with a filter of higher order (LCL) is one of the possible challenges. By creating more sophisticated cost function, the control technique can be improved. The work shows promising results and by using computer control and RT-Lab, the controller can be easily updated.

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