DC-Link Current Optimal Control of Current Source Converter in -DFIG

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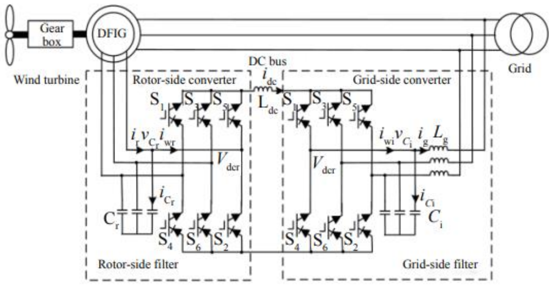
Abstract :

A novel control strategy of current source converter (CSC) is proposed for doubly-fed induction generator (DFIG) wind energy conversion system (WECS). Most of the studies on wind forms are based on voltage source converter, nevertheless, with the development of semiconductor technology and high switching frequency reverse block insulated gate bipolar transistor (RB-IGBT) devices being used in CSCs, the shortcomings of conventional CSCs including low switching frequency, large passive devices and slow dynamic performance can be overcome. Furthermore, WECS based on CSCs has various advantages, such like robustness, inherent short-circuit protection, fault ride through capability and so on. To implement the CSCs in DFIG wind energy conversion system, this paper analyzes the system configuration, operation principles, modulation strategy and control strategy. In addition, a novel control strategy based on DC-Link current optimal control is proposed. The simulation and prototype experiments verify the validity of system configuration and control strategy.

Introduction :

In recent years, wind power has become one of the most important solutions for global energy crisis, which has been widely developed and adopted in the world. Until the end of 2019, the cumulative installed capacity of global wind power generators has reached 650 MW. As one kind of the typical generators, doubly-fed induction generator (DFIG) accounts for the highest among all kinds of wind power generators that have been put into operation. Voltage source converter (VSC) is the major option for doubly-fed induction generator, but it has a lot of disadvantages including high failure rate [1], parameters influence on control effect, bad performance in parallel operation and overcurrent fault caused by upper and lower bridges which shoot through due to disturbance.

However, it is the inductor in DC side of current source converters (CSCs), the implementation of open-loop current control enables the bridges to avoid withstanding short circuit and it shows a strong robustness in the system configuration and flexible strategy for paralleled converters. With the development of semiconductor technology, Fuji electric of Japan launches a new type of reverse block insulated gate bipolar transistors (RB-IGBT), whose switching frequency has been greatly improved to several kilohertz.



Configuration diagram of CSC-based DFIG WECS.

which it injects the maximum power in both steady state and transient state by following sinusoidal reference voltage and this paper analyzes the converter losses through using the error performance index of the simulation results. But in this paper, an optimal operation strategy aiming at the minimum loss target is not introduced. For CSCs, DC-Link current is changed while operating power fluctuates, the smaller DC-Link current, the less total loss. Therefore, for the wind power converter system that does not need high dynamic response, DC-Link current can be reduced property to make the loss down and to improve the system operating efficiency.

To sum up, this paper proposes to apply the PWM current source converters on the DFIG wind energy conversion system. In addition, this paper analyzes the WECS's configuration, operation principles, modulation strategy and control strategy. Furthermore, a novel control strategy based on DC-Link current optimal control for CSCs is proposed. The validity of all the above contents is verified by simulation and prototype experiment.

Related Work :

"Reliability of capacitors for DC-link applications in power electronic converters"

H. Wang and F. Blaabjerg (2014)

DC-link capacitors are an important part in the majority of power electronic converters which contribute to cost, size and failure rate on a considerable scale. From capacitor users' viewpoint, this paper presents a review on the improvement of reliability of dc link in power electronic converters from two aspects: 1) reliability-oriented dc-link design solutions; 2) conditioning monitoring of dc-link capacitors during operation. Failure mechanisms, failure modes and lifetime models of capacitors suitable for the applications are also discussed as a basis to understand the physics-of-failure. This review serves to provide a clear picture of the state-of-the-art research in this area and to identify the corresponding challenges and future research directions for capacitors and their dc-link applications.

"Hybrid isolation process with deep diffusion and V-groove for reverse blocking IGBTs"

H. Nakazawa, M. Ogino (2011)

We newly developed a 1200V Reverse Blocking (RB)-IGBT used to form bi-directional switches in advanced Neutral-Point-Clamped (A-NPC) 3-Level modules. It featured a hybrid through-silicon isolation structure combining wafer front-side boron deep diffusion with back-side V-groove etching. Collector layer was implanted into the back-side and the surface of the V-grooves, and electrically connected to the front-side boron diffusion after activation to achieve reverse-blocking capability. Thermal budget for the surface deep boron diffusion was thereby shortened more than a half of that in full diffusion case to improve both throughput and yield. Sufficient reverse blocking capability was experimentally verified.

"Reverse-blocking IGBTs with V-groove isolation layer for three-level power converters,"

H. Nakazawa, D. H. Lu, M. Ogino (2013)

Multilevel power converters are among the most effective approaches to reduce power loss and to improve efficiency in power conversion systems. Reverse-blocking IGBTs (RB-IGBTs) have been improved and extended to higher breakdown voltage to be used as bidirectional switches in multilevel converter applications. In this work, a hybrid isolation process by combining thermal diffusion and V-Groove etching is developed to form 1200-1700-V RB-IGBTs. The details on 1700-V RB-IGBTs are presented in this paper. Compared with that of full diffusion, the thermal budget of the frontside surface deep boron diffusion has been reduced to less than one-third. Sufficient reverse-blocking capability and switching robustness have been successfully demonstrated. At the same switching loss level, on-state voltage of a 50 A-rated planar gate RB-IGBT is reduced to approximately 1.9 V compared with that of serially connected trenchgate field-stop IGBT (FS-IGBT) and free-wheeling diode (FWD). Experimental benchmarking on 1200-A module demonstrated that the energy loss in three-level inverter was reduced to 18% by using RB-IGBTs instead of IGBT and FWD pairs at typical switching frequencies for high-power, medium-voltage applications.

"High-efficiency RB-IGBT based low-voltage PWM current-source converter for PMSG wind energy conversion systems"

J. Zhang, P. Li, J. Wang, and X. Cai, (2016)

A low-voltage (LV) pulse-width modulated current-source converter (CSC) using reverse-blocking insulated gate bipolar transistor (RB-IGBT) devices is proposed in this paper for megawatt wind energy conversion systems (WECSs) with a permanent magnet synchronous generator. Benefiting from using the latest generation of reverse-blocking power semiconductors, the presented configuration is able to push the switching frequency to a higher range and overcome the traditional drawback of low efficiency in LV CSCs. Design of the configuration, switching scheme, and system control are briefly introduced. Semiconductor and converter loss models are developed for detailed efficiency study of the proposed system. The overall high-efficiency performance of the LV CSC based WECS is verified by simulation results and comparison with the state-of-the-art solution using voltage-source converters.

High-Power Converters and AC Drives

B. Wu and M. Narimani (2016)

This new edition reflects the recent technological advancements in the MV drive industry, such as advanced multilevel converters and drive configurations. It includes three new chapters, Control of Synchronous Motor Drives, Transformerless MV Drives, and Matrix Converter Fed Drives. In addition, there are extensively revised chapters on Multilevel Voltage Source Inverters and Voltage Source Inverter-Fed Drives. This book includes a systematic analysis on a variety of high-power multilevel converters, illustrates important concepts with simulations and experiments, introduces various megawatt drives produced by world leading drive manufacturers, and addresses practical problems and their mitigations methods. This new edition:

- Provides an in-depth discussion and analysis of various control schemes for the MV synchronous motor drives
- Examines new technologies developed to eliminate the isolation transformer in the MV drives
- Discusses the operating principle and modulation schemes of matrix converter (MC) topology and multi-module cascaded matrix converters (CMCs) for MV drives, and their application in commercial MV drives

"Modulation schemes for medium-voltage PWM current source converter-based drives: An overview,"

Q. Wei, L. Xing, D. Xu, B. Wu, (2019)

Pulsewidth modulation current source converter (CSC)-based drive is one of the widely used drives in high-power (megawatt level) medium-voltage (MV) (2.3-6.6 kV) applications. The switching frequency of the MV CSC is limited to around 500 Hz to satisfy thermal requirement and reduce switching loss. Under such a condition, the overall performance of the used modulation scheme, especially its harmonics performance, is an important consideration for CSC-based drives. To date, a couple of modulation schemes have been proposed for MV CSCs, and this paper aims to present an overview of these modulation schemes. Traditional modulation schemes are reviewed, the recent advances are illustrated and analyzed, and the challenges and trends are discussed.

"Space vector modulation for DC-Link current ripple reduction in back-to-back current-source converters for microgrid applications,"

X. Guo, D. Xu, J. M. Guerrero, and B. Wu(2015)

Back-to-back converters have been typically used to interconnect microgrids. For a back-to-back current-source converter, the dc-link current ripple is one of the important parameters. A large ripple will cause electromagnetic interference, undesirable high-frequency losses, and system instability. Conventionally, with a given switching frequency and rated voltage, the current ripple can be reduced by increasing the dc-link inductor, but it leads to bulky size, high cost, and slow dynamic response. To solve this problem, this paper reveals that the current ripple can be significantly reduced by adjusting the gate patterns of space vector modulation between the rectifier and the inverter in a back-to-back converter. The experimental results verify the effectiveness of the proposed method.

"Space vector modulation for five-level current source converter with optimal vector sequence and DC current balancing control"

H. Gao, D. D. Xu, B. Wu, and N. R. Zargari(2017)

Multilevel current source converter (MCSC) is an effective way to increase the power rating of conventional current source-fed motor drive, especially its current rating. However, there are still several challenges existing in this kind of configuration, which mainly focus on its space vector modulation (SVM) technique and the inherent DC current imbalance issue. In this paper, an SVM scheme with optimal vector sequence and DC current balancing capability is proposed for five-level current source converter (5L-CSC). A kind of five-segment sequence is finally determined as the optimal one over high modulation index operating range. Moreover, a DC current balancing method, which is involved into the SVM scheme, is also designed in this paper, in which the switching states, which generate the small vectors, are selected based on the magnitudes of the DC current differences at positive and negative DC trails. The proposed SVM scheme is verified on a (2MW/4160V/278A) back-to-back 5L-CSC system through simulation**.**

"A simple and effective solution for superior performance in two-level four leg voltage source inverters: Predictive voltage control,"

V. Yaramasu, J. Rodriguez (2010)

In this paper predictive voltage control strategy is proposed to control the output voltage of a three phase four-leg inverter. The four-leg inverter is developed to deliver power to three-phase loads under light, heavy, balanced and unbalanced load and source conditions and it can produce three output voltages independently with one additional leg. To predict the voltage behavior for each valid switching state, discrete model of the converter and load is developed. The control method chooses a state with minimum error between the output voltages and their references. The performance of the proposed predictive voltage control scheme is compared with carrier-based PWM method which is an equivalent to the symmetrically aligned-class I 3-D SVPWM. The feasibility of the proposed method is verified by MATLAB/Simulink. These results show that the proposed method has good performance and the capacity to compensate disturbances compared to classical methods.

"Model predictive control for five-level current source converter with DC current balancing capability,"

H. Gao, D. Xu, B. Wu, and N. R. Zargari (2017)

Multilevel current source converter (MCSC) is an effective way to increase the power rating of conventional current source-fed motor drive, especially its current rating. However, there are still several challenges existing in this configuration, which mainly focus on its modulation and control techniques, and the inherent DC current imbalance issue. In this paper, a model predictive control (MPC) scheme with DC current balancing capability is proposed for a five-level current source converter (5L-CSC). The optimal space vectors for 5L-current source rectifier (5L-CSR) and current source inverter (CSI) are selected for their respective control objects. Moreover, the DC-side model of a 5L-CSC is analyzed, which is used for DC current prediction based on the applied switching states at both 5L-CSR and CSI sides. Finally, optimal switching states are selected and applied to realize

DC current balancing. The proposed MPC scheme is verified on a (2MW/4160V/278A) back-to-back 5L-CSC system through simulation.

“Design of line/motor side capacitors for PWM CSR-CSI drives to achieve optimal power factor in high power fan/pump applications,”

Y. Xiao, B. Wu, N. R. Zargari (1997)

The input power factor of GTO PWM current source rectifiers using a delay angle control scheme is investigated. It is discovered that with an optimal design of line and motor side capacitors for CSR-CSI induction motor drives having fan/pump loads, the input power factor is close to unity (over 0.95 for 30% to 100% of rated load). The concept of near unity power factor operation is presented. The procedures for the capacitor design are discussed. A switching pattern suitable for the delay angle control with a low harmonic distortion is also introduced. The line current of the rectifier is near sinusoidal due to the use of the switching pattern and line side capacitor. Experimental results on a 5 HP drive are given to verify the theoretical analysis.

“An input power factor control strategy for high-power current-source induction motor drive with active front-end”

Y. W. Li, M. Pande, N. R. Zargari (2010)

This paper proposes an input power factor control strategy for a current-source drive with active front-end. The proposed strategy is realized without modification of the drive's pulsewidth modulation and speed control schemes through the collaborative use of two methods: a modulation index regulation method and a flux adjustment method. Specifically, the modulation index regulation method functions to directly control the dc-link current and voltage, and it can effectively correct a leading input power factor as long as the space vector modulation is used for the inverter. On the other hand, the flux adjustment method can improve the power factor when the power factor is lagging or when the selective harmonic elimination modulation is used for the inverter at high motor speeds. When implemented together, the two methods will complement each other's functionalities and improve the overall compensation performance. Experimental results are obtained from a 600-hp and an 1100-hp drive system.

“A novel optimal space vector modulation technique of current source inverter for solar power integration,”

K. Gnanasambandam, A. K. Rathore, A. Edpuganti (2018)

The goal of the paper is to develop a novel modulation technique that combines merits of space vector modulation (SVM) scheme and synchronous optimal pulse-width modulation (SOPWM) technique for current source inverter (CSI). SVM provides better dynamic performance but unable to produce less total harmonic distortion (THD) on inverter current at low device switching frequency (<; kHz). SOPWM provides less THD even at low device switching frequency however it needs a conversion technique to operate CSI and it needs an additional control technique to improve dynamic performance. Hence to overcome these limitations, this paper develops a single modulation technique called optimal SVM technique that can achieve less THD as well as better dynamic performance. The proposed method do not require an additional conversion technique to operate CSI and it provides less THD even while operating under low device switching frequency of 450 Hz. Experimental results prove that the proposed modulation technique can provide better steady state performance as well as dynamic performance.

“A passivity-based control strategy for threephase current source inverter based on interconnection and damping assignment,”

P. Li, J. Wang, and J. Bai (2018)

To reduce the limiting feature of switching frequency in the high power current source inverter (CSI) and minimize effects on CSI output performance, this paper proposes a interconnection and damping assignment passivity-based control (IDA-PBC) strategy for three-phase CSI. The lumped-parameter model of three-phase CSI with independent storage unit is established, moreover, its port-controlled Hamilton (PCH) model in Park reference frame is proposed. Based on solving the parametric partial differential equation of the interconnection and damping matrix, the design of the closed-loop system controller is studied in this paper, and the system stability is analyzed by Lyapunov function. Furthermore, simulation reports for three-phase CSI demonstrate the feasibility and efficiency of the introduced design, and show that the inverter has strong anti-interference ability to the load disturbance.

"Topology and control of a split-capacitor four-wire current source inverter with leakage current suppression capability,"

Y. Sun, Y. Liu, M. Su, H. Han (2018)

This paper proposes a split-capacitor four-wire current source inverter, which is the dual of the split-capacitor four-wire voltage source inverter. Since the midpoint of the dc link is tied to the neutral point of ac filter capacitors, the common-mode voltage (CMV) is reduced significantly. Consequently, the leakage current issue is effectively addressed. The proposed circuit is cost-effective as no extra switch is added. This paper, first, establishes the equivalent common-mode circuit of the proposed inverter. The impact of the neutral line inductance on CMV is also analyzed. Then, a specific modulation is introduced to balance the dc-link voltages/currents. To achieve good input/output performance, a nonlinear control method is developed based on time-domain models. Finally, all the proposed methods and related theoretical analysis are verified by simulations and experimental results.

"Analysis and comparison of current-source converter-based medium-voltage PMSG wind energy conversion systems,"

Q. Wei and B. Wu (2016)

CSC topology with natural advantages in terms of simple structure, grid friendly waveforms, controllable power factor, and reliable grid short-circuit protection is considered to be a promising converter configuration for use in medium voltage (kV) high-power (MW) PMSG based wind energy systems. In view of this, three types of configurations for current source converter (CSC) based medium-voltage PMSG wind energy conversion system (WECS) are investigated, analyzed and compared in this paper. The advantages and disadvantages of these configurations are illustrated. And detailed control scheme for each configuration is analyzed and conducted. Comparisons are carried out based on analysis and simulation results in terms of converter cost, operation range, generator-side current THD, maximum power point tracking (MPPT), dynamic performance, and number of control freedoms. Among all, the back-to-back pulse-width modulated (PWM) current source converter is considered to be the most promising converter. Additionally, it is further illustrated that the DC-current value determined by both generator-side and grid-side can ensure a full operation range under all operation conditions.

"A multifunctional current source inverter control for wind turbine grid interfacing,"

M. S. Hamad and K. H. Ahmed, (2015)

This paper presents a multifunctional PWM current source based wind energy conversion system for wind turbine interfacing. The proposed predictive controller exchanges the power with the grid and the load and achieves active power filtering function by improving the grid power quality due to the distortion caused by non-linear loads. The proposed system is modeled using MATLAB/Simulink and the performance is tested for different operation conditions.

"Analysis and design of a control strategy for tracking sinusoidal references in single-phase grid-connected current source inverters,"

C. R. Baier, M. A. Torres (2018)

This paper aims to present the analyzes of different grid current controllers applied in a full-bridge inverter used in distributed generation (DG). The presence of harmonic interaction in the grid, can be explained by the impedancegrid resonance problem between the equivalent grid impedance and the inverter impedance. The analyzes of different control strategies involve aspects such as power losses, quality of the current injected into the grid and dynamic performance during grid disturbances. In order to study the converter performance connected to the grid, it is made a comparison in this work by means of three controllers: proportional and integral (PI), proportional resonant (PR) and repetitive (RT). The simulation results show the higher efficiency of the PR and RT controllers in grid distorted conditions. The modulation techniques and discretization methods also affect the grid power quality, focusing in particular on the Bipolar technique. Therefore, this work proposes with these mechanisms to improve the performance of the operation DG grids, and consequently to increase the system power quality.

"DC-Link current optimal control of current source PWM converter,"

C. Zhu, H. Wang, J. Zhang, X. Cai(2020)

The doubly-fed wind energy conversion system (WECS) based current-source converter has the advantages of robustness, inherent short-circuit protection and fault ride through capability. In addition, with the development of semiconductor technology and high switching frequency reverse resistance devices, the weakness of conventional current source converter (CSC) including low switching frequency, large passive components and slow dynamic performance can be improved by PWM current-source converter technology with high switching frequency. To apply this technique on doubly-fed induction generator, this paper analyzes the system configuration, operating principles and control strategies, then introduces an operation point calculation method for minimum DC bus current control of converters. The simulation results and prototype experiments verify the validity of system configuration, the optimization design of parameters and control strategies.

Methodology :

Configuration and Operation Principles

- **Back-to-back Current Source Converter**

DFIG wind energy conversion system based current-source converter is shown in Fig. 1. The rotor side converter (RSC) and grid side converter (GSC) adopt back-to-back topology by interconnecting with DC-side inductor. Converters adopt three phase configuration, each phase consists of upper and lower bridge arms that adopt RB-IGBTs. RB-IGBTs have reverse blocking capability, based on space vector PWM (SVPWM), PWM current pulse with sinusoidal fundamental are built by DC current chopping in AC side. The inductor current must be continuous, thus during the turn-off process of RT-IGBT, a capacitor is required to buffer the AC side inductor current for assisting commutation. Therefore, capacitors are installed in the AC side, and they also make up low-pass filter with AC inductors for eliminating higher harmonics to meet the requirements of the grid and generators; Rotor-side capacitors can compensate exciting current for induction motor without the need for forcing converters to provide reactive current, thus it helps to reduce the capacity of converters.

In addition, DC-side inductor enables bridges to avoid the short circuit fault. RSC and GSC are both able to control active power and reactive power separately and decoupled. The DC bus is utilized for active power transport and enables the converters operate in four quadrants.

- **DFIG Wind Power Conversion System Based on CSCs**

The stator of DFIG connects with grid by boosting transformer and rotor connects with grid by converters, which realizes DFIG WECS feeds back to grid in double terminals. According to the DFIG theory, the delivered active power is decided by motor slip s:

$$s = 1 - n/n_s$$

Rotor mechanical speed and synchronous speed of DFIG are represented by n and ns separately. There are three operating conditions named hypersynchronous, synchronous, and sub-synchronous, separately corresponding to s > 0, s = 0 and s < 0. Under hypersynchronous condition, both stator and rotor delivery active power to the grid, while in the synchronous condition, only the stator deliveries active power. And under sub-synchronous condition, stator deliveries active power but rotor consumes active power. RSC controls the torque of DFIG to keep wind turbine work in variable speed; GSC stabilizes DC-Link current to realize active power transport between two converters and achieve reactive power adjustment by decoupling active power and reactive power controls. Different from conventional current inner-loop control and voltage outer-loop control of VSC, the AC side current control of CSCs can adopt open-loop strategy because of the current-source character of DC part. Open-loop control is a simple control strategy and it is helpful for avoiding unstable control due to grid parameters fluctuating. This kind of control strategy can improve the robust of converter and flexibility toward the grid. Because the characters of VSC, there are many restrictions such as grid-tied voltage, linearity of modulation and devices insulation as well as that the DC voltage must be constant. However, for CSCs, the DC-Link current can be flexibly varied according to the power. Therefore, a new DCLink optimal current control strategy of DFIG based CSCs is proposed to improve the efficiency of WECS.

- **Modulation Strategy**

Based on modulation strategy, CSCs can produce PWM output current. Three phase capacitors paralleled in AC side of inverter assist commutation and eliminate higher harmonics components in output currents. The main typical modulation methods are specific harmonic elimination (SHE), trapezoidal pulse width modulation (TPWM) and space vector modulation (SVM).

System Control Strategy

- **Rotor-Side Converter Control**

The purpose of rotor-side converter is to control the rotor speed for catching the maximum power point and to control stator-side reactive power. Because DFIG's stator is connected directly to the grid, stator voltage and flux linkage will keep constant if the three-phase grid voltages are balanced and disturbance can be neglected. So, control strategy based on stator flux is adopted in this paper. speed controller controls the rotor speed to follow the desired speed value which is calculated based on maximum power point tracking (MPPT) algorithm, the output value is torque current Irq (q-axis current in stator-flux orientation d-q rotating coordination system). The Ird (d-axis current) comes from stator-side reactive power instruction. Both above two currents minus rotor-side filter capacitor current separately, then the output current of converter (Iwrd and Iwrq) can be obtained. Adopting polar coordinate transformation, output current of converter can be transformed to the modulation ratio and rotating angle of current controller, then SVPWM model produces RBIGBT's trigger signal.

- **Active and Reactive Power Decoupling Control of GSC**

The control objective of GSC is to stabilize the DC-Link current for active power transporting between rotor and the grid. Furthermore, GSC is in charge of controlling reactive power delivered to grid by following the reactive power instructions. Assuming the voltage of grid is stable, GSC adopts vector control strategy based on grid voltage orientation.

DC bus current controller exports d-q axis grid-connected current (Igd and Igq), the q-axis current is obtained from grid-connected reactive power instruction. Combining the grid current with grid-side capacitor current, output current of GSC can be achieved and represented as Iwid and Iwiq. Transforming them to the modulation and rotating speed of current controller, SVPWM model produces RBIGBT trigger signal.

DC-Link Current Optimal Control

Assuming the inverting lapping angle can be neglected, the DC-Link current is equal to the peak value of converter's output current. Taking the peak value of AC current of both RSC and GSC (Irsc_max and Igsc_max) into consideration, if the larger one between them is chose as DC bus reference current, the converter will be able to operate in stable situation and realize DC-Link current optimal control.

Conclusion

The DFIG wind energy conversion system which adopts current source converters is beneficial for system robust, short circuit protection and fault ride-through capability. Moreover, it has a good performance even when converters operate in parallel. Based on high-frequency RB-IGBT, CSC can achieve the same performance of VSC and even better. Thus, this paper decides to conduct research on CSC-based DFIG wind power converter system. Firstly, this paper analyzes the configuration, operation modulation strategy and control strategy of DFIG WECS.

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