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Control of Active Front-End Rectifier of the Solid-State Transformer with Improved Dynamic Performance during Precharging

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Abstract—The control of the active front-end rectifier of the three-stage solid-state transformer (SST) system is addressed in this paper. A comprehensive precharging sequence is introduced for the active front-end rectifier of the SST to limit the inrush current during the start-up process to its nominal current. The proposed precharging algorithm consists of two phases, passive and active precharging. The precharging resistor limits the current during the passive precharging, while a ramp increase of the voltage reference is used in the controller during the active precharging to prevent large inrush currents. Additionally, a feedforward voltage compensator is added to the voltage reference of the controller to improve the dynamic response at the beginning of the active precharging. The proposed algorithm is detailed and simulation results on a 4-kW active front-end converter are presented to validate its performance. The simulation results under various operation conditions show the ability of the proposed algorithm to limit the converter current to its nominal value during the precharging as well as to control the dc-link voltage under different load changes.

Index Terms—Active front-end converter, grid-connected rectifier, precharging sequence, single-phase neutral-point-clamped converter, Solid-state transformer.

I. INTRODUCTION

Solid-state transformer (SST) was initially introduced by Mc-Murray in 1970 [1] and has attracted a lot of interest in the last five decades [2], [3]. In the recent years more attention was focused on the prototype topology [4]–[6] and the basic control algorithms [7]. However, the reality is still challenging in achieving a low-cost, high-efficiency and long-life SST topology, which can be comparable with the conventional line-frequency transformers [8]. Several SST topologies have been investigated in the literature. Single-stage SST topology with ac switches in the input and output is investigated in [9], [10], while the two-stage topology with an ac-dc converter followed by an inverter is proposed in [2], [11]. The three-stage SST topology consists of an ac-dc, dc-dc (including isolation) and dc-ac inverter [12], [13], as depicted in Fig. 1. In this topology, the ac-dc converter, referred as active front-end converter in this paper, is used to rectify the grid ac voltage to the dc voltage on the medium-voltage-side (MV-side) dc-link capacitor. Afterwards, a dc-dc converter with an isolation transformer (dual active bridge converter) transfers

Fig. 1. Block diagram of three-stage solid-state transformer.

the power from the MV-side dc-link capacitor to the low-voltage-side (LV-side) dc-link capacitor. Finally, the dc-ac inverter converts the dc power from the LV-side dc-link to a suitable ac power for the load or low-voltage grid. The SST converter has a bidirectional power flow structure and is also able to transfer the power from the LV-grid to the MV-grid. Based on several studies [8], [14], it is concluded that the three-stage SST topology shows the best performance and controllability, compared to the single- and two-stage topologies. Hence, the three-stage SST topology is considered in this paper.

Various power converter topologies and control algorithms are available in the literature for the active front-end converter of the SST. A three-phase three-level neutral-point-clamped (NPC) converter is considered in [15]–[17] as the front-end converter, in which the dc-link voltage and current are controlled through PI controllers in the dq-frame. At the beginning of the SST operation, the voltages of the MV-side dc-link capacitors are zero. As a result, the direct connection of the converter to the grid results in large inrush currents, which can trigger the protection system or damage the power converter components. However, a comprehensive precharging algorithm, which ensures that the transient currents are limited to the converter nominal current, is not addressed in the literature [2], [3], [9]–[17].

Motivated by the above, this paper introduces a comprehensive precharging sequence for the single-phase active front-end converter of the SST, which limits the inrush current at the beginning of its operation to its nominal value. The proposed precharging algorithms consists of passive and active precharging modes. A precharging resistor is used to limit

Fig. 2. Circuit configuration for the active front-end converter.

the converter current during the passive precharging, while a linear-ramp voltage reference is applied in the controller to limit the current during the active precharging. Additionally, a feedforward voltage compensator is added to the calculated voltage reference to prevent from large inrush currents at the beginning of the active precharging stage. A fictive-axis-emulator is implemented in the controller to calculate the β -axis current, based on the α -axis voltage, filter inductance and resistance. The performance of the proposed control algorithm is simulated on a 4-kW single-phase three-level NPC active front-end converter under various operating conditions and results are presented.

The rest of the paper is organized as follows. Section II provides an overview of the active front-end converter circuit configuration. The detailed implementation of the proposed algorithms for capacitor precharging as well as the normal operation of the converter are explained in Section III. Simulation results of a 4-kW grid-connected three-level neutral-point-clamped active front-end converter are provided in Section IV, while the conclusions of the work are summarized in Section V.

II. CIRCUIT CONFIGURATION

The circuit configuration of the active front-end converter is illustrated in Fig. 2. The converter is connected to the grid through a filter inductor (L), which reduces the injected current harmonics to the grid in order to comply with grid standards [18], [19]. The resistance of the filter and connection wires is modeled as R . The dc-link capacitor of the converter is connected to the load, which can be passive or active. Different types of converters can be used as the active front-end converter, including two-level or a multilevel single-phase converters. The proposed precharging sequence and control strategy are general algorithms and can be implemented for different types of grid-connected single-phase converters.

The circuit breaker CB1 is used for the connection/disconnection of the converter from the grid. During faults, the protection system disconnects the converter from the grid by switching off CB1. The precharging resistor ($R_{precharge}$) is used for the precharging of dc-link capacitors at the beginning of the operation of the converter. The circuit breaker CB2 bypasses the precharging resistor during the normal operation of the converter. The details of the proposed operation sequence for precharging the dc-link capacitors are explained in the following sections.

Fig. 3. Proposed capacitor precharging sequence for the active front-end converter of the solid-state transformer.

III. PROPOSED CONTROL STRATEGY

The operation of the active front-end converter consists of two operation modes: 1) Precharging the dc-link capacitors at the beginning of the operation and 2) normal operation of the converter with controlling the dc-link voltage. At the beginning of the SST operation, the proposed precharging sequence is implemented and afterwards the converter starts its normal operation.

A. Proposed Precharging Sequence

The proposed capacitor precharging sequence is depicted in Fig. 3. Before the start of the operation, the circuit breaker CB1 is off. At the beginning of the precharging sequence, CB1

Fig. 7. Simulation verification - circuit configuration of the grid-connected single-phase three-level neutral-point-clamped active front-end converter.

TABLE I
SIMULATION PARAMETERS OF THE ACTIVE FRONT-END CONVERTER

Parameter	Symbol	Value
Nominal power	P_{nom}	4 kW
Grid voltage	v	760 V _{rms}
Filter inductor	L	8 mH
Filter resistance	R	0.6 Ω
Precharging resistance	$R_{precharge}$	70 Ω
dc-link voltage	V_{dc}	1450V
dc-link capacitor	C_U / C_L	1.5mF
Switching frequency	f_{sw}	5 kHz
Voltage level to change to active precharging	V_2	900 V

The PI controller is easy for implementation compared to the proportional resonant (PR) controller and it is also more robust to grid voltage harmonics [22], [23]. Hence, the current controller is executed using the PI controller in the dq-frame. I_d^* and I_q^* are calculated from the dc-link voltage controller and grid requirement for reactive power injection, as mentioned above. The α - and β -axis currents are necessary for the calculation of instantaneous d- and q-axis currents (i_d and i_q). The α -axis current (i_α) is equal to the measured current of the converter (i). A fictive axis emulator (FAE) is applied in this study for the calculation of the β -axis current (i_β). The diagram of the FAE is illustrated in Fig. 6 and comprehensive explanation can be found in [24].

The errors between the instantaneous dq-axis currents and their calculated reference values are fed into two PI controllers, which calculate the dq-axis voltage references (v_d^* and v_q^*). These values are transferred to $\alpha\beta$ -frame using the inverse Clark transformation and the calculated voltage angle (θ) from the PLL. In order to achieve a fast response during grid voltage variations and low transient current at the beginning of the operation of the controller, a feedforward voltage compensator is applied to the calculated $\alpha\beta$ -frame voltage references, as shown in Fig. 5. The feedforward compensator for α - and β -axes are v_α and v_β , respectively, which are calculated from the PLL. Finally, the voltage reference (v_a^*) is fed into the pulse-width-modulation (PWM) technique to calculate the switching signals.

Fig. 8. Simulation results: *Case I* - performance of the proposed algorithm during the precharging of the dc-link capacitors: (a) Grid voltage, (b) grid current, (c) dc-link capacitors voltages and (d) active and reactive power of the converter.

IV. SIMULATION RESULTS

A 4-kW active front-end single-phase rectifier is modeled and developed using PLECS toolbox. A three-level neutral-point-clamped (NPC) converter is considered as the converter in this study. The circuit configuration of this system is illustrated in Fig. 7, while the main system parameters are listed in Table I. The NPC converter applies two series connected capacitors (C_U and C_L) in the dc-link. Therefore, a voltage balancing algorithm is required to ensure that the voltage of these capacitors are close to each other during all of the operation conditions. For this purpose, a voltage balancing algorithm with the modification of the voltage reference, based on the implemented algorithm in [25], is applied in this study. Three case studies are considered for the evaluation of the performance of the proposed algorithms: *Case I*: Precharging operation, *Case II*: ramp reduction of the load power and *Case III*: step increase of the load power.

Case I: The performance of the proposed precharging sequence is evaluated in this case study and results are

Fig. 9. Simulation results: *Case II* - performance of the proposed algorithm under the ramp decrease of the load power: (a) Grid voltage, (b) grid current, (c) dc-link capacitors voltages and (d) active and reactive power of the converter.

illustrated in Fig. 8. At the beginning, the voltages of the dc-link capacitors are zero, as presented in Fig. 8(c). The passive precharging increases the dc-link voltage to 900 V within a period of 0.18 s. During this period, the current flows through $R_{precharge}$ and its maximum value at the first cycle is smaller than 15 A, which is within the nominal current range of the rectifier. The current waveform, shown in Fig. 8(b), is similar to the current waveform of a passive diode converter. It also can be observed that by increasing of V_{dc} , the maximum value of the injected current is reduced.

At $t = 0.18$ s, the dc-link voltage reaches the voltage value V_1 , which is set in the controller and hence the operation mode of the converter changes to the active precharging by enabling the switching signals of the NPC converter. There is no high transient current at the starting of the active precharging, due to the feedforward compensation added to the controller, as presented in Fig. 5. Additionally, V_{dc}^* linearly increase from 900 V to 1450 V in a period of 0.4 s. As a result the converter

Fig. 10. Simulation results: *Case III* - performance of the proposed algorithm under the step increase of the load power: (a) Grid voltage, (b) grid current, (c) dc-link capacitors voltages and (d) active and reactive power of the converter.

current increases linearly in order to regulate the dc-link voltage to V_{dc}^* .

After reaching V_{dc} to its nominal reference value (1450 V) at $t = 0.55$ s, the converter current and power reduces close to zero, as depicted in Fig. 8(d). Afterwards, at $t = 0.6$ s the precharging resistor is bypassed and the switching of the converter is also disabled. According the current becomes zero during this period. Finally, after receiving the connection feedback from circuit breaker at $t = 0.62$ s, the converter starts its normal operation and load can be connected to the output of the converter.

Case II: The performance of the proposed control algorithm under a ramp reduction of the load is investigated in this case study and results are presented in Fig. 9. Before $t = 0.1$ s, the load power is equal to 3.5 kW and accordingly, the peak current of the rectifier is 8 A and the converter regulates V_{dc} to 1450 V. During the ramp reduction of the load power, the converter current is decreased linearly, while the implemented controller is able to regulate the dc-link voltage

at its reference value. During the reduction of the power, the phase shift between the voltage and current remains at zero; hence, the converter reactive power is zero, as shown in Fig. 9. It should be noted that due to the implementation of the voltage balancing algorithm, the dc-link capacitors are equal to each other during all of the operation conditions.

Case III: In this case study, the performance of the implemented controller under a step increase of the load from 0.5 kW to 3.1 kW is evaluated and results are depicted in Fig. 10. As a result of this load power step-change, the rectifier current increases from 1 A to approximately 5 A in less than 0.05 s. Additionally, the dc-link voltage is regulated to its reference value, after a small decrease. The simulation results show the applicability of the implemented control algorithm in adjusting the dc-link voltage under various load change conditions. Additionally, the evaluation results during the precharging of capacitors show the capability of the proposed precharging sequence in limiting the active front-end rectifier current to its nominal value at the beginning of the operation of the SST.

V. CONCLUSION

A precharging sequence consists of a passive and an active precharging algorithms for the active front-end rectifier of the SST system has been proposed in this paper. A linear ramp voltage reference increment has been implemented during the active precharging to prevent from high transient currents in the rectifier. Additionally, a feedforward voltage compensator has been applied to improve the dynamic performance at the beginning of the operation and under grid voltage sags. The implementation of the proposed precharging sequence as well as the controller during the normal operation have been explained in detail. The evaluation results on a 4-kW simulation platform have also been provided in the paper. The improved performance of the proposed algorithms in limiting the inrush current to its nominal value and regulating of the dc-link voltage to its reference value under various load changes makes it suitable for three-stage solid-state transformers.

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