

A Modular Isolated DC-DC Converter for Current Source Converter-Based Wind Energy Conversion System

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Abstract—Medium-frequency transformer-based isolated DC-DC converters were proposed for series-connected wind energy conversion systems, offering reduced size and weight compared to conventional solutions. While this converter suffers two main challenges. One is that the megawatt-level, low-voltage generator suffers high power loss due to high current. The other is that the manufacturing technology for high-power MFTs with high-voltage insulation is not mature. To address these challenges, a generator-side power converter with a parallel input and parallel output connected isolated DC-DC converter is proposed in this paper. And the corresponding control scheme is designed to ensure current sharing of DC-DC converters. Simulations are conducted to verify the effectiveness of the proposed converter and the control scheme.

Keywords— Current source converter, wind energy conversion system, parallel input, parallel output.

I. INTRODUCTION

The series-connected current source converter (CSC)-based wind energy conversion system (WECS) eliminates the central substation, thereby reducing system cost, footprint, power loss, and complexity [1]–[6]. Several generator-side converters have been proposed for this configuration [4]–[6], including isolated DC-DC converter-based topologies. As shown by the green block in Fig. 1, the medium-frequency transformer (MFT)-based isolated DC-DC converter used as the generator-side DC-DC power stage consists of a full bridge (FB), an MFT, and a diode bridge. The use of the MFT addresses the generator insulation issue while reducing size and footprint compared with conventional solutions. However, in low-voltage (LV), MW-level generator systems, this converter suffers from high power dissipation due to the large current. In addition, the MFT must withstand high-voltage DC (HVDC) insulation stress, while the manufacturing technology for such high-power MFTs is still immature. To overcome these limitations, this paper proposes a generator-side converter based on parallel input and parallel output (PIPO)-connected isolated DC-DC converters, together with a control scheme that achieves current balancing and ensures stable system operation.

II. PIPO CONNECTION FOR LV GENERATOR SYSTEM

In a CSC-based series-connected WECS, n turbine-generator-converter units are connected in series to achieve the HVDC level. On the grid side, pulse-width-modulated (PWM) CSCs are connected in series at their inputs to withstand the HVDC voltage. Because all turbine-generator-converter units are identical, only one unit is analyzed in

this paper. The proposed PIPO-connected isolated DC-DC converter-based series-connected WECS for a single-turbine system is shown in Fig. 1. Each turbine-generator-converter unit consists of an LV generator, a diode rectifier, and a PIPO-connected MFT-based isolated DC-DC converter. The use of diode rectifiers offers high efficiency, reliability, and scalability. By employing the PIPO configuration, the current stress on each DC-DC converter is reduced to $1/m$ of the original current rating, thereby significantly reducing power loss. The MFT provides isolation between the generator and the HVDC bus, enabling the use of generators with regular insulation levels in this wind system. In addition, since the manufacturing technology for MFTs with HVDC-level insulation is not yet mature, splitting the power among the MFTs also helps ease manufacturing.

III. PROPOSED CONTROL SCHEME

The control scheme of the series-connected wind system includes generator-side, grid-side control and DC current sharing control, as shown in Fig. 1.

The proposed generator-side converter is controlled to achieve maximum power point tracking (MPPT) and generator speed regulation. MPPT is implemented based on the optimal tip speed ratio. To achieve generator-side control, there is a minimum generator-side DC-link current requirement I_{dc_gen} .

On the grid side, DC-link current and reactive power (or power factor) are controlled. Voltage-oriented control (VOC) with modulation-index and delay-angle control is applied to the grid-side PWM CSC. To achieve grid-side control objectives and minimize power loss, a minimum grid-side DC-link current I_{dc_grid} is required. For the control scheme for each module, please refer to [6] for details. To ensure all the control objectives to be achieved simultaneously on both sides and minimize the power loss of the system, the maximum DC-link current of above currents is selected as reference.

$$I_{dc} = \max \{I_{dc_gen}, I_{dc_grid}\} \quad (1)$$

This PIPO introduces current unbalancing issue due to parameter mismatch, which requires balancing control. As shown in Fig. 1, 6 modules are used as an example for analysis. The reference average current is obtained by averaging average currents of 6 modules. Then by comparing the current of each module with the reference average current, the current error is obtained for each module. PI controllers output additional duty cycles, Δd_1 for module #1, and Δd_m for module #m. Then the duty cycle for the DC-DC converter of #m is achieved by the sum of the

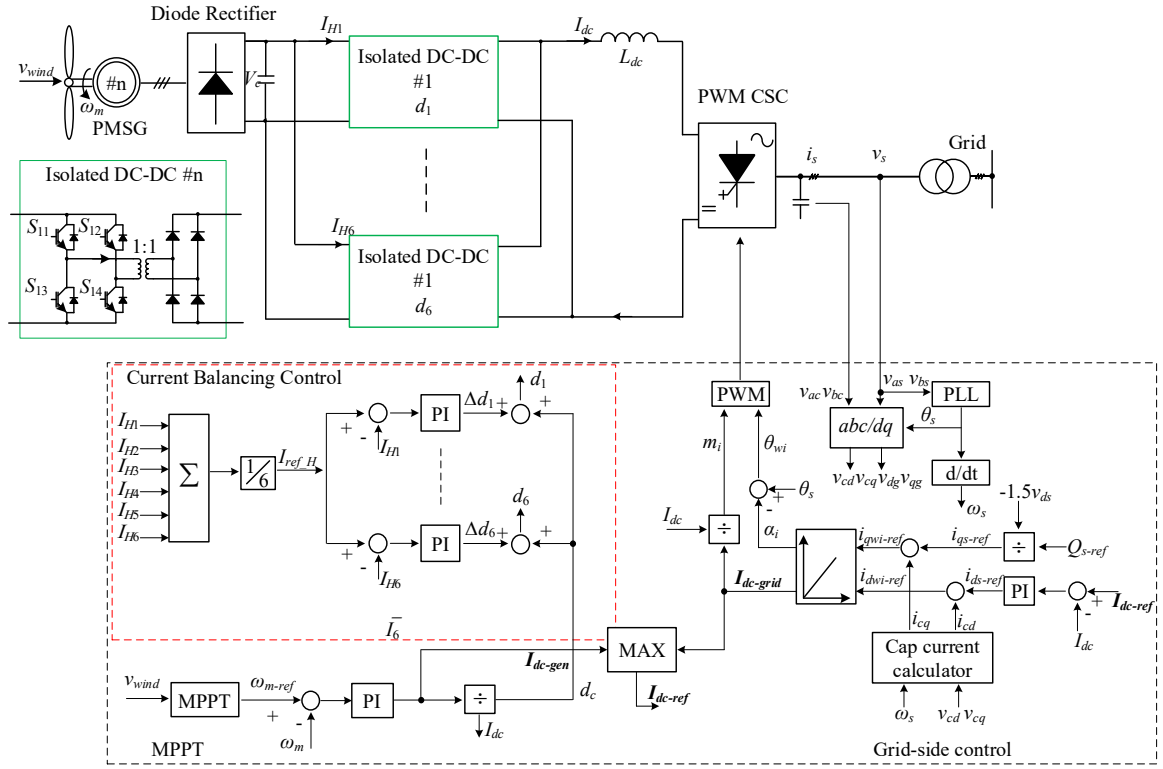


Fig. 1. PIPO-connected isolated DC-DC-based power converter for series-connected WECS, and the proposed control scheme.

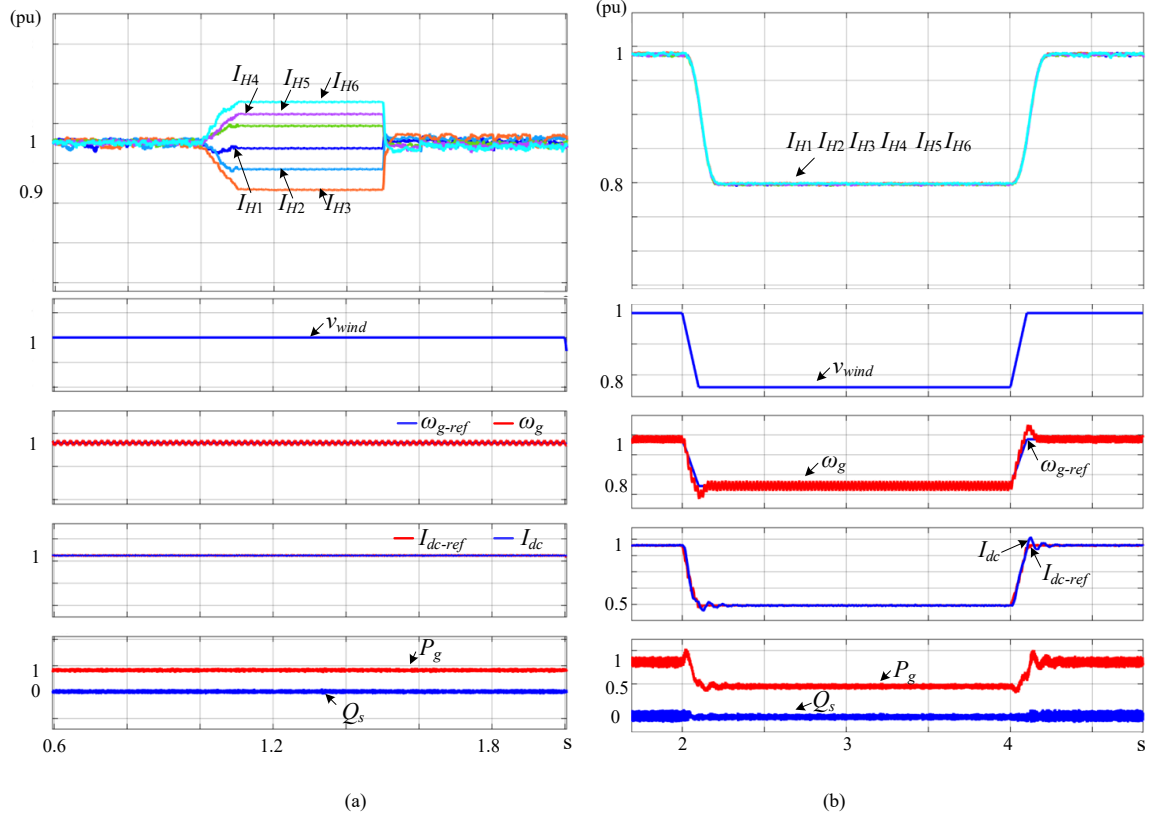


Fig. 2. Simulation results for the proposed converter under steady and dynamic states.

common duty cycle (d_c) and the corresponding additional duty cycle d_m . As a result, both MPPT and current balancing are achieved.

IV. SIMULATION RESULTS

The proposed control scheme is verified using MATLAB/Simulink and the main parameters used are listed in Table I. The simulation results are shown in Fig. 2. Note that: as this is a single-turbine system, in order to match the voltage level of the generator, the low grid voltage is selected. In a WECS, the grid voltage can be LV/MV (several thousands of volts, such as 4160 V).

TABLE I. SIMULATION PARAMETERS

Nominal power	$P_g = 1$ MW
Generator voltage	$V_g = 690$ V
Grid voltage	$V_s = 690$ V
Generator rated speed	22.5 rpm
Number of modules	$m = 6$
Transformer turn ratios	1:1 (#1); 1:1.03 (#2); 1:1.06 (#3); 1:0.96 (#4); 1:0.95 (#5); and 1:0.94 (#6)

Fig. 2 (a) shows the simulated results with and without the proposed current balancing control under rated conditions. Under rated wind speed, the average input currents of the six modules of the isolated DC-DC converter ($I_{H1} - I_{H6}$) are imbalanced without the proposed current balancing control scheme. When the proposed balancing control scheme is applied, these currents are well balanced and controlled. And Fig. 2 (a) also provides simulation waveforms including generator-side speed regulation, DC-link current (I_{dc}), and captured real and reactive power (P_g and Q_s) and the results show the successful operation of the converter under rated conditions.

The simulated waveforms with the proposed current balancing under dynamic state are shown in Fig. 2 (b). When wind speed changes from 1 pu to 0.8 pu the six modules of the MFT-based modular converter with the proposed current balancing control have balanced at average currents. The dc-link current (I_{dc}) is reduced from 1 pu to around 0.5 pu correspondingly, such that control objectives and reduced power reduction can be guaranteed. The DC-link current changes from 1 pu to 0.5 pu according to the control scheme. The real power (P_g) is reduced from 1 pu to 0.5 pu as the power is proportional to the cube of the wind speed, while the reactive power (Q_s) is controlled at zero to ensure unity power factor. After $t = 4$ s, the wind speed increases to the nominal wind speed, as a result, the generator speed, DC-link current and real power return to their nominal values.

V. CONCLUSION AND FUTURE WORK

This paper proposes a modular isolated DC-DC converter for a current source converter-based wind energy conversion system. Compared with conventional solutions, the proposed converter offers reduced size and weight. With the PIPO-connected structure, it reduces system power loss and eases manufacturing. A control scheme is developed to achieve MPPT, generator speed control, DC-link current control, and reactive power control. In addition, a balancing control scheme is proposed to ensure current sharing among the converter

modules. Simulation results verify the effectiveness of the proposed converter and control scheme. Future work will focus on experimental validation.

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