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Passivity-based control of cascaded multilevel converter based D-STATCOM integrated with distribution transformer

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ABSTRACT

This paper proposes a novel adaptive passivity-based control (PBC) of cascaded multilevel converter based D-STATCOM integrated with distribution transformer for medium voltage reactive power compensation. A cascaded multilevel converter-based D-STATCOM is connected to a group of taps on the primary windings to form an integrated structure. The power transformer is used as coupling transformer at the same time. The structure is helpful to achieve a flexible connection point voltage and improve the capacity utilization of the transformer. The winding currents distribution and compensation capacity constraint are analyzed in detail by steady-state phasor diagrams. A nonlinear passivity-based control is designed to achieve reference currents tracking. Furthermore, an adaptive control is also presented to attenuate the effects of parameters perturbation on the performance of the D-STATCOM. Finally, down-scaled prototype experimental results are provided to verify the steady and dynamic performances of the integrated D-STATCOM with PBC for reactive power compensation.

1. Introduction

With the development of cascaded multilevel converter (CMC), CMC-based distribution static synchronous compensators (D-STATCOMs) have been considered as one of the most promising custom power devices in medium voltage (MV) distribution networks. However, conventional CMC-based D-STATCOMs suffer from high voltage stress resulting in a large number of H-bridge in series, which drives up the initial costs and also increases the control complexity and unreliability.

To reduce the voltage stress for voltage source converter (VSC), a combination of passive devices (C, LC, LCL or their combination) and VSC has been proposed. The VSC was connected in series with passive LC filters to reduce its power rating in Refs. [1–3]. Since the capacitors mainly sustain fundamental voltage at the point of common connection (PCC), the VSC can operate at a lower dc-link voltage level. However, the dynamic performance of the system was not discussed in their work. In Refs. [4] and [5], the thyristor-controlled reactor (TCR) was connected in series with a small rating VSC to achieve reactive power compensation and harmonic elimination. The VSC sustains low fundamental voltages and its rated capacity is greatly reduced. However, the dynamic response time is longer than conventional STATCOM, because reactive power is mainly provided by TCR. In addition, the coordination control of passive parts and active parts is also a great challenge for the controller design.

For the hybrid structures mentioned above, the VSC is connected to the grid indirectly to achieve lower connection point voltage. Motivated by the structure of autotransformer, the authors in Refs. [6] and [7] proposed a hybrid power quality system integrated with the traction transformer for the electrical railway system. The VSC was connected to the winding taps on the delta-connected windings. To make full use of the spare capacity of the distribution transformer and obtain a flexible connection voltage for D-STATCOM, a reactive power compensation technology of STATCOMs integrated with distribution transformer has been presented in our previous work [8]. Three diode clamped three-level compensation modules are placed on the three vertexes of the delta-connected windings of the distribution transformer. The connection point voltage is only twenty percent of the line voltage, but the structure is not so economical (it needs three sets of D-STATCOM).

Unlike the previous work, the main contributions of this paper can be summarized as follows.

1) The structure of a cascaded multilevel converter (CMC) based D-STATCOM connected to a group of taps on the primary windings of a transformer is proposed in this paper.

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2) The compensation principle and winding current distribution are clearly clarified and validated by experimental results.
3) The nonlinear PBC method is introduced to control the CMC based D-STATCOM to enhance the robustness and simplify the controller design of the proposed system. An adaptive design is also proposed to attenuate the influences of parameters perturbation.

The compensation performance of the D-STATCOM mainly hinges on the control method for the inner current loop. Linear control methods such as proportional-plus-integral (PI) control were widely used to control the inner current loop of the D-STATCOM, which were based on a linearized model at the nominal operating point [9–11]. However, the load changes frequently in distribution networks so that the operating point of the D-STATCOM also changes frequently. Therefore, it is not easy to guarantee uniform and satisfactory control performance over the entire operating range for PI controllers. Furthermore, it is hard to find the suitable parameters for the PI controller design. To enhance the robustness and simplify the controller design, PBC as a nonlinear control has been investigated in power converters [12–19]. The PBC method is an energy shaping-based approach by considering the system dissipation. According to the Lyapunov stability theory, the PBC is guaranteed that the equilibrium point of the system is locally exponentially stable in the operating range. The nonlinear PBC controller was used in STATCOM in Refs. [16–19]. Nevertheless, the studies of PBC applied to CMC-based D-STATCOM are still rare and there are no discussions of parameters perturbation problems in these literatures. Comparisons analysis between the conventional PI control approach and PBC method are provided in this paper. Furthermore, an adaptive control is also presented to attenuate the effects of parameters perturbation on the performance of the D-STATCOM.

In this paper, a CMC-based D-STATCOM is connected to a group of taps on the primary windings of a distribution transformer to form an integrated structure to achieve centralized dynamic reactive power compensation. The compensation currents are injected to the system via the taps to achieve reactive power compensation. To prevent primary windings from overcurrent, a detailed phasor analysis of the winding current distribution is presented. A nonlinear passivity-based control (PBC) is applied to enhance robustness and simplify the controller design. Moreover, an adaptive design is proposed to attenuate the influences of parameters perturbation. The prototype experimental results have verified the effectiveness and good performance of the integrated structure with PBC.

2. System configuration and model

2.1. System configuration

The proposed D-STATCOM integrated with distribution transformer is shown in Fig. 1. The existing parts are shown by the gray-colored components. The system consists of a multi-taps transformer, a *LCL* filter and a CMC-based D-STATCOM. Three winding taps (labeled as A1, B1 and C1) are designed on the primary windings of the D-Y connection transformer to reduce the voltage stress for the D-STATCOM. The *LCL* filter with passive damping is used to eliminate the switching harmonics injection.

Suppose that the power switches are working under ideal condition. u_{TA}, u_{TB} and u_{TC} are the three-phase voltage of the winding taps (connection point voltage). u_{A}, u_{B} and u_{C} are the three-phase output voltage of D-STATCOM. i_{SA}, i_{SB} and i_{SC} are the three-phase supply current. i_{TA}, i_{TB} and i_{TC} are the three-phase injection current. L_1 is the inductor at the gird side, and L_2 is the inductor at the converter side. C_f is the filter capacitor. R_d is the damping resistance.

The winding taps can be designed flexibly as long as the line-to line voltages $u_{\mathrm{A1\_B1}}$, $u_{\mathrm{B1\_C1}}$ and $u_{\mathrm{C1\_A1}}$ are symmetrical. The advantages of the proposed structure can be summarized as follows:

1) The initial investment is reduced. Initial and operational costs are the major constraints for the application of D-STATCOM in power system. The reactive power requirements increase with time, so it is not necessary to install a large capacity D-STATCOM at the very beginning. Compared with conventional transformer-less configuration (D-STATCOM connected to the MV buses directly), the initial connection point voltage is decreased, so less modules are needed to block the voltage. Less modules will also decrease the complexity and unreliability of the system.
2) The capacity utilization of the transformer is improved. The distribution transformer is expected to operate more than twenty years. In the first few years, the load ratio is relative low and the spare capacity is not fully utilized, so it is potential to use the spare capacity for reactive power compensation. There is no need to configure an auxiliary coupling transformer.
3) It can expand according to reactive power requirements increasing. We can design several groups of taps on the primary windings. With the increase of reactive power requirements, we can change connection taps to increase the connection point voltage to improve the compensation capacity. We can also add extra H-bridge cells owing to the good expansibility of CMC-based D-STATCOM.

Nevertheless, it also has some weaknesses.

1) For the Dyn connection distribution transformer, the single phase line-to-ground fault occurred at the primary side may cause overvoltage at the connection point, which may damage D-STATCOM. Therefore, the proposed structure needs the sensitive over-voltage protection for D-STATCOM.
2) Compensation capacity would be reduced under heavy load, low power factor condition. This will be discussed in detail in Section 2.4.
3) It is not technically difficult to design taps on the transformer winding. However, it may be a potential commercial disadvantage because there is a non-standard transformer configuration.

2.2. Compensating principle

Fig. 2 shows the three-phase structure of the transformer. Taking one phase as an example, say phase a, W_1, W_2 and W_3 are the number of turns of winding A_A1, A1_B and the secondary winding, respectively. $\dot{I}_{\mathrm{A\_A1}}$ and $\dot{I}_{\mathrm{A1\_B}}$ are the currents of winding A_A1 and A1_B. The current reference direction is shown by solid arrows in Fig. 2. In phase b and c, we have the analogous definitions.

According to Kirchhoff's current law (KCL), we can obtain

$$\begin{cases} \dot{I}_{\mathrm{C1\_A}} + \dot{I}_{\mathrm{SA}} = \dot{I}_{\mathrm{A\_A1}} \\ \dot{I}_{\mathrm{A1\_A}} + \dot{I}_{\mathrm{TA}} = \dot{I}_{\mathrm{A1\_B}} \\ \dot{I}_{\mathrm{A1\_B}} + \dot{I}_{\mathrm{SB}} = \dot{I}_{\mathrm{B\_B1}} \\ \dot{I}_{\mathrm{B\_B1}} + \dot{I}_{\mathrm{TB}} = \dot{I}_{\mathrm{B1\_C}} \\ \dot{I}_{\mathrm{B1\_C}} + \dot{I}_{\mathrm{SC}} = \dot{I}_{\mathrm{C\_C1}} \\ \dot{I}_{\mathrm{C\_C1}} + \dot{I}_{\mathrm{TC}} = \dot{I}_{\mathrm{C1\_A}} \end{cases} \tag{1}$$