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Output voltage control system for a three-level neutral-point clamped quasi-Z-source inverter

***Abstract**. This paper presents three closed loop control systems for a three-level neutral-point-clamped quasi impedance source inverter. These control systems are designed and simulated to enable validation of their operation for improvement of the capabilities of the three-level neutral-point-clamped quasi impedance source inverter during variable input voltage situations. PID controller-based control systems could be used in photovoltaic applications in which the output voltage of the solar array depends on the irradiance and the temperature produces variable input voltage.*

***Streszczenie.** W artykule przedstawiono trzy algorytmy sterowania w pętli zamkniętej, bazujące na regulatorach PID, dla trójpoziomowego przekształtnika z diodami poziomującymi zasilanego ze źródła quasi-Z. Przeprowadzono badania symulacyjne omawianych algorytmów, w celu potwierdzenia ich pozytywnego wpływu na pracę przekształtnika w warunkach zmienności napięcia wejściowego. Proponowane strategie mają potencjalne zastosowanie w fotowoltaice, gdzie występują zmiany napięcia wyjściowego w zależności od temperatury i nasłonecznienia. (**Sterowanie napięciem wyjściowym dla trójpoziomowego falownika z diodami poziomującymi zasilanego ze źródła quasi-Z**).*

Keywords: Multilevel converter, renewable energy system, PID controller.
Słowa kluczowe: przekształtnik wielopoziomowy, energia odnawialna, regulator PID.

Introduction

oday's power system scenarios differ from traditional configurations due to several factors, such as increased electrical consumption, liberalization of the electricity market, need for reducd pollution and CO_2 emissions, and the new technological development that configures the distributed generation (DG).

Distributed generation, also called distributed resources (DR), distributed energy resources (DER) or dispersed power (DP), is the use of small-scale power generation technologies located close to the load being served. These technologies include reciprocating engines, microturbines, combustion gas turbines (including miniturbines), fuel cells, photovoltaic plants and wind turbines. Some advantages of DG are: lower costs and losses, reliability improvement, reduction of emissions, expansion of the energy options, addition of redundancy that increases grid security, contribution to competition in the energy pool and increase of the energy autonomy, and the development of isolated regions.

Many of the renewable energy resources, for instance, solar arrays or fuel cells can only produce dc voltage and a DC/AC conversion stage is required [1]. In the last decade, several inverter topologies for solar power conversion have been analyzed [1-10].

A three-level neutral-point-clamped quasi-Z-source inverter (3L-NPC qZSI) proposed in [11-12] is a new modification of the qZSI (Fig. 1).

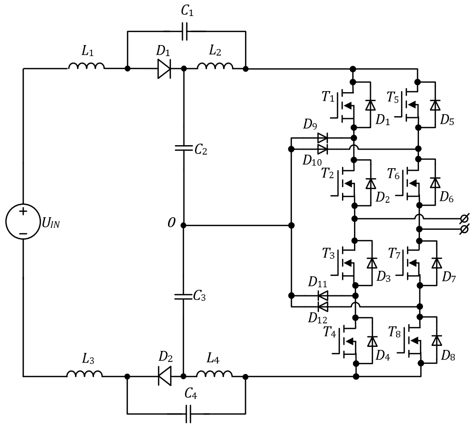

Fig.1. 3L-NPC qZSI topology.

This topology combines advantages of the two topologies [11-12, 17]. At the same time, in a closed loop, control systems are required to improve the 3L-NPC qZSI capabilities due to the unpredictable and non-manageable behaviour [13] of the some renewable resources such as photovoltaic energy.

This paper presents the design and simulation of three closed loop control systems for the 3L-NPC qZSI that allow constant output voltage to be achieved during variable input voltage situations in an isolate photovoltaic system. These systems can be used in photovoltaic plants in which the output voltage of the solar array depends of the irradiance (*W*) and temperature (*T*) [14-15]. Changes in these parameters produce variable input voltage in the inverter where the array is connected, for example, in situations when shadows appear.

Block diagram and 3L-NPC qZSI plant

Fig. 2 illustrates the open loop block diagram of the analyzed plant. The plant is composed by the qZS stage, the 3L-NPC inverter and the L-C output filter which compose the power stage.

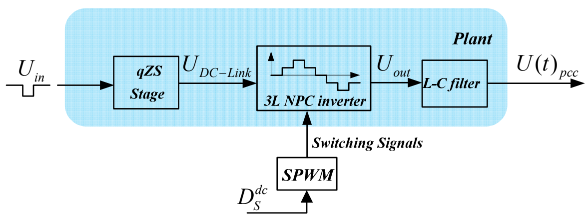

Fig.2. Open loop block diagram of 3L-NPC qZSI.

Shoot-through sinusoidal pulse width modulation

In order to generate switching signals of each transistor, a shoot-through sinusoidal pulse width modulation (SPWM) proposed in [16-17] was chosen. Fig.3 shows a sketch of this modulation technique. This technique has several advantages such as: distributed shoot-through states with constant width during the whole output voltage period, **smaller** size of the passive element, low value of the total harmonic distortion (THD) in the output voltage due to the achieved symmetry at the control signals, low input current ripple and higher capacitor voltage balance.

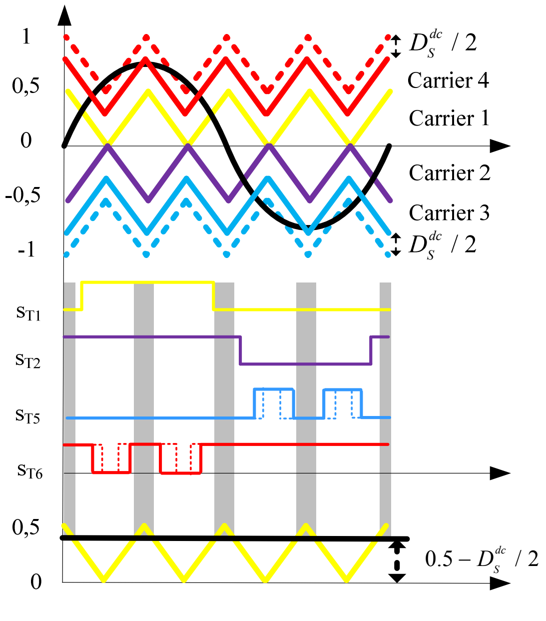

Fig.3. Sketch of the chosen modulation technique.

To obtain the boost performance of the analyzed topology, the shoot-through duty cycle ($D^{dc}{}_S$) is defined as:

(1) $$D_s^{dc} = \frac{t_s^{dc}}{T},$$

where: $D^{dc}{}_S$ – constant shoot-through duty cycle, $t^{dc}{}_S$ – total time that the shoot-through state is applied, T – output voltage period.

Another important feature of the used shoot-through SPWM is that we can use the ratio:

(2) $$D_{s\_MAX}^{dc} \le 1 - M,$$

where: M – modulation index of reference signal, $D^{dc}{}_{S\_MAX}$ – maximum value of $D^{dc}{}_S$ that could be applied [18]. Equation (2) prevents overmodulation. Also, we can use the equation

(3) $$B = \frac{U_{DC}}{U_{IN}} = \frac{1}{1-2D_S^{dc}},$$

where: B – boost factor, U_{DC} – dc link voltage, U_{IN} – input voltage.

Equations (2) and (3) allow control algorithms to be developed in a closed loop system, improving the 3L-NPC qZSI abilities.

PID controller for variable input voltage conditions in a 3L-NPC qZSI and control system design

In order to maintain the output voltage in a 3L-NPC qZSI constant, it is necessary to develop a control system when the input voltage is not constant. For example, in photovoltaic systems, the output voltage of the solar array depends on the irradiance (W) and temperature (T) [14-15]. Changes in these parameters produce variable input voltages in the inverter where the array is connected.

A. PID controller

Proportional-integral-derivative (PID) controllers [19-20] are widely used in industrial control systems because of the reduced number of parameters to be tuned. They provide control signals that are proportional to the error between the reference signal and the current output (proportional action) to the integral of the error (integral action) and to the derivative of the error (derivative action). The main features of PID controllers are the capacity to eliminate the steady-state error of the response and the ability to anticipate output changes.

The structure of a PID controller is

(4) $$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt + T_d\frac{d\,e(t)}{dt}\right),$$

where: $u(t)$ – control signal, $e(t)$ – error signal, K_p, T_i, T_d – parameters to be tuned.

B. Closed loop systems and control system designs

Figure 4 shows the sketch of the first proposed closed loop control system for the 3L-NPC qZSI during variable input voltage conditions.

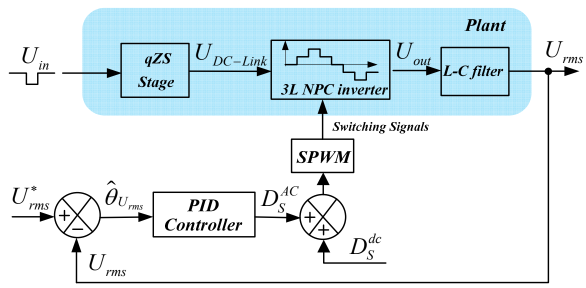

Fig.4. Closed loop block diagram of 3L-NPC qZSI. Proposal 1.

Input voltage is considered as the disturbance of the system. RMS output voltage value is the variable to control and the shoot-through duty cycle is the control variable. It is composed of two components, one of them is constant ($D^{dc}{}_S$) in order to assure a minimum shoot-through duty cycle and as a consequence a minimum value of the boost factor to avoid instabilities [17]. The variable component of the shoot-through duty cycle ($D^{ac}{}_S$) is adjusted by the PID controller to maintain the error between the voltage RMS reference and the measurement in zero. The maximum value of the total shoot-through duty cycle is limited by equation (2) taking into account the chosen modulation index in the SPWM.

Figure 5 shows the sketch of the second proposed control system for the 3L-NPC qZSI. In this case, instantaneous output voltage value ($U(t)_{out}$) is the variable to control. The rest of the variables are the same as in the previous proposed control system.

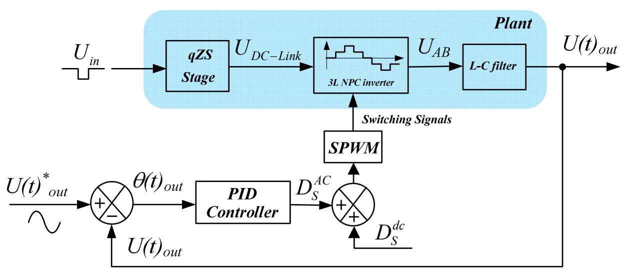

Fig.5. Closed loop block diagram of 3L-NPC qZSI. Proposal 2.

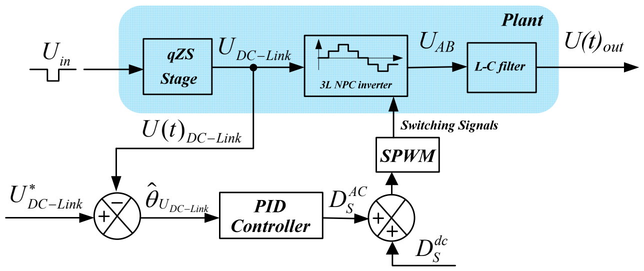

Fig.6. Closed loop block diagram of 3L-NPC qZSI. Proposal 3.

Figure 6 shows the sketch of control system 3 for the 3L-NPC qZSI during variable input voltage conditions. In this case, DC-Link voltage value ($U_{DC\text{-}Link}$) is the variable to control.

C. Tuning of PID controller parameters

There are several procedures in order to tune a PID controller. The method used in this work is the Ziegler-Nichols procedure based on the response curve. This is a heuristic method defined as follows:

1) Adjust the open loop plant in a normal operation point by using $u(t)$. In our case it will be D^{dc}_{S}. After that the plant is stabilized in $y(t)= y_0$ (output voltage in the studied system) when $u(t)= u_0$.
2) Apply a step in $u(t)$ from u_0 to u_∞ between 10% or 20% of the nominal value of $u(t)$.
3) Analyze the response of the open loop system when the new operation point is stabilized in y_∞.

In order to develop this tuning procedure, a simulation model of 3L-NPC qZSI and the control system have been implemented in SimPowerSystems of Matlab/Simulink.

The parameters of the simulation are described in Table I.

Table I. Simulation parameters

Input voltage U_{IN}	230 V
Inductors L_1,L_2,L_3,L_4	0.29 mH
Inductor resistance r_L	0.1 Ω
Capacitors C_1,C_2,C_3,C_4	4mF
Resistance load R_{load}	80 Ω
Switching frequency of carriers	100 kHz
Shoot-Through Duty Cycle	0.1667
Output frequency	50 Hz
Filter inductance	2 mH

According to the exposed methodology, the model of the plant in open loop has been tested with the parameters shown in Table II.

Table II. Used parameters for the Zieglel-Nichols method

Normal operation of shoot-through duty cycle D^{dc}_{S}	0.13
Nominal shoot-through duty cycle D^{dc}_{S}	0.16
Step amplitude (20% of nominal D^{dc}_{S})	0.162
Step input time (s)	2

The different parameters to be calculated in the tuning of the PID controller after analyzing the obtained response are:

$$k_0 = \frac{y_\infty - y_0}{u_\infty - u_0}, \tag{5}$$

$$\tau_0 = t_1 - t_0, \tag{6}$$

$$\gamma_0 = t_2 - t_1, \tag{7}$$

where: t_0 – time when the step is applied, t_1 – time when the maximum slope line is cut with y_0, t_2 – time when the maximum slope line is cut with y_∞.

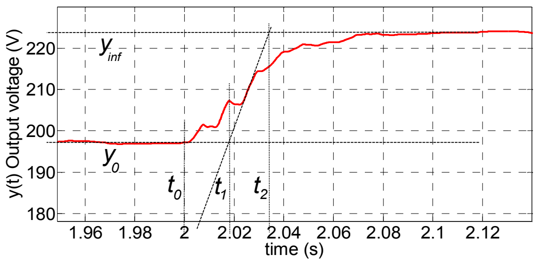

Fig.7. Open loop system response of 3L-NPC qZSI when a step input (D^{dc}_{S}) is applied.

The response (RMS output voltage value) of the open loop system is presented in Fig. 7 with the different necessary values to calculate K_p,T_i, and T_d. Obtained parameters for the PID controller are shown in Table III.
All of these values have been calculated and are shown in Table III.

Table III. Obtained parameters for the PID controller

Parameter	Value
u_0 (initial shoot-through duty cycle)	0.13
u_∞ (final shoot-through duty cycle)	0.162
y_0 (initial output voltage)	197 V
y_∞ (final output voltage)	223 V
t_0 (step time)	2 s
t_1 (cut time between maximum slope line and y_0)	2.018 s
t_2 (cut time between maximum slope line and y_∞)	2.034 s
k_0 parameter	831.5
τ_0 parameter	0.018
γ_0 parameter	0.016

Once obtained, the shown parameters for the PID controller using the Ziegler-Nichols method based on the response curve have been refined according to [21] in order to obtain improvement in the control system performance. Finally, the values of the PID controller are shown in Table IV.

Table IV. Constants for the PID controller

	K_p	T_i	T_d
Expression of PID parameters	$\frac{1.2\gamma_0}{K_0\tau_0}$	$2\gamma_0$	$0.5\gamma_0$
Obtained values for the PID controller	0.013	0.036	0.009
Used values for the PID controller after refinement	0.001	0.1	0.0001

Simulation results

Figure 8 shows the variable input voltage in the analyzed system whereas this profile has been used in every proposed control system. When time is equal to 1.5 s, a step in the input voltage is applied from 230 V to 180 V and the duration of this lower input voltage level is one second. After this, the same step is applied but in order to return to the initial state.

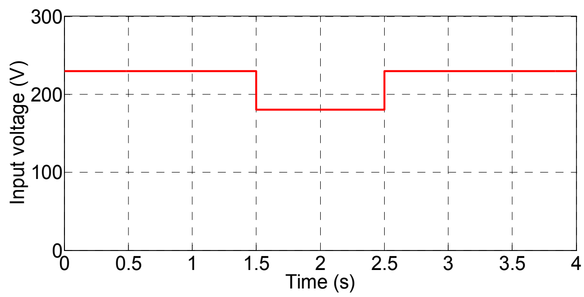

Fig.8. Applied variable input voltage in the 3L-NPC qZSI.

Figure 9 shows the output RMS voltage in the 3L-NPC qZSI when the output RMS reference voltage (U_{RMS}) is equal to 230 V using control system 1. The system tracks with high accuracy the reference during the different levels of input voltage due to the adjustment of the variable component of the shoot-through duty cycle (D^{ac}_{S}). This adjustment can be seen in Fig. 10 where the total shoot-through duty cycle is shown.

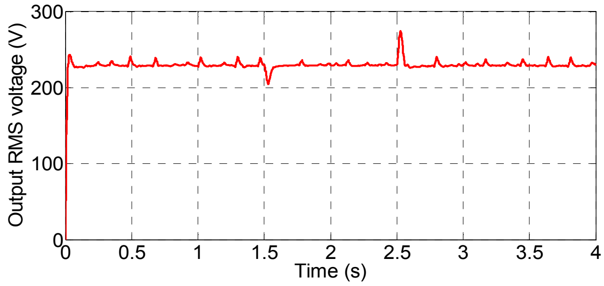

Fig. 9. Output RMS voltage in the 3L-NPC qZSI using control system 1.

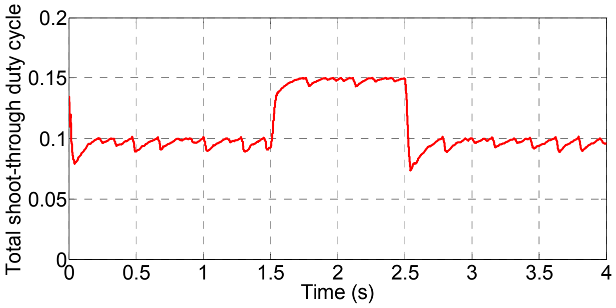

Fig.10. Total shoot-through duty cycle (constant and variable components) using control system 1.

Figures 11 and 12 show the output RMS voltage and the adjustment of the shoot-through duty cycle using control system 2. The reference signal (*U(t)*$_{out}$*) is a sinusoidal wave with an amplitude of 325 V.

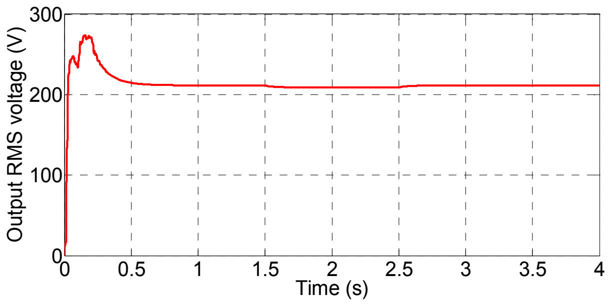

Fig.11. Output RMS voltage in the 3L-NPC qZSI using control system 2.

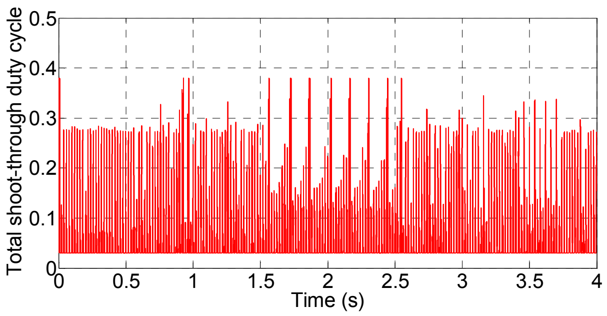

Fig.12. Total shoot-through duty cycle (constant and variable components) using control system 2.

Control system 2 presents a larger overshoot than in the previous case. It is because the sinusoidal reference is more difficult to be tracked.

Figures 13 and 14 show the output RMS voltage and the adjustment of the variable component of the shoot-through duty cycle when control system 3 is used. The reference signal is the voltage level of the DC-Link (*U(t)$_{DC-Link}$*) equal to 406 V in order to obtain 325 V as a maximum value in the output voltage according to (8):

(8) $$U_{out}^{MAX} = U_{DC-Link}(1-M).$$

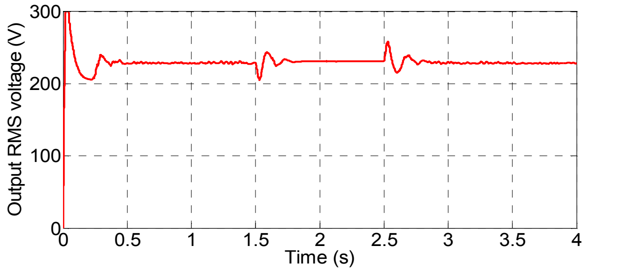

Fig.13. Output RMS voltage in the 3L-NPC qZSI using control system 3.

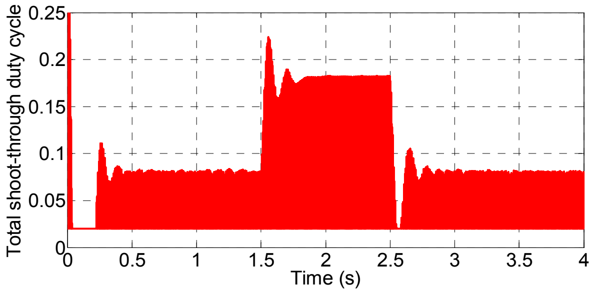

Fig.14. Total shoot-through duty cycle (constant and variable components) using control system 3.

In this case, similarly to control system 1, good accuracy in the tracking of the reference is obtained due to very good adjustment of the shoot-through duty cycle.

Finally, Figs. 15, 16 and 17 show the instantaneous output voltage during the step. Total harmonic distortion (THD) has been calculated in each case.

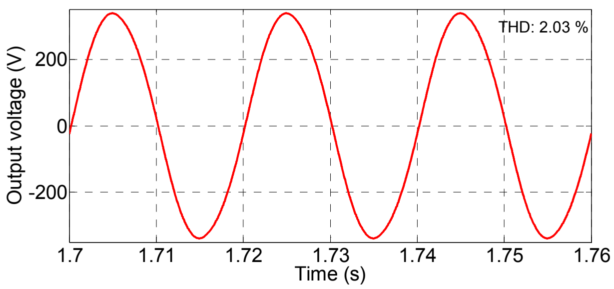

Fig.15. Output voltage using control system 1.

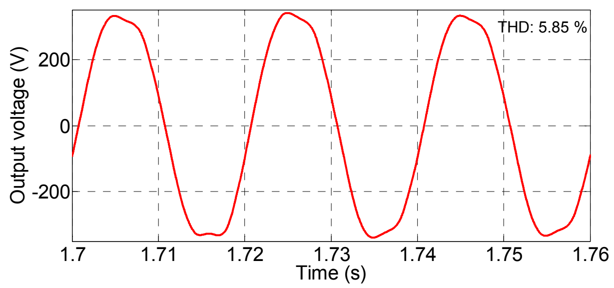

Fig.16. Output voltage using control system 2.

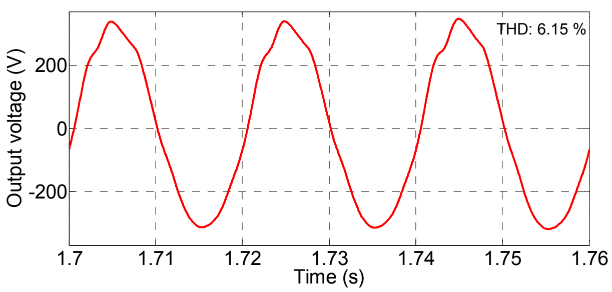

Fig.17. Output voltage using control system 3.

Conclusions

This paper has proposed three closed loop control systems based on the PID controller for the 3L-NPC qZSI that allows constant output voltage during variable input voltage situations to be obtained. It can be used in photovoltaic plants in which the output voltage of the solar array depends on the irradiance and temperature. Control system 1 based on the RMS output voltage value has demonstrated the best dynamic response and a lower value of THD but as a drawback, it requires higher computational cost than the other two proposals that are based on instantaneous values.

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