

Simulation Study of Nonlinear PI-Controller with Quasi-Z-Source Derived Push-Pull Converter

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Abstract – This paper is focused on the control issues of the quasi-Z-source derived push-pull converter with integrated magnetic elements. The proposed converter is intended for applications that require a high gain of the input voltage and galvanic isolation, i.e. power conditioning systems for renewable energy sources, such as variable speed wind turbines with direct driven permanent magnet synchronous generators. Magnitude and frequency of the output voltage of such turbines are variable due to intermittent nature of the wind power. Despite number of advantages converter has complicated dynamic behavior. Simulations showed change of stability margin depending on current operation point of the wind turbine and output load. Closed loop control system should provide fast response and stable operation in the wide range of wind speeds. Simulations showed that the conventional PI-controller with saturation cannot satisfy those requirements. Nonlinear PI-controller was derived by adding adjustment block to the conventional PI-controller. Adjustment block is drastically changing proportional and integral gains of the controller according to sign of the output voltage error. Proposed controller is compared with conventional one by means of simulation in PSIM. Simulation results prove that proposed nonlinear control system has improved regulator performance.

Keywords – DC-DC power converters, automatic voltage control, closed loop systems, control system synthesis.

I. INTRODUCTION

Quasi-Z-source inverters (qZSI) were proposed in 2008 [1]. qZSI provides wide regulation freedom, continuous input current and high EMI immunity. These advantages make qZSI suitable for renewable power applications (solar panels, fuel cells, wind power generators, etc.) [2]-[5] and electric drive vehicle applications [6]. DC/DC converters derived from qZSI show high performance as an intermediate voltage matching converter between renewable energy source and grid-tied inverter [7]-[9].

Nowadays the permanent magnet synchronous generators (PMSG) are widely used in wind power applications [10], [11]. They are well known for high efficiency, low volume and relatively small weight. Multipole construction of PMSG allows its direct coupling to the blades. Elimination of gearbox improves volume and reliability of wind energy conversion system. PMSG-based small wind turbines can be used in residential power systems instead of diesel generators [12]. Quasi-Z-source DC/DC converters with galvanic high frequency isolation are suitable solution for three-stage grid integration system for PMSG-based wind turbines, which is shown in Fig. 1 [8]. In this configuration some energy storage

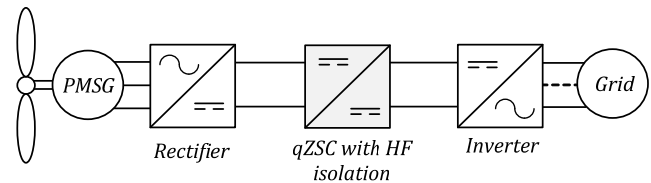


Fig. 1. Block diagram of PMSG-based wind turbine grid-integration system with intermediate qZSC with high-frequency isolation.

system can be easily integrated into DC-link between intermediate converter and grid-tied inverter.

Recent results in the analysis of the dynamic behavior of quasi-Z-source converter (qZSC) family revealed high complexity in estimation of their stability margins [13]. Small-signal stability of qZSC depends on values of elements, duty cycle of shoot-through state and properties of the load [14]. Also, oscillations are possible as a result of input voltage disturbances [6]. These circumstances impose restrictions on controller design. Input voltage from renewable energy sources depends on instantaneous weather conditions and load. It follows therefore that the design of closed-loop control systems for renewable qZSC-based applications requires comprehensive analysis of stability and special types of controllers, for example, PI-compensator with feed forward control loop [14].

This paper is devoted to the control issues of the qZS-derived push-pull converter (qZSPPC). The converter was specially developed for the high frequency (HF) isolated intermediate stage of the interface converter for PMSG-based wind turbines. This step-up converter is able to operate in wide range of input voltages and provide continuous input current.

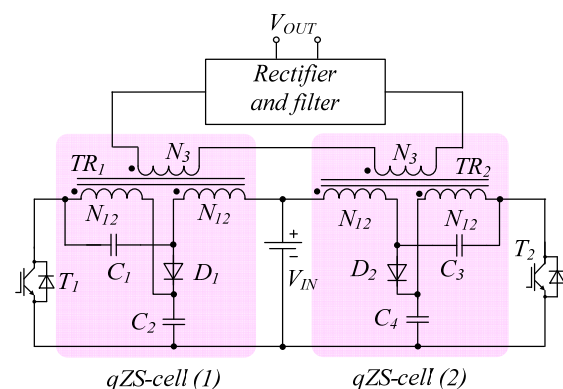


Fig. 2. Quasi-Z-source-derived push-pull converter (qZSPPC).

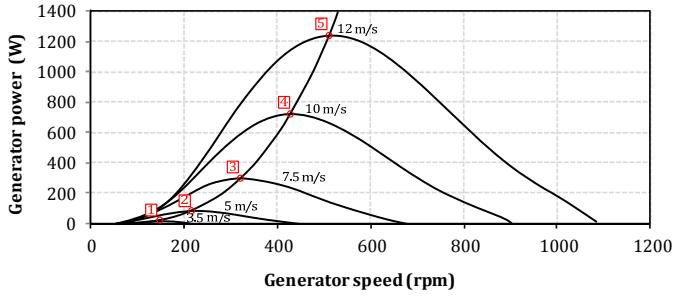


Fig. 3. PMSG-based WT power curves at various wind speeds.

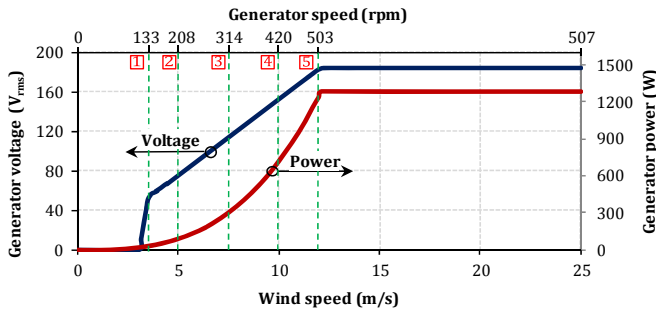


Fig. 4. PMSG-based WT power and voltage curves with MPPT.

II. DESCRIPTION OF THE STUDIED SYSTEM

Novel topology shown in Fig. 2 was firstly proposed in [15]. It was derived from the one-switch non-isolated qZSC by using coupled inductors. Two arms are working interleaved. Output windings are connected in series. Magnetizing inductances of three-winding transformers serve as energy storage elements in corresponding arms. Detailed steady-state analysis of this topology can be found in [15]. Each transistor is switched with the duty cycle $D_A < 0.5$. qZSPPC was reported as suitable solution for PMSG-based wind turbines [16]. Static voltage gain of this converter in continuous conduction mode (CCM) is:

$$G = \frac{V_{OUT}}{V_{IN}} = \frac{N_3}{N_{12}} \cdot \frac{2 \cdot D_A}{1 - 2 \cdot D_A} \quad (1)$$

Parameters of case study wind turbine were described in [16]. This data will be also used for simulations in the given paper. Both frequency and magnitude of the output voltage of PMSG-based wind turbine (WT) depend on the wind speed. Each value of wind speed corresponds to some rotation speed of the PMSG with maximum output power. It means that this type of WTs requires MPPT algorithm. Power curves for turbine are shown in Fig. 3. Red dots with indexes from 1 to 5 indicate maximum power operating points. This WT has cut-in speed 3.5 m/s. WT is operating with maximum output power at wind speeds between 12 m/s and 25 m/s. It must be stopped at the wind speeds above 25 m/s to avoid damage of WT [17].

Power and voltage curves in maximum power points for WT mentioned above are shown in Fig. 4 as functions of wind speed. Table I indicates values for open-loop operation of the qZSPPC for operating points 1...5 marked on Fig. 4. Load resistance, gain and duty cycle are calculated according to the next assumptions: CCM operation, $V_{OUT} = 400V$, $N_{12} = N_3$.

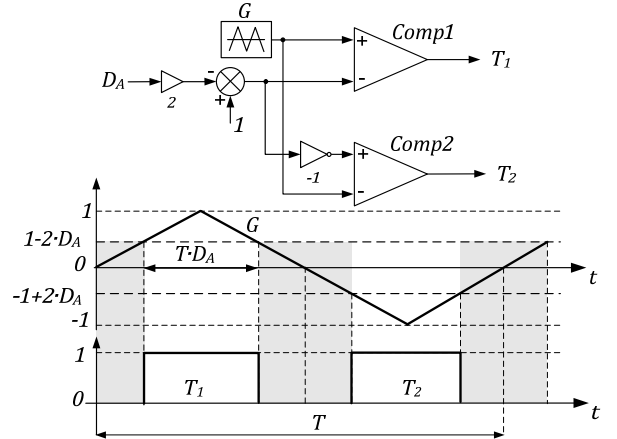


Fig. 5. Switching controller.

Converter is working in discontinuous conduction mode (DCM) in point 2 and close to the boundary between DCM and CCM modes in point 3. Operating point 5 corresponds to high wind speed when generator starts synchronous operation and CCM operation of the converter with highest input power.

From this it can be seen that the converter with closed-loop control system should be able to operate in complex behavior. The main challenges for control system:

- output power depends on load, but it is limited by weather conditions;
- control system should keep stable operation in wide range of frequencies of input voltage ripple from WT in variable speed – variable voltage operation mode;
- controller in combination with MPPT algorithm should provide sufficient stability and dynamic characteristics of transition processes in wide range of possible wind speed fluctuations [18].

III. NUMERICAL SIMULATION OF CONVERTER DYNAMICS

A. Open-Loop Operation

Converter model was built using PSIM software environment according to schematics in Fig. 2. Transformers have 1 mH magnetizing inductance and the values of qZS capacitors $C_1...C_4$ are equal to 15 uF. Full wave rectifier is used at the output in combination with passive LC-filter: 500 uH and 12.5 uF. The scheme of simple switching controller is shown in Fig. 5.

In this subsection WT and rectifier are substituted with DC-voltage source. Modeling of the start-up processes for operating points 2...5 was made to estimate converter

TABLE I
SELECTED OPERATING POINTS OF THE qZSPPC

Operating point	V_{IN} , V(DC)	Gain	D_A (simulated)	Power, W	Load, Ohm
1	65	6.15	0.168	19	8421
2	107	3.74	0.318	84	1905
3	159	2.50	0.330	302	530
4	216	1.85	0.307	717	223
5	259	1.54	0.295	1276	125.4

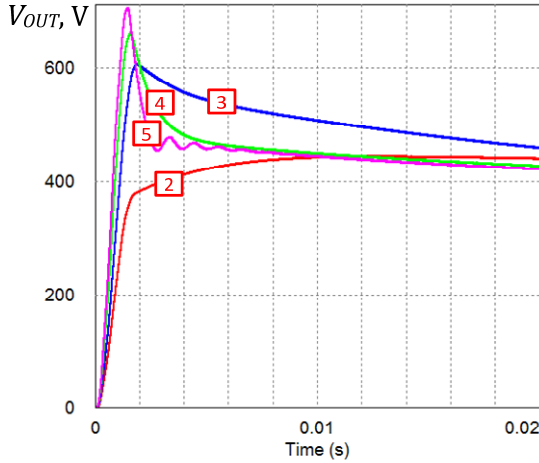


Fig. 6. Simulation results of start-up processes for operating points 2...5.

dynamics in five predefined operating points. Table I contains calculated values for modeling and measured simulated active duty cycle. From point 2 to point 5 input power of converter varies up to 15 times. As shown in Fig. 6 the overshoots appear in the output voltage during the starting of the WT. The higher is the input power the greater is the overshoot magnitude and shorter settling time. Operation with inrush voltage overshoot requires using overrated power semiconductors. This is additional challenge for control system to suppress overshoots and ensure satisfactory dynamics. Such behavior can be explained by the transition between DCM and CCM. QZSPPC can operate in one CCM mode and three DCM modes [19]. This means that the dynamics of the converter changes considerably in wide range of wind speeds.

B. Closed-Loop Control System with PI Controller

As far as there is no comprehensive small signal model of the investigated converter, closed-loop system based on PI-controller can be adjusted manually by using numerical simulators. But it is possible that ideal numerical model will not reveal all possible challenges. If closed-loop system with PI controller loses stability, converter can be damaged. Adaptive PI- or PID-controller can improve system stability but requires complicated analysis with disputable assumptions to determine control law.

Closed-loop system based on the PI-controller was implemented in PSIM to illustrate how stability margins can

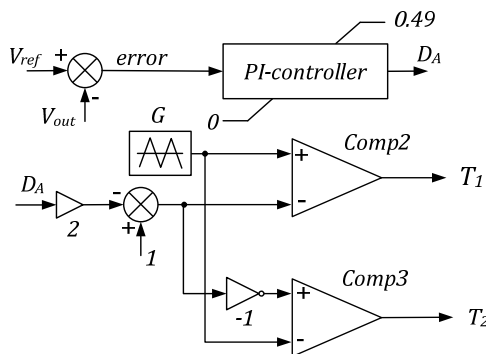


Fig. 7. Closed-loop control system with linear PI-controller.

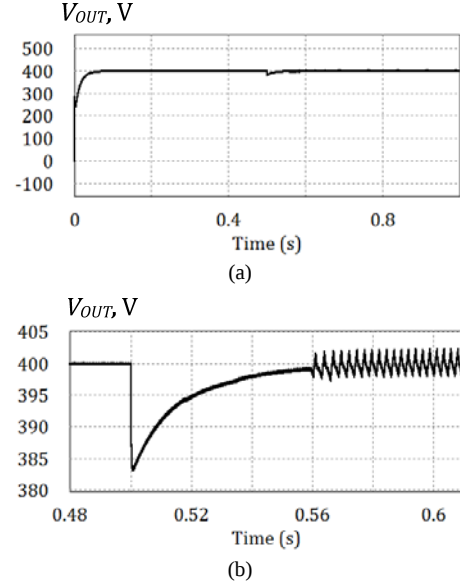


Fig. 8. Load step response of the closed-loop control system with linear PI-controller for operating point 4: (a) on a large scale and (b) detailed scale.

move dependently on the operation mode. PI-controller shown in Fig. 7 has transfer function: $PI(s) = k \cdot (1+sT)/(sT)$. Also, anti-windup principle was implemented with additional limiter. It keeps output of PI-regulator (active duty cycle) in realistic range from 0 to 0.49. Parameters of PI-controller were adjusted manually to the next values: $k = 0.001$, $T = 0.01$. In the model implemented the converter has constant input voltage. This assumption removes one of the complexities of real system – variable frequency ripple of the output voltage of WT. It was made to analyze closed-loop dynamic of the converter separated from influence of the real input source.

Simulations were made to show how closed-loop system behaves when the output power increases from 50% to 100% out of maximum output power of WT in corresponding operating point. In points 1...3 and 5 system showed satisfactory response. Problems with stability occur in point 4: $V_{IN} = 216$ V, $P_{OUT} = 302$ W. Fig. 8(a) shows start-up process with 50 % load and load step to the 100 % at $t = 0.5$ s. Detailed load step response is shown in Fig. 8(b). After the load step the overall system stability has changed noticeably. Considerable rise of the output voltage ripple after $t = 0.56$ s means that the dynamic behavior of a system has changed after the load step. Detailed estimation of stable operating region is impossible with numerical simulation.

C. Modeling of the WT

In previous simulations PMSG-based WT and input rectifier were substituted with the constant voltage source. Real WT generates variable frequency voltage and has internal parasitic inductances in phases. Case study WT has 8 poles, phase resistance 1.2 Ohm and internal phase inductance 5 mH. WT generates sinusoidal voltage with line-to-line RMS value 46 V...183 V and frequency 16.6 Hz...63.4 Hz. In further simulations WT and rectifier are substituted with three-phase sinusoidal voltage source $e_{g1}...e_{g3}$, three resistors $R_{g1}...R_{g3}$, three inductors $L_{g1}...L_{g3}$ and uncontrolled three-phase diode rectifier $D_1...D_6$ as shown in Fig. 9. Uncontrolled rectifier

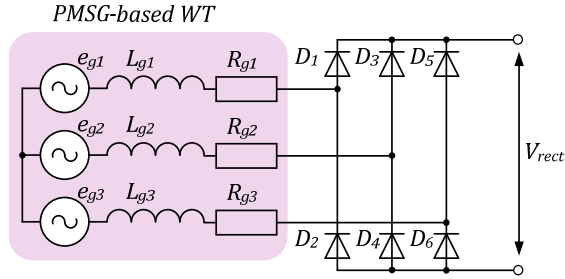


Fig. 9. Used equivalent circuit for WT with three-phase rectifier.

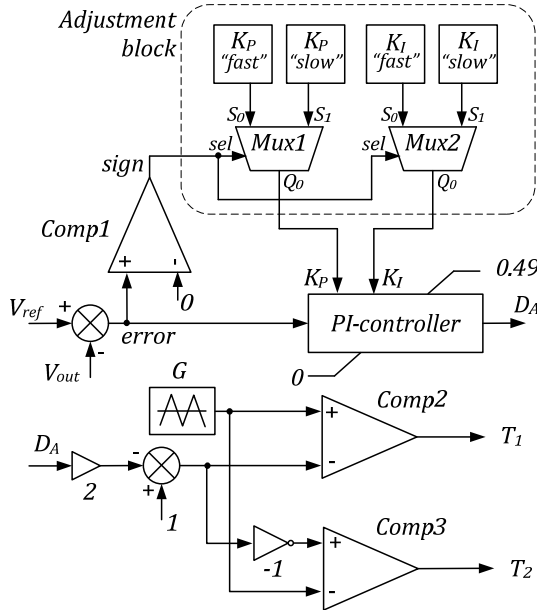


Fig. 10. Structure of the proposed controller.

possesses merits such as reduced component count and low price. Additionally, it does not allow torque and speed control at first stage of grid integration system and has poor energy utilization at low speeds [20], [21].

It was practically impossible to tune analytically linear PI-controller with used equivalent circuit for WT. Conventional open-loop tuning methods, such as Ziegler-Nichols and Cohen-Coon methods, cannot be used due to AC component in the input voltage. In this case the design of controller requires comprehensive stability analysis also for the large signal.

IV. PROPOSED CONTROL SYSTEM

Fig. 10 shows the proposed nonlinear controller. The main difference with linear PI-controller is adjusting block. It changes gains of the proportional and integral components of PI-controller according to the sign of error signal. Transfer function of used PI-controller: $PI(s) = (K_I + K_P \cdot s)/(s)$. Positive error corresponds to the relatively slow response of the controller. In case of negative error PI-controller gets higher integral (K_I) and proportional (K_P) gains. Comparator *Comp1* detects sign of the error signal. Adjustment block contains two multiplexers *Mux1* and *Mux2*. Error sign defines which of two inputs is connected to the output in each multiplexer. *Mux1* provides gain for the proportional component (K_P) of the PI-controller. *Mux2* in its turn provides gain for the integral component (K_I) of the PI-controller. Also driven PI-controller utilizes anti-windup technique to improve stability.

Change of the wind speed is relatively slow comparing to the converter switching frequency. In residential applications start-up and load step processes are the most challenging for

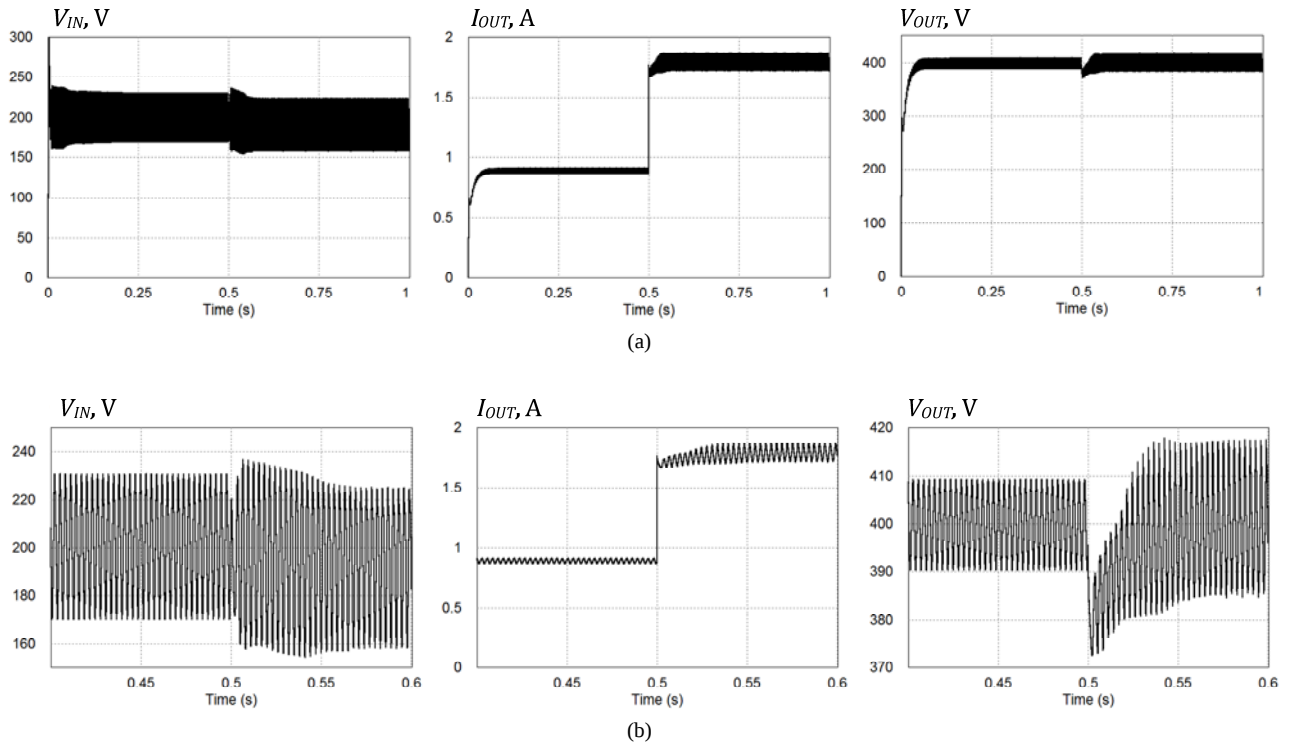


Fig. 11. Start-up and load step transient of the converter with PI-controller: (a) large and (b) detailed scale.

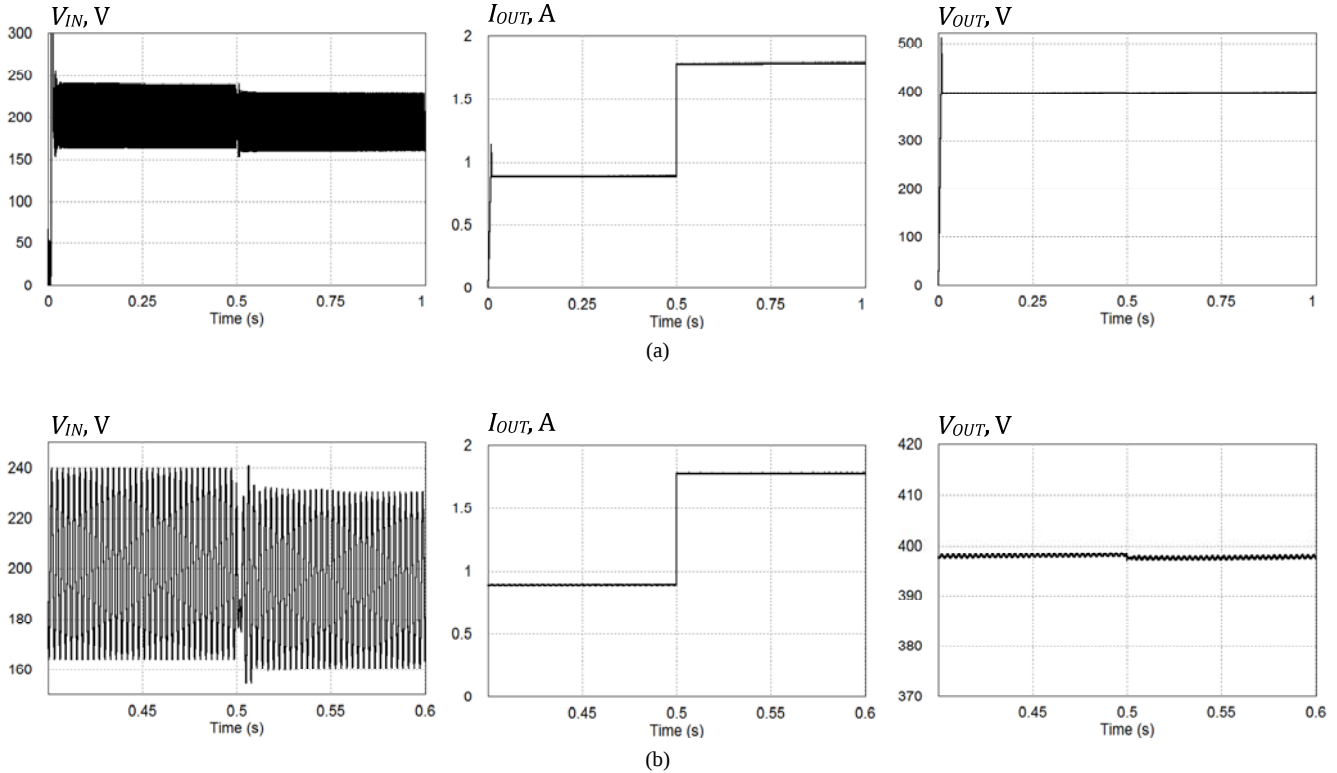


Fig. 12. Start-up and load step transient of the converter with proposed nonlinear controller: (a) large and (b) detailed scale.

the closed-loop system. Proposed and conventional PI-controllers were compared by means of PSIM software. Start-up and load step transients were analyzed. Parameters of PI-controllers are described in previous section. Adjustment block of the proposed controller contains two pair of constants: $K_p = 0.05$, $K_i = 0.1$ ("slow") and $K_p = 0.1$, $K_i = 1$ ("fast"). Output voltage is 400 V. Start-up process begins at $t = 0$ s with 50 % load. Load step to the 100 % load occurs at $t = 0.5$ s. Simulation was made for the fourth operating point of WT as in previous section. The circuit from Fig. 9 is used as input voltage source for qZSPPC. The parameters of WT are line-to-line RMS voltage 153 V, voltage frequency 56 Hz, phase resistance 1.2 Ohm, phase inductance 5 mH.

Fig. 11 shows simulation results for the converter with the conventional PI-controller. This controller has slow dynamics as shown in Fig. 11(a). After the load step from 50 % to 100 % the output voltage sag is 7 % (28 V) lower than the reference value (400 V), as shown in Fig. 11(b). Moreover, rise of the output voltage ripple is 80 %, from 19 V to 34 V. Theoretically PI-controller with faster response should improve system dynamics. Faster PI-controller has wider pass band, which leads to higher ripple of the output voltage. Hence, closed-loop control system requires PI-controller with slow dynamics, which results in undesirable long settling time. Therefore in this system PI-controller cannot satisfy both fast dynamic and output voltage ripple mitigation requirements.

The proposed controller shows fast response and output voltage ripple mitigation, as shown in Fig. 12. Parameters of this controller were manually adjusted using numerical simulation. At start-up output voltage settled faster comparing to system with conventional PI-controller, but has overvoltage,

as shown in Fig. 12(a). Overvoltage is almost twice smaller than that compared to the start-up of the open-loop system (Fig. 6). Fig. 12(b) shows that the controller successfully suppresses the output voltage ripple regardless high magnitude of the input voltage AC component. Also load step-up does not have any noticeable impact on the output voltage. Controller can be used in highly nonlinear systems to accelerate design process. The main disadvantage of the proposed nonlinear PI-controller is manual tuning.

V. CONCLUSIONS

This paper presents nonlinear closed-loop control system for qZS-derived push-pull converter. PMSG-based WTs generate output voltage in wide range of frequency and magnitude. Proposed converter showed superior performance for grid integration of these WTs. This nonlinear control system provides stable operation in CCM and DCM regardless variable frequency AC component of the input voltage. Proposed nonlinear controller can be used in systems where classical controller design requires complicated analysis.

Additional research is required to design fast tuning algorithm suitable for renewable energy integration systems. Manual tuning cannot provide optimal values of gains for proposed controller. Additional analysis of converter for small and large signal is required.

ACKNOWLEDGEMENTS

This research work was financed by Estonian Ministry of Education and Research (project SF0140016s11), Estonian Research Council (Grant G8538), European Social Fund and MOBILITAS Postdoctoral Research Grant (MJD391).

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